A Simulation Framework for Integrated Water and Energy Resource Planning

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1. Introduction

Affordable electricity and accessible, clean water are fundamental to economic production and human livelihood. They are so much so in fact that wars are now fought over energy resources and access to water commonly separates the poor from the desperate and oppressed poor (World Bank, 2010). While these problems are world-reaching, even the richest nations struggle to equitably and economically plan for the acquisition, use, and distribution of energy and water resources. In the United States for example, groundwater aquifers are being drained for agricultural production, electricity generation suffers unplanned shutdowns during extreme droughts, and questions surrounding hydraulic fracturing of natural gas are causing many to doubt the future of their water supplies. I suggest that improved water and energy planning can help avoid these negative outcomes.

The primary purpose of this work is to improve the holistic value of electricity development strategies by integrating water resources management criteria into the electricity system planning process. I concentrate on electricity system planning because I believe many private electrical utilities are failing to incorporate the long term public interest while targeting least-cost expansion. Therefore, I bring multiple decision criteria for water and energy stakeholders into a framework for integrated water and electricity planning. Currently, there exists a large amount of separation in the range of tools that attempt to couple power development, public policy, and water resources. I developed a modeling framework that combines the most salient aspects of many tools into one system. My plan for this framework – the Water and Energy Simulation Toolset (WEST) – is to expose decision makers and stakeholders to a coupled representation of water and energy systems subject to multiple development and management scenarios. With this exposure, collective decisions can be made that represent the criteria of many instead of a system that defends the criteria of a few.

I begin with an overview of how and why we plan for water and energy development, primarily from a resource management viewpoint. I show how computer modeling has improved the water resource planning process by allowing humans to better integrate various bodies of knowledge and manage the resulting complexity. Regarding energy planning, I discuss the current framework of private and public interaction for electricity development, and continue by examining the modeling approaches for energy resource planning. I pose that energy and water planning are not integrated enough, and give examples why. Furthermore, I propose a more integrated process and discuss how this approach would be structured, with an eye always to managing complexity. I introduce WEST, which is the collection of computer modeling tools that I developed to aid decisions within this more integrated planning process.

I propose how WEST may improve integrated water and energy planning, and discuss how such an approach may be used in the western United States (herein: *the West*).

2. Energy and Water Interdependency on the Snake River

Effective planning for the sustainable use of water resources requires understanding of how the intricacies of law set the rules for the use of water. In the West, laws governing water use have evolved in a commonly water-limited environment. As the West was settled rapidly in the mid 1800's, early state and territory governments (most notably in Colorado and California) found that traditional riparian water law limited the productive and equitable use of land, particularly for the agricultural and mining interests that dominated early settlements (Reisner, 1993). These pioneers developed the water governing system of prior appropriation, which is commonly summarized as "first in time, first in right." Ownership of the water is assigned to the state, but the right to divert and apply that water to a beneficial use may be held by an individual. That individual is said to have a water right, which confers an associated date of appropriation, a location of use, and an amount of water ideally commensurate with the stated beneficial use. According to Title 42 of Idaho Code, it is the state's obligation to "equally guard all the various interests involved" by appropriately allocating and managing the system of water rights. It is the state's role to ensure that all senior water rights holders are given priority over those junior, if in fact the seniors continue to put their water to beneficial use and that use is within the laws that govern waste and abandonment.

A problem that water planners and attorneys deal with frequently is that the laws of prior appropriation govern diversions, or water withdrawals. The right to consume, which is hydrologically equivalent to the right to evapotranspire, is governed by sector-specific laws concerning wasteful practices. An alfalfa farmer may possess a senior water right for a rather large flow and will evaporate over half of his diversion, while a hydropower dam downstream with a junior right must wait for any return water, even though the dam consumes a relatively small fraction of its total flow and can put that flow to greater economic use. Essentially, prior appropriation does not reflect the relative value of water that is being irreversibly consumed. The West governs on diversion, but value is measured relative to consumption.

When high-value water consumers with senior water rights are upstream of more junior low-value water consumers, prior appropriation tends to distribute water effectively. However, when upstream senior low-value, high consumption users evaporate a large portion of flow and leave the high-value users downstream of them dry, the downstream users have three options. One is to simply buy a more senior water right from one of the upstream users, assuming an individual is willing to sell, and go through the process of transferring that right to the new use. This may or may not be possible, since in many regions water rights are closely tied to property values and means of life that people do not wish to part with. The second option is to either increase local efficiency or pay upstream consumers to increase their efficiency. Efficiency may be measured in terms of diversion efficiency, which is the amount used beneficially divided by the amount diverted, or by consumption efficiency, which is the amount used beneficially divided by the amount consumed. An increase in either type of efficiency may lead to greater utilization of the water resource, but only diversion efficiency improves one's standing relative to water law. Again, the West governs on diversion, not consumption.

Figure 1: Swan Falls Dam on the Snake River, Idaho

The third option is litigation. In Idaho, one of the most famous instances of invoking this option is also a prime example of a problem for integrated energy-water management. A group of ratepayers in 1983 sued the Idaho Power Company (IPCo) claiming that the electric utility was not doing everything in its power to protect its water rights at its older dams. In response, IPCo initiated Idaho Power Co. v. State (104 Idaho 575) seeking a determination of validity for water rights at all of its dams and contesting the state water plan at the time. The state Supreme Court confirmed that IPCo did indeed hold a portfolio of water rights dating 1900-1919 at the Swan Falls dam, and that the water rights at all of IPCo's other dams were subordinate to all current and future upstream uses as stated in their licenses. To settle the amount of water right, the Idaho Department of Water Resources (IDWR) and IPCo entered into what is now known as the Swan Falls Agreement of 1984, in which IDWR agreed to seek funding for full adjudication of the Snake River, and IPCo agreed to a partitioning of its right at Swan Falls into subordinated and unsubordinated portions (Slaughter, 2004). The unsubordinated portion was assigned priority dates between 1900 and 1919 and the priority amount is 3,900 ft^3/s from April 1 to October 31 and 5,600 ft^3/s from November 1 to March 31. The subordinated right means that IPCo may use whatever those users upstream do not, but this portion of their right will always be junior to those upstream. The adjudication performed by IDWR consists of a database of all water rights holders with their associated priority and diversion amount, from which IDWR may make a determination of lawful water allocation. The Snake River Basin Adjudication process officially began in 1987 and is not complete to this day (Idaho Power Co, 2011; Otter et al. 2009).

The Swan Falls Agreement and subsequent adjudication highlight the need for integrated management from a water law perspective in Idaho. Not only did IDWR realize that a database and hydrologic model were needed to integrate all water rights into a cohesive system, they would soon find that groundwater would have to be managed conjunctively with surface water. This is because surface water had been appropriated to the point that the Snake River became dry during the summer below Milner Dam, approximately 150 miles upstream of Swan Falls, making Swan Falls fully dependent on baseflow from the Thousand Springs area during this time of year. Thousand Springs flow comes directly from the Eastern Snake Plain Aquifer (ESPA), which itself gains a significant portion of its recharge from other agricultural diverters upstream. With a dose of irony, the groundwater pumpers who had spread along the plateau after promises of cheap electricity from IPCo and IDWR would now technically be junior to most surface right holders as a consequence of the protection of those low power rates. IDWR's current plan to protect some of these pumpers and increase full utilization of the water resource is called the Comprehensive Aquifer Management Plan (CAMP), which promises to transfer pumpers to surface water, practices managed spring recharge of the aquifer, and enters land into fallowing programs at a cost to taxpayers (IDWR, 2009a).

3. Water Resource Planning in the West

The act of planning for water resource use and development is critical to ensure sustainable development and avoid dangerous “overshoot and collapse” scenarios similar to those believed to have been experienced by the Mayan and Khmer civilizations (Diamond 2005, Stone 2009). These civilizations created highly advanced systems for acquisition, delivery, and use of water, becoming rich and powerful in their eras. Ultimately, both suffered the loss of their wealth and power due in part to a failure to foresee changes in water supply and demand brought about by population increase, loss of government oversight, or changing climate.

On the surface, planning for water resource management seems simple: assess the resource, assess the need, and allocate the resource to the need equitably and appropriately. In practice, the details of this process create difficulty for even the richest societies. For instance, water quality and water availability are closely coupled with economic development and the productivity of managed and natural ecosystems. Merely assessing water availability can be a daunting task, highly dependent on spatial and temporal scales. Finally, to appropriately plan one must understand the potential for changes in all of these aspects through time. This is not to mention the effort of navigating a thick political atmosphere, bureaucratic red tape, and the host of private interests all trying to manipulate the planning process for personal gain.

In practice, the United States suffers from a fragmented approach to water resource planning and management. Over 20 different federal agencies have various responsibilities for national water policy, and in most cases water resource planning is performed at a state level by an additional host of agencies (US DOE, 2006; Jackson et al., 2001). In an assessment on water resource planning research, the National Research Council found that government organizations overseeing management of water lack top-down vision because authority is spread among these agencies at both federal and state levels (Committee on Assessment of Water Resources Research, 2004). Currently, water resource planning in the West does not fully incorporate all viewpoints, nor does it involve comprehensive and holistic decision criteria. In fact, many states decouple the management of water quality and quantity, with separate agencies commonly attempting to coordinate via interpersonal communication and offline agreement. Instead, a comprehensive water resource plan should include policy to manage water availability and quality from a holistic viewpoint. The plan should be comprehensive not only in its technical breadth, but also in the people it involves in the process and the viewpoints it incorporates, in order to truly understand how to best increase benefit to the public.

4. Electricity Resource Planning in the West

The electrical power system of North America is perhaps the largest machine on earth, with an overall demand of 830 gigawatts and 211,000 miles of high voltage transmission lines (Munson, 2005). Reliable and efficient delivery of electricity is so important to the economy that impacts of the one-day blackout of northeastern North America in 2004 are estimated at $6 billion in losses (US-Canada Power System Task Force, 2006). Electricity generation, transmission, and distribution are co-dependent with multiple public resources such as water, air, and land. Fossil fuel plants pollute the air, hydropower relies on reliable water flows, and transmission lines disturb miles of public lands. Because of these interdependencies, as well as the just-in-time delivery nature of electrical power grids and the lead times involved in generation expansion, electric power resources must be planned far in advance to meet demand reliably and economically.

Most electric utilities in the United States are owned by shareholders and are referred to as investor-owned utilities (IOUs). Classically, IOUs are managed as private enterprises, generating profit through the generation, transmission, and/or distribution of electricity. Many of these IOUs retain a territorial monopoly, in return agreeing to work within state-enacted regulatory frameworks. Therefore, while planning for water resource acquisition and use is largely performed by state agencies with feedback from private interests, planning for energy resource development is primarily a private endeavor with regulatory oversight from state and federal agencies.

In exchange for being allowed a territorial monopoly, in most states IOUs are required to submit a document that plans their acquisition and use of energy resources, commonly for twenty years into the future. This document is submitted and reviewed by the states’ Public Utilities Commission and is commonly called an Integrated Resource Plan (IRP). Public utilities that are commonly managed by municipalities may also generate an IRP in the interest of their residents. Ideally, the IRP process should balance utility profit with consumer interests for equitable economic production. However, often the criteria of most importance to the public are not represented in the IRP. Because insufficient resources exist at the state regulatory level, it is difficult to adequately guide the IRP towards the public interest.

5. Standard modeling practices for water resource planning

To plan for changes in water supply and demand, state agencies employ a suite of computer models that are designed to assess changes in basin management approaches. As an example, the Snake River Planning Model (SRPM) was developed by the Idaho Department of Water Resources (IDWR) as proprietary FORTRAN code in the 1970’s. Its goal was to project changes in water allocation based on changes in basin management practices such as diversion practices and reservoir operations. The measure of performance for the tested management plan is whether these procedures short users of water that would otherwise have received it, all else being equal. The SRPM has been updated using a stock-and-flow modeling framework (SD-SRPM) and is in the process of being updated using the commercial tool RiverWare™ (Hoekema, 2011). The structure of SRPM simulates operations given the supply and demand of water, which are calculated externally. Normal runs of the SRPM use historic supply information in the form of river reach gains, and historic demand information in the form of diversion data. Essentially, SRPM contains the rules of operating the system of canals, dams, pumps, levees, locks, and anything else managed by the state for water quantity goals. Because supply and demand are calculated externally, it can be a heavy undertaking to answer certain questions with the SRPM – namely questions where supply, demand, and operations are heavily interdependent.

To project how water supply may change, these agencies often employ the help of colleagues who run state-of-the-art physical models. These models normally do not simulate both supply and demand. For instance a model such as the Variable Infiltration Capacity (VIC) macroscale hydrologic model simulates the climate's impact on runoff, the results of which are sent to a routing model that calculates streamflow and can create the stream reach gain information for a model like the SRPM (Lohmann et al, 1998; Hamlet et al., 2009). Models such as VIC are distributed and physical in structure. This means that they are set up over a grid, and each grid cell uses physically layered parameters related to soil, vegetation, slope, etc. to calculate a three-dimensional water and energy balance. Running a distributed physical model takes a large body of inputs, but can give precise and reliable insight into the behavior of water supply if this information is available.

IDWR does have an in-house model that they turn to for selected questions about changing demand. The IDWR accounting model is a spreadsheet-based calculation that uses an internal database to assign location, amount, and timing to every water right in Idaho. This model has been updated to employ a geospatial framework and can be accessed via the internet (IDWR, 2013). Using the accounting model, planners can change demand profiles based on their hypotheses about how water users behave. The accounting model will return the list of diversions by priority based on inputs of user water requests. User behavior, however, is not built in. It must be calculated externally. In practice, this is a speculative task driven primarily by historical water use data (Hoekema, 2011).

Once supply and demand are forecasted and an operations plan is tested, agencies have one more set of tools at their disposal to assess the public's view of water management plans. These tools employ an aggregated view of the system, thereby conveying impacts of the water plan to multiple stakeholders. One example of an aggregated systems model is the Snake River Explorer developed by Ford (1996). This model aids in public understanding and contribution to integrated water management strategies by using multiple criteria. It is a computer simulation model based on the Snake River Basin in which the user is invited to set management practices and observe the status of criteria relevant to agricultural, environmental, and power industry stakeholders. One of Ford's conclusions from presenting the Snake River Explorer to stakeholder groups was that the tool was not as well received by seasoned water resource analysts who were used to working with more detailed models. To gain acceptance from these types of stakeholders, it is important to base the systems model on more detailed technical analyses whenever possible.

6. Standard modeling practices for electricity resource planning

To plan for changes in electricity supply and demand up to twenty years into the future, IOUs utilize a series of computer models. First, to forecast electricity demand – called load – two metrics are forecasted: energy sales in units of MWh, and peak demand in MW. Energy sales most commonly drive projected revenue, while peak demand drives the need for capacity expansion. The two most widely-used methods are economic regression and end-use models. Economic regression analysis heavily relies on historic behavior as an indicator of future performance. Often, the forecasted energy sales will be transformed into a peak demand by an empirically-determined load factor coefficient. This coefficient can itself be adjusted based on assumptions about climate or consumer behavior. End-use models are able to more explicitly account for effects of climate change and human behavior in their algorithms (Stoll, 1989). Some utilities, especially those with large amounts of hydropower resources, also run models that project future supply from existing resources. Those utilities with hydropower may also have in-house hydrologic modeling capabilities to test potential scenarios affecting their generation resources. Otherwise, utilities often assume that the historic supply of generation resources will stand as a reliable projection for the future.

Once existing supply and forecasted demand are projected, expansion plans are constructed to meet a desired excess generation capacity. These plans may include building and improving generators, managing demand, or building and improving transmission connections to other utilities. Development of expansion plans is part economic, part technical, and part subjective. On the economic front, planners use technology-screening curves to hypothesize sizes and types of units to add. On the technical front, each potential scenario is screened for reliability by running a multi-year reliability simulation. Potential scenarios are judged on the number of days per year with capacity shortages, termed the loss-of-load-probability (LOLP) index. Generators that are dispatchable – meaning their power can be tightly controlled throughout the day – are more capable of decreasing LOLP. Hydropower resources provide the benefit of being dispatchable and having low production costs. At the heart of developing expansion scenarios is the planner, who uses intuition and experience to decide the types of technologies that are used in these models (Bebic, 2008; Stoll, 1989).

Once a collection of scenarios is developed, a comprehensive economic model is run. First this model develops production cost curves that project multi-year production costs given fuel price forecasts, load forecasts from the first round of models, and dispatching rules. The cost from the production simulation is included in the economic model that includes the investment costs of each scenario as well as the projected revenue, and compares them all on the basis of their net present value. At the end of this entire process, the net present value is only one criterion in a multi-criteria decision process for integrated resource planning. Every utility has their own criteria and their own method of evaluating these criteria, and some use additional models for these purposes. Utilities that depend on water resources heavily, such as those with high hydropower penetrations, may include water-related criteria in this process.

From this study of the power system planning process, I observe that the modeling methods are in-depth and complex. They primarily utilize end-to-end coupling in which the outputs of one model are fed to another, and interdependencies between water impacts and expansion plans may take many iterations of this process to simulate, if they are simulated at all. I have not come across any mention of models that couple the planning criteria of power expansion plans with the planning criteria of water resource plans.

7. Toward more integrated water and electricity resource planning

As indicated in the preceding descriptions, many problems that involve energy and water feedback require tightly coupled understanding of these systems' co-dependencies. For example, changes in climate may spark increased demand for water resources and energy resources, leading to a higher demand for hydropower but lower hydropower availability. The belief that drives my work is that proposed solutions which concentrate on the management criteria of one problem will cause sharp changes in criteria for managing other problems, and that a holistic and integrated approach can examine all criteria for these problems at once, resulting in more equitable solutions and providing insight to those that have the ability to enact these solutions.

There are three distinct aspects to increased integration of energy and water resource planning. Figure 2a depicts the dependencies that society currently uses when planning for electricity and water resources development. Electric power system planners project electricity supply and demand, perhaps taking external, non-climate-biased projections of water supply into account for projections of hydropower. They fail to account for the drivers of climate change and the potential for changing water acquisition behaviors' influence on electricity demand. Conversely, water resource planners understand the water demands of electricity generation, and are increasingly accounting for climate change impacts on water supplies. However, they are not necessarily taking into account the influences of changing electricity prices on water demands, nor do they frequently assess the climate's role in changing behaviors in the electricity system. So in saying that energy-water planning is not integrated enough, I partially mean that we don't adequately account for the physical coupling between these systems, and that we should strive for a more coupled analysis such as that represented by figure 2b.

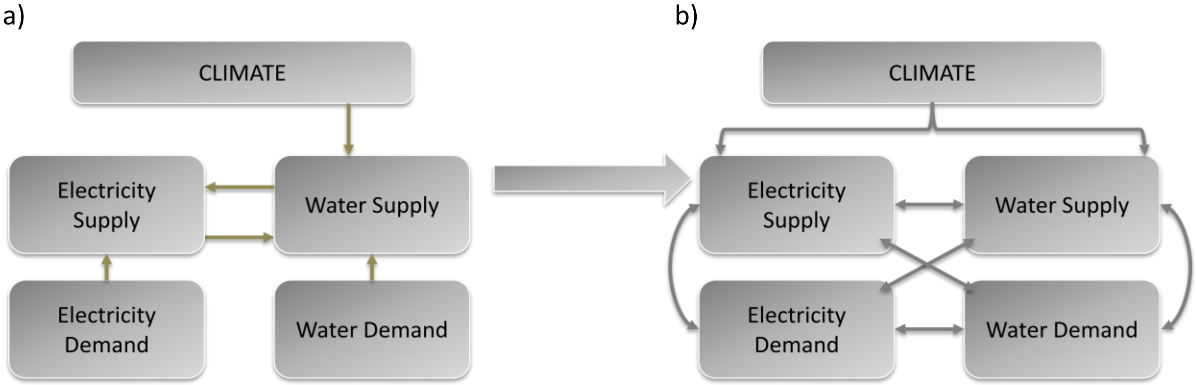

Figure 2. a) My current account of the amount of coupling in energy and water resource planning. b) My view of the amount of coupling required for integrated water and energy resource planning.

By calling for increased integration, I also mean that the potential for conflict among users is not explicitly approached when performing energy and water resource planning. For instance, the Snake River Basin Adjudication process is a prime example of a need to incorporate future behavior of electricity supply and demand within water resource planning under a changing climate. Power interests are likely to request the protection of the Swan Falls right during this process, while surface water agricultural interests will want to know that water stored in the upper basin reservoirs remains designated for agriculture and not for downstream power. Groundwater agricultural interests are likely to prefer the status quo, in which they are partially protected from curtailment. Environmental interests are likely to prefer that river flows return to a more natural state, and will be cautious with their approval of aggressive modifications to Idaho's rivers. So, when integrating the water and energy resource planning process, the viewpoints and criteria of all water users must be accounted for, and the best way to do this is to integrate them into the process itself.

Finally, increasing integration in energy and water resource planning calls for the integration of multiple approaches to water basin planning. Just as the water resource analyst may require high fidelity to achieve the desired level of precision, the modeler targeting stakeholder engagement requires clear representation of how performance metrics and decision criteria are affected by potential plans or policies. An approach that integrates the utility of both methods while managing inherent complexity will not only gain insight into the interconnected nature of the energy-water problem, but improve acceptance among a diverse set of users.

With these three concepts of integration in mind – integration of systems, integration of stakeholder viewpoints, and integration of approaches – I developed the diagram shown in figure 3, which outlines my complete view of a more integrated energy and water resource planning process. My approach retains the goal of usability by a diverse group of users, but does not rely on the same level of simplification as the aggregated stakeholder involvement models categorized in section 5. I use a fully coupled representation of the energy-water physical system, and simulate the performance metrics relevant to agencies such as IDWR, as well as private interests such as IPCo and irrigated agriculture. My vision is that such an approach will help to serve as a forum for decision makers and stakeholders on both the energy and water sides of issues to discuss the merits of proposed policies, plan for foreseeable changes to the system, and evaluate plans once they are underway. The faster this loop closes, meaning the more iterations of the outer loop in figure 3 occur, the more successful an integrated planning process will be.

8. Object-oriented System Dynamics: Managing complexity to merge precision and usability

While the energy-water interdependency has been highlighted by multiple authors (Jackson, 2001, Sovacool, 2009, Tidwell 2009), development of coupled models that incorporate the criteria of water management interests has been somewhat limited. There are three core examples which highlight the range of approaches that have inspired my work. First, the study by Hamlet et al. (2009) is extremely thorough and reflects some of the best knowledge about the impact of changing climate on natural hydrology processes and hydropower generation. It is a primary example of how, with a large amount of work, detailed models can be coupled with the best available system data to address an energy-water problem. These modeling systems have multiple models at their core, starting with climate drivers and ending with hydropower calculators. However, they do not employ cross-sector dynamic feedback nor are they very usable by non-professionals. Sandia National Laboratory employs two approaches to better integrate water and energy planning. The first is that of Tidwell et al. (2009), in which large amounts of data drive statistical models designed to predict future energy demands on water resources. This method, however, is not as useful for determining the coupled future water management impacts on energy resources. In contrast, Tidwell et al. (2004) apply a stakeholder-oriented consensus-building approach using simplified hydrologic models tightly coupled to models of human behavior and planning metrics. This is much more useful for understanding how the behavior of management criteria are impacted by potential plans, but these models are not meant to accurately examine the physical behavior of these systems. In order to develop a model that can be accepted by specialists and non-specialists alike, I incorporated each of these studies' inferences into WEST, combining physical accuracy, system coupling, and stakeholder involvement.

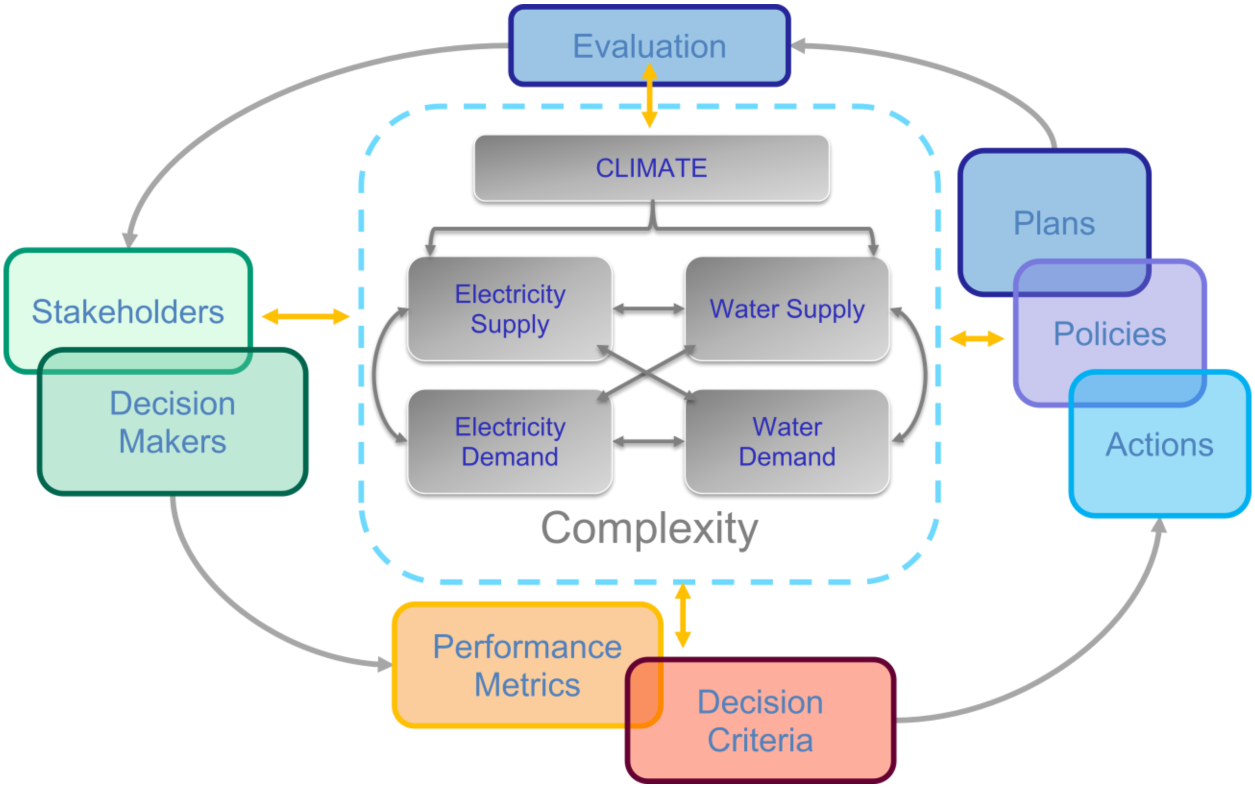

Figure 3. My vision of an integrated water and energy resource planning process using tightly coupled, physically accurate models to speed decision-making and evaluation while including multiple viewpoints.

To abstract the appearance of structural complexity in WEST, I utilized an approach that I call object-oriented system dynamics. Object-oriented system dynamics utilizes a combination of the object-oriented programming philosophy with the system dynamics modeling philosophy. The object-oriented element of my approach allows me to abstract structural complexity while conveying meaning, and makes WEST usable by more than hydrology modelers (Meyer, 2000). The system dynamics element helps me concentrate on the links between variables, and eventually between objects that define the coupled nature of water resource systems managed for multiple goals (Forrester, 1971; Ford, 2009). With object-oriented system dynamics, the modeler is constantly encouraged to think of individual component behavior in conjunction with big-picture feedback loops involving multiple components. In the case of integrated energy-water planning, the use of object-oriented system dynamics modeling can provide coupling between multiple human and physical systems in addition to autonomous and abstract behavior of components within these systems. In this way, the use of object-oriented system dynamics is as much a mindset as a methodology.

9. Introduction to WEST and its components

The Water and Energy Simulation Toolset, or WEST, is my answer to the failure of electricity expansion planning to account for the complexity of water resource systems within its planning process. It is my answer to the lack of coupling between electricity and water models that leads to a lack of analysis capability. It is also my answer to the lack of a public forum for how best to allocate water resources and how to collectively grow an economy that is heavily dependent on access to clean water and dependable, inexpensive energy.

WEST is currently primarily a hydrology modeling tool with human-initiated demand response. I use the term *currently* because WEST is structured in such a way as to evolve depending on the problem at hand. It simulates multiple criteria relevant to water resource managers and electricity development planners, but it uses hydrologic variables such as streamflow, snowpack, and agricultural diversions to determine these criteria. Its primary purpose is to elucidate the impact of water management plans and variations in climate on the criteria. WEST includes the behavior of water users and their water management decisions. It absolves from categorical complexity and it abstracts structural complexity to the point of usability in multi-stakeholder decision analysis forums. It has been designed to determine the long-term, broad scale impacts of water management policies on goals that are important to the entire basin, and to confer this knowledge to energy planners, water resource planners, and the public.

WEST is not designed to predict the near future, or even the long-term future values of the variables it simulates. Rather, WEST models predict modes of behavior given certain changes to basin management practices or external climate drivers. WEST does not simulate the physics of electricity generation, transmission, or distribution, nor does it include a determination of the overall economic impact of the water management plans under testing. WEST does not simulate behavior at the level of individual water users, nor does it simulate fine temporal behavior. Instead, it aggregates these measures to a level that simplifies the approach while still being applicable to water and energy management decisions. It does not simulate the demand for energy, other than to suggest that changes in water demands can cause changes in energy demands.

I constructed WEST using the object-oriented system dynamics philosophy. WEST models are constructed using objects, which I call *WEST components*, to create an overall hydrologic simulation of a physical basin. A collection of WEST components can create a simulation of a large geographic area in which water has multiple physical states and multiple uses. WEST components represent aggregate behavior of a certain type within an area, whether that area is a watershed, a reservoir, or an aquifer. This area sets the geospatial precision with which WEST models may apply. All WEST components adhere to a single global temporal resolution. I have to date tested a monthly resolution, and do not expect WEST results to be valid if driven towards daily resolutions.

Behavior within WEST is largely endogenous. Endogenous behavior means that most variables within WEST are dependent on other internally-calculated variables. As a result of the largely endogenous behavior, WEST components and models have few inputs and few outputs. Rather than calculating certain aspects of the basin under study, WEST models strive to *be* the basin under study. One of the largest difficulties of the endogenous behavior is that WEST models can become difficult to calibrate to observed behavior. This difficulty stems from the thick interconnected web of variables created with heavily endogenous models. Every time the modeler changes one relationship, it affects multiple dynamic variables. The primary benefits of WEST's endogenous behavior are twofold. First, it allows WEST models to have very few inputs. In fact, the only inputs to my WEST model of the Snake River Basin are precipitation and temperature. Second, WEST models do a good job at extrapolating behavior into unobserved operating modes. This is because more of the relationships between predictive variables are explicitly included in endogenous models.

The four WEST components that have been tested are the natural water balance, irrigated agriculture, managed reservoir, and groundwater aquifer components. A high-level view of the inputs and outputs for each component is shown in figure 4. Every component-level input in figure 4 that is not precipitation or temperature is calculated using other components, giving rise to the endogenous behavior. In contrast to the low number of inputs, WEST models can simulate hundreds of water and electricity-related variables, many more than can be included in figure 4. This is because a large number of physically representative behaviors are simulated endogenously by each component. A summary of the most relevant physical variables for each component is included in table 1.

Table 1. A list of selected physical variables within each WEST component

Component Name	**Stock variables**	**Rate Variables**
Natural water balance	snow water equivalent, upper Soil Moisture, lower Soil Moisture	snowfall, rainfall, incident moisture, direct runoff, surface runoff, baseflow, evapotranspiration, soil seepage, groundwater seepage
Irrigated agriculture	N/A	surface agriculture diversions, surface managed recharge diversions, groundwater pumping, groundwater pumping losses, canal losses, water applied to fields, field evapotranspiration, lateral returns, groundwater seepage
Groundwater aquifer	groundwater storage	total recharge, total pumping, interaquifer flow, springflow
Managed reservoir	reservoir storage	reservoir inflow, reservoir outflow

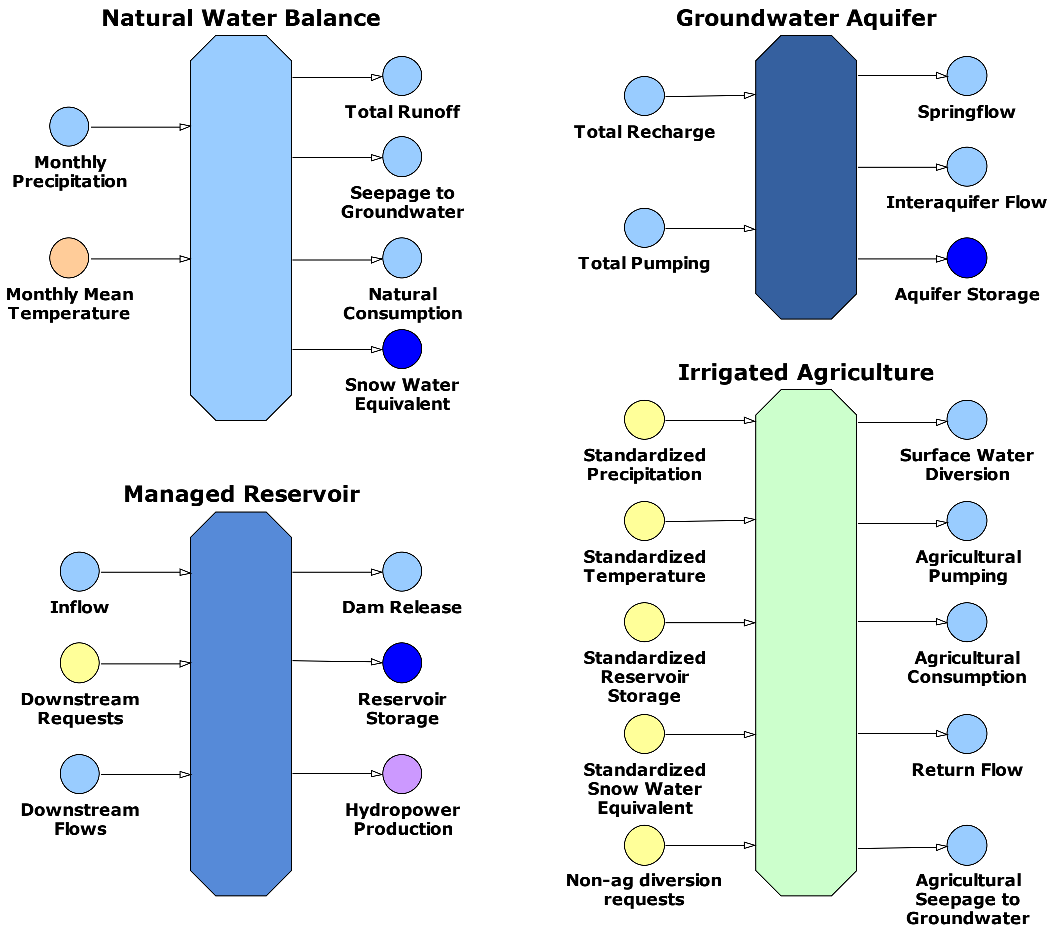

Figure 4. An "input-output" depiction of the four WEST components. Octagons are the modeling components, while circles are variables that pass in and out of the components. Yellow variables denote information flow, light blue denotes water flow, dark blue denotes water storage, orange denotes atmospheric energy flow, and purple denotes electrical energy flow.

The natural water balance component is used to simulate the unaltered hydrology of a specified watershed. The irrigated agriculture component simulates the diversion, application, consumption, and return of water due to agricultural practices within an area. The watershed boundary of the natural water balance component sets the boundaries for irrigated agriculture components. The managed reservoir component commonly exists between two watersheds, and simulates the management of dam releases for multiple criteria. The groundwater aquifer component simulates the storage of water within the physical boundaries of an underground aquifer, and the dynamic connection between that aquifer and the surface.

Because WEST components simulate aggregate behavior within their boundaries, only one value of each variable shown in table 1 is simulated every timestep per component. Streamflow in WEST can be combination of variables from multiple components. The spatial resolution for the natural water balance component, however, most commonly sets the locations where streamflow is simulated within WEST models.

I implemented the WEST components using the Powersim Studio system dynamics environment. Powersim is a visual computer modeling environment in which the system dynamics stocks are represented as squares and flows are represented as thick arrows with valves. Causal relationships between variables are represented as thinner arrows, and static dependencies that never change are represented with dotted thin arrows. Other variables that explain the relationships between stocks and flows are called auxiliaries and are represented as circles. Powersim is perhaps the most industrial of the available system dynamics modeling tools. It is used more commonly for large or complex models because of its professional features such as database connectivity and built-in programming interface. Some of the teaching-friendly features in other system dynamics tools, however, are not included in Powersim. The most obvious omission is the lack of an ability to display variables from multiple model runs on a single time graph.

10. Application of WEST to the Snake River Basin

I developed a proof-of-concept model named the *Cutthroat River Model* in order to demonstrate the capability of WEST to simulate a holistic water balance for planning of water and energy development. The Cutthroat River model simulates hydrologic behavior relevant to energy and water planning in a real world basin – the Snake River in southern Idaho. A simplified layout of the Cutthroat River Basin is shown in figure 5. This system has been constructed using the WEST framework and carefully calibrated to represent both hydrologic and human behavior of key elements of the actual Snake River Basin from its headwaters near Yellowstone National Park to its passage through Hells Canyon on the Idaho-Oregon border. Table 2 explains the reasoning behind creating a somewhat fictional system that closely mirrors a real one, that reasoning being rooted in system dynamics philosophy. I named the basin after the Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*), which is native to the upper Snake River and puts up a good fight to the eager angler.

To model the Cutthroat River Basin, I linked the appropriate object-oriented WEST components to one another and to climate inputs from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) group at Oregon State University, whose results are available for download (PRISM, 2011). I call the completed model the Cutthroat River Model. It simulates water storage and flows relevant to the water and energy management goals described in Table 3.

I built the Cutthroat River Model in conjunction with designing the first generation of WEST components. By doing so, I was able to learn through trial and error about the structural relationships between these components necessary to simulate the wide array of conditions present in a basin such as the Snake River. I interconnected WEST components to create models of watershed-scale behavior, including every salient aspect of the water balance. The only water exogenously introduced is from the atmosphere as precipitation, and the only water that leaves before the last streamflow is by consumption. Figure 6 shows the interconnection of WEST components that make up the Cutthroat River Model. Connections in this diagram are only the physical water and energy flows – the full spread of connections includes information passed both up and downstream for human decisions.

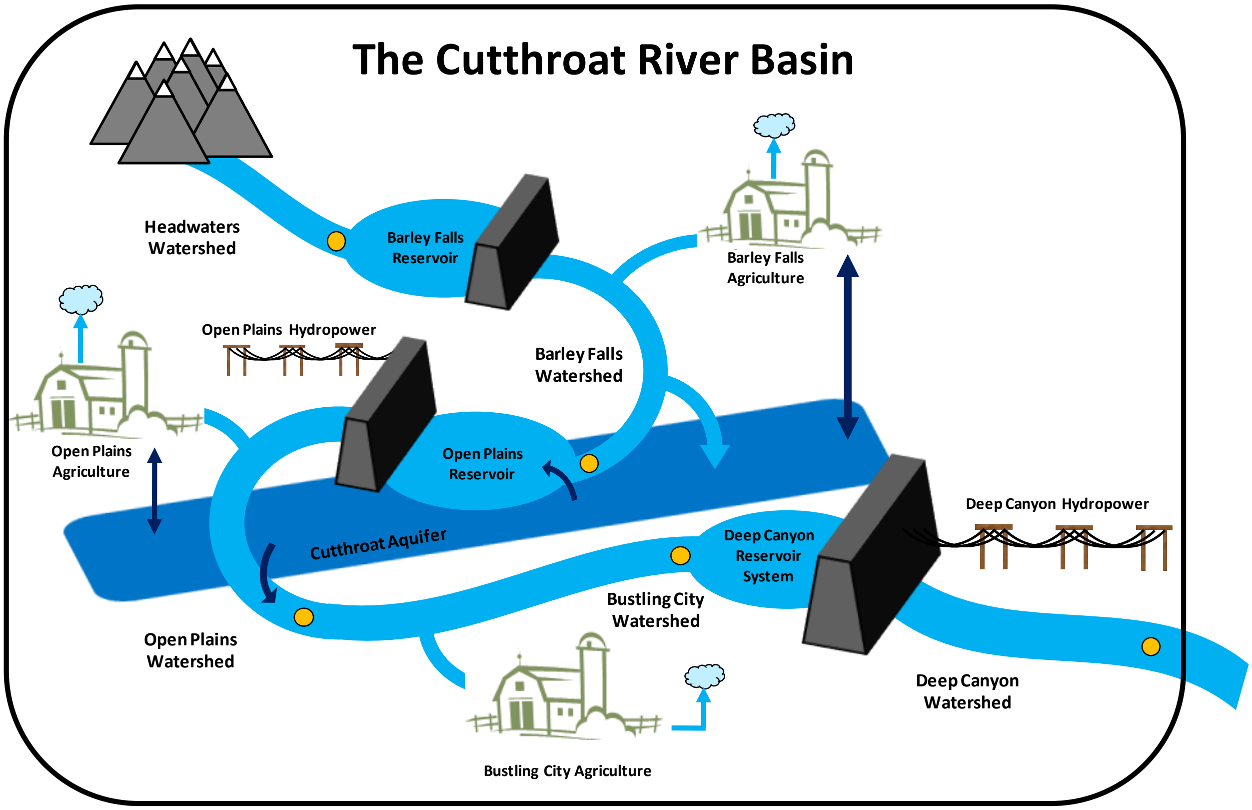

Figure5. Water interaction diagram of the Cutthroat River Basin. Water flows from the top left to bottom right. The yellow circles represent locations in which river flow is simulated within the Cutthroat River Model. Clouds represent components with major water consumption. Dark blue arrows indicate flows in which surface water and groundwater systems interact.

The primary dynamic problem in the Snake River Basin that is simulated using the Cutthroat River Model is centered around declining springflows from the Eastern Snake Plain Aquifer. In the model, these springflows are represented by King Springs and Barley Springs. Declining springflows are a result of the proliferation of groundwater pumping in the 1960's through 1980's driven in part by new pumping technology and low electricity prices (Slaughter, 2004). They are also partially linked to recent improvements in diversion efficiency by canal diverters, which has decreased water applied per acre and decreased recharge to the aquifer. As a result of the declining springflows, downstream average hydropower has decreased, and in dry years water that would normally be used by irrigators must instead be released from upstream reservoirs to meet IPCo's water right downstream of the Open Plains watershed. When this happens, surface water irrigators try to convince the state that they should curtail the groundwater pumpers on the system that are most junior in their rights. However, some of these groundwater pumpers are physically far removed from the main river channel and if they stopped pumping, recovery of springflows would be far from instant. Rather, the net change to the groundwater flow balance ends up being spread over several years if not decades. If this scenario worsens, there is a real potential for expensive litigation involving any combination of IPCo, IDWR, groundwater pumpers and surface water diverters.

Table 2. Why the altered names? Fictional names and their real-world representations.

While the WEST proof-of-concept model is based entirely on the Snake River Basin, the names of geographical features have been changed for several reasons. First and foremost, I altered the names to enhance learning by developing an immersive, seemingly-fictional environment for the first-time user. I want users to learn about water resource management goals and how they affect energy resource planning, not necessarily about the geographical area of the Snake River Basin. The fictional environment allows users to concentrate on these learning goals, without becoming distracted by real-world specifics. Although I have been rigorous in designing and calibrating the model of the Cutthroat River Basin, it is meant to be used descriptively, not prescriptively, and to design beneficial policy but not to forecast exact outcomes. Fictional names allow the Cutthroat River model to describe a world where water management and use may be different from those in the real Snake River, without causing stakeholders to protest because a specific detail was left out.

Fictional Name Within Cutthroat Basin	Real-World Representation
Cutthroat River	Snake River
Barley Falls	Watershed from Palisades Dam to American Falls
Open Plains	Watershed from American Falls to King Hill
Perched Hills	Lost Basins watershed
Bustling City	Watershed from King Hill to Weiser
Deep Canyon	Hells Canyon watershed
Cutthroat Aquifer	Eastern Snake Plain Aquifer (ESPA)
Barley Springs	Snake River springs near Blackfoot
King Springs	Thousand Springs of the Snake River
Barley Falls Reservoir	Palisades Reservoir
Open Plains Reservoir	American Falls Reservoir
Deep Canyon Reservoir System	Hells Canyon Complex
Independent Power Company	Idaho Power Company

Table 3. Water Management Goals in the Cutthroat River Model

Water Management Goal	Metric of Performance	Units
Electricity generation	Average energy generated per year	aMW
Flood control	Average yearly volume above flood stage	AF/yr
Agricultural delivery	Percentage of agricultural requests denied	%
Environmental protection	Average volume of deficit versus targets	AF/yr
Groundwater maintenance	Mean flow from King and Barley Springs	ft^3/s

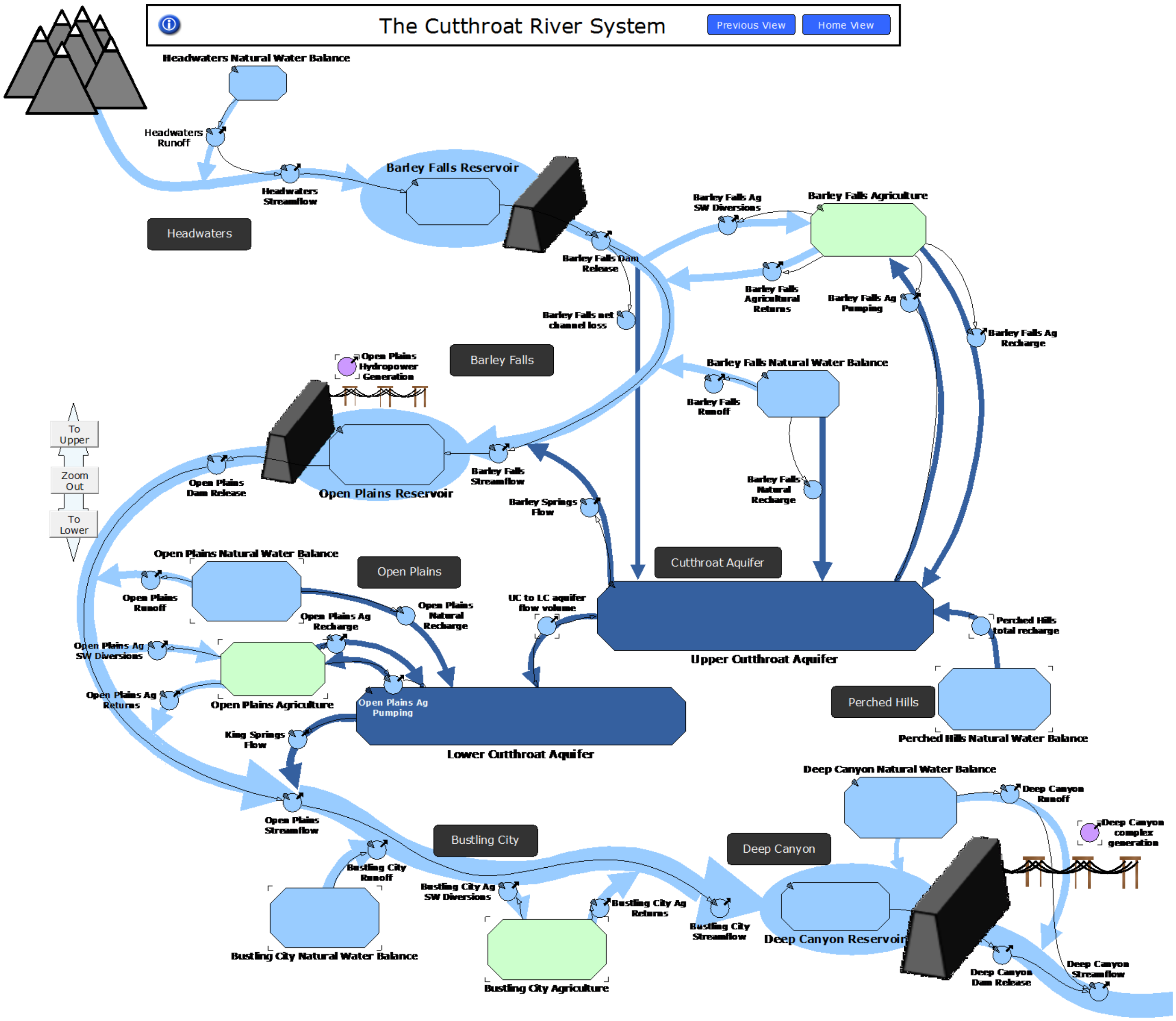

Figure 6. A diagram of the Cutthroat River Model showing the water interactions of WEST components. Components are represented by elongated octagons, while variables are shown as circles. Light blue arrows are surface flows while dark blue arrows are groundwater flows. Thin black arrows indicate passage of information within the model.

The declining springflows at Barley Falls and King Springs, the release of Open Plains Reservoir storage for IPC's rights that would nominally be used for Open Plains agriculture, and the restraint and curtailment of surface water users that are nominally senior in right to groundwater pumpers are all reflected with endogenous behavior within the Cutthroat River Model. To assess long-term performance of water management in the Cutthroat River Basin, I track five performance metrics associated with water management goals presented in table 3. One of the goals is the stabilization of springflow declines, while each of the other four are partially affected by these springflows. There are a few water resource management goals I did not track, such as improving recreation opportunities, ensuring commercial travel, and providing municipal drinking water, but these management goals are not primary on the Cutthroat River. I time-averaged each performance metric for the period in which it was being examined in order to represent each goal with a single number. For example, the amount of energy generated for hydropower is measured in average megawatts (aMW), and represents the average generation over a period of interest.

In addition to tracking performance metrics, I split the simulation into three climate eras: past, present, and future. These are so named because they are structured to represent three bodies of distinct behavior. The past era simulates historic behavior from 1970 through 1999, and uses the aggregated PRISM climate inputs for that period. The present era runs from 2000 through 2029, and reproduces the 1970-1999 climate data as if the precipitation and temperature inputs were looped on record. This allows me to test changes in behavior based on controlled forcings such as the declining springflows without changes in climate forcing. Similarly, the future era begins in 2030 and runs through 2059. I also preset a three year buffer before 1970 to give the model a warm-up period. Thus, the simulation begins with hypothetical inputs in 1967, runs through the observed climate and behavior for the past era, and projects using the looped climate inputs for the present and future eras. I call this the long-term planning mode of the Cutthroat River Model.

Figure 7 illustrates the stacked springflow at Barley Springs and King Springs for the business-as-usual simulation. My first takeaway is that this springflow exhibits an asymptotically declining long-term behavior mode. While springflow is still declining by the end of the simulation, the rate of decline has slowed. The reason for this behavior is a negative feedback loop between springflow and the water stored in the Cutthroat Aquifer. I have assumed that pumping and recharge to the aquifer are independent of hydraulic head in the aquifer. But springflow decreases the hydraulic head, which decreases springflow, which lessens the rate at which head is declining, creating a balancing loop. If allowed to reach equilibrium, Barley springs settles just under 2,300 ft^3/s and King Springs settles at 4,400 ft^3/s by the year 2080.

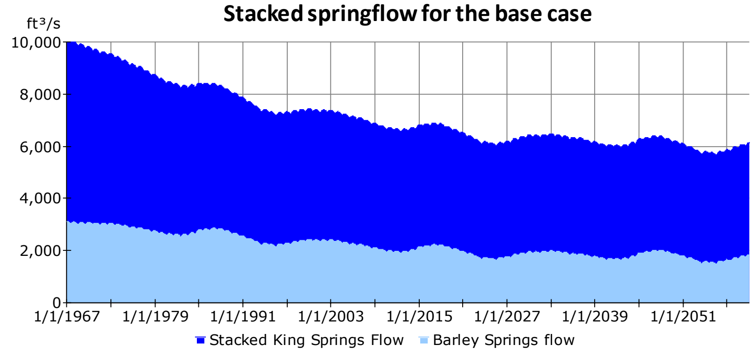

Figure 7. A stacked plot of springflows within the Cutthroat River Model for three consecutive eras indicates asymptotic decline behavior.

These results indicate that King Springs will stabilize 425 ft^3/s lower than the simulated power-related flow target at the outlet of Open Plains. The deficit suggests that Open Plains Reservoir will have to release this 425 ft^3/s more consistently, and agricultural users will need to watch it pass by their diversion points. In addition, the decline in Barley Springs flow means that more surface water storage from both Open Plains Reservoir and Barley Falls Reservoir will likely be relied upon for surface-diverting agriculture in Open Plains. This is because Open Plains agricultural users historically have relied on the consistent flow from Barley Falls as part of their natural flow.

Figure 8 summarizes the impact of declining springflows for the remaining management criteria. Hydropower at the Deep Canyon Complex decreases by 36 aMW (5%) between past and future eras. The monthly hydropower profiles suggest this decrease happens nearly equally in every month. A greater number of agricultural delivery requests are denied in Open Plains, and in the future more requests are denied in Open Plains than in Barley Falls. This suggests that it may be harder to follow priority of water rights in the future because Open Plains agricultural users will rely more heavily on storage higher in the system. Environmental flow deficits are increasing at Deep Canyon but stay stable in Barley Falls, and flooding declines on average. As suggested, Open Plains releases an increasing amount of water to meet IPC’s instream right.

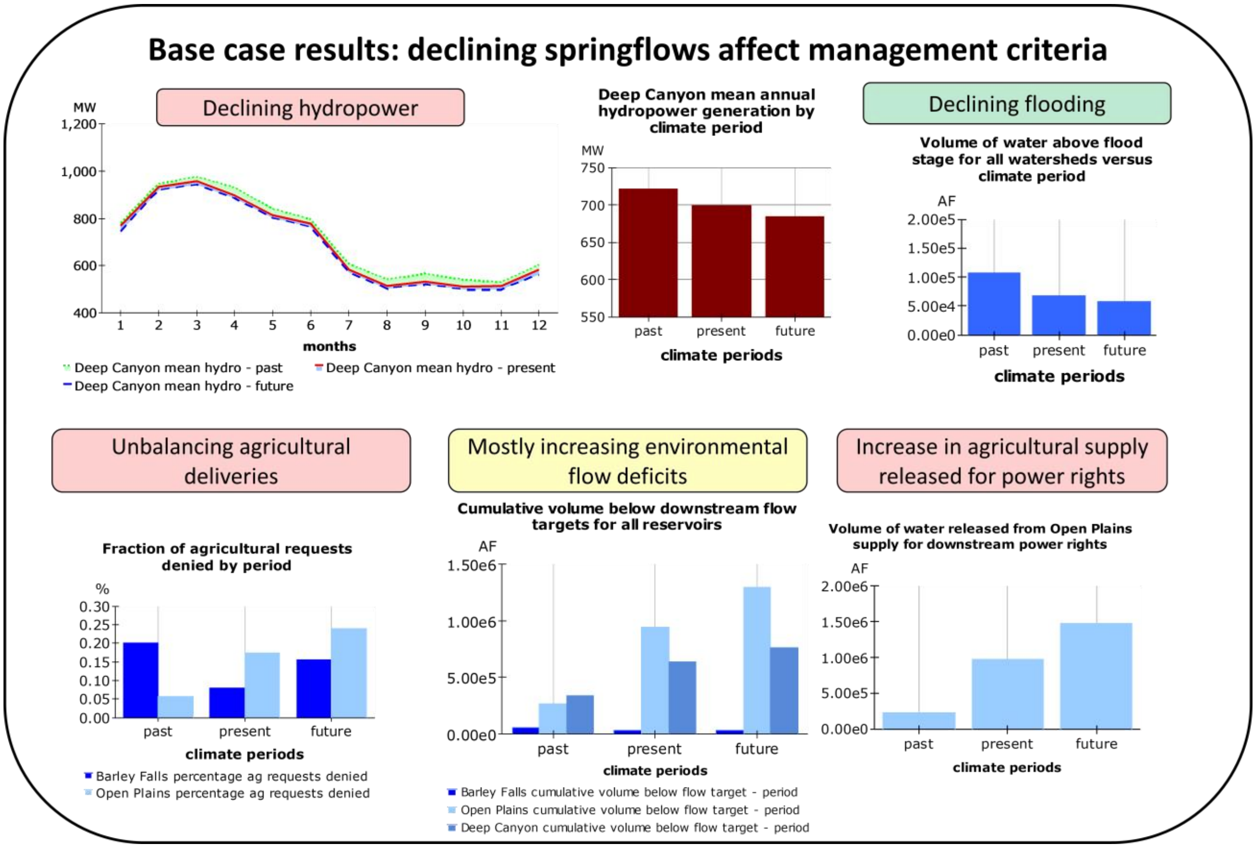

Figure 8. Due to the declining springflows, a number of management criteria exhibit negative outcomes. These outcomes are summarized with my reaction above each graph. Undesirable outcomes are colored red, while desirable outcomes are in green and mixed outcomes in yellow.

11. Testing management policies using WEST

The results of the base case indicate that, with no action, declining springflows will lead to an increase in the number of years with competition for water between agricultural and energy users, as well as among agricultural users themselves. This behavior has been suggested on the Snake River for some time (Hoekema, 2011; Slaughter, 2004). Table 4 outlines the policies that IDWR have suggested and the Idaho legislature has approved for reversing the declining springflows. The collection of these policies is known as the Comprehensive Aquifer Management Plan, or CAMP. Using the Cutthroat River Model, I determined whether CAMP is indeed comprehensive in terms of my five management goals. I simulated the effects of each CAMP policy to compare their effectiveness in each management category. This policy testing also has the benefit of building additional confidence in the model's ability to simulate multiple conditions.

The policy of groundwater to surface water conversions entails the physical transfer of farmers' dependence on groundwater to surface water. In practice, it involves extending canals or developing alternative surface water conveyance systems from nearby canals. Large areas have been designated both in Barley Falls and Open Plains as the initial least-cost options for conversion (IDWR, 2009b). In general, more groundwater pumpers are located near accessible canals in Open Plains than in Barley Falls, so I assumed the split to be 75/25% between conversions in Open Plains and conversions in Barley Falls. Of the 100 kAF/yr in demand reduction, 75 kAF/yr will come from Open Plains which has an average diversion demand of 1,430 kAF/yr for 290,000 acres of cropland. This translates in a 5.2% decrease in demand, or the conversion of 15,200 acres to surface water usage. For Barley Falls, a reduction of 25 kAF/yr from their 2,400 kAF/yr diversion demand on 472,000 acres translates to conversion of 4,900 acres. For the groundwater to surface water conversion policy, I tested the impact of subtracting this acreage from the *groundwater irrigated area* and adding it to *surface water irrigated area* in each respective watershed.

Table 4. Comprehensive Aquifer Management Policies

Policy Name	Description
Groundwater to surface water conversion	Approximately 100 kAF/yr by transitioning groundwater pumpers to surface water use
Agricultural demand reduction	Reducing withdrawal by 250-350 kAF/yr between surface and groundwater users by means of contractual agreements, crop mix changes, fallowing, land purchases, or other mechanisms
Managed aquifer recharge	Increasing the aquifer water budget by 150-250 kAF/yr by diverting from surface water to managed recharge sites, nominally in spring and fall when demand is low
Weather modification	A pilot program to increase precipitation through cloud seeding. Not simulated in the Cutthroat River model.

The agricultural demand reduction policy involves a number of techniques to simply reduce consumption without transitioning supply. One such method is the Conservation Reserve Enhancement Program (CREP), a voluntary program set up by the US Department of Agriculture that helps farmers retire land for the benefit of the environment and provides financial assistance to do so. Another option is the development of leasing and agreements directly with the state to not divert that legally protect the landowner's water right from forfeit through non-use. IDWR is also pursuing technical options to increase agricultural consumption efficiency. For the Cutthroat River Model, I assumed demand reduction can reach the upper end of IDWR estimates, which is 350 kAF/yr. I implement demand reduction simply by reducing the *surface water irrigated area* and *groundwater irrigated area* in each watershed. If economic output of irrigated land is to be tracked in future iterations, this implementation will need to be revised since some measures actually reduce cropland, but others increase efficiency. I assumed a 50/50% split in demand reduction between Barley Falls and Open Plains, and a 50/50% split between surface diverters and groundwater diverters in each watershed. For Barley Fall, this effectively calls for the removal of 7,300 acres and 17,200 acres from surface water and groundwater irrigation, respectively. For Open Plains the removal is 8,200 acres and 17,700 acres, respectively. Less land is required for the same diversion savings in Barley Falls compared to Open Plains because the soils drain more readily.

The policy of managed recharge involves diverting surface water into canals that lose a significant portion of their flow as seepage to the aquifer. Some canals are already lossy and can be used right away for this practice, while some will have to be altered with extensions or pipelines to lossier areas. Figure 9 describes the timing, amount, and behavior of managed recharge practices. Managed recharge occurs in spring and to a lesser extent in fall, and I assumed the ratio to be 75/25% spring to fall. In spring, IDWR's plan is to split recharge 50/50% between Open Plains and Barley Falls, while in fall the concentration will be on Open Plains recharge. I assumed an 80/20% split between Open Plains and Barley Falls for autumn managed recharge. I also defaulted to the higher amount of recharge, 250 kAF/yr for initial policy testing. I concentrated managed recharge diversions around April, May and October to lower the overall impact on surface water diverters. Managed recharge will not occur when surface water supply is tight, so I used a relationship between the fraction of total managed recharge and the *Headwaters snow index*. For this level of managed recharge the impact to surface water supply is minimal in all but the driest years, so I assumed only SWE indices lower than -1.0 would cause restraint.

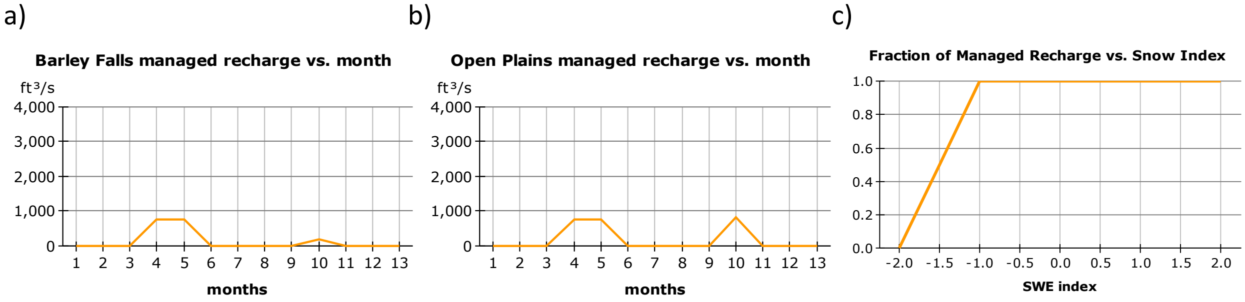

Figure 9. Yearly profiles of managed recharge for a) Barley Falls watershed and b) Open Plains watershed by month. c) At low snowpack values, the manager decreases the managed recharge, as indicated by the fraction of managed recharge versus the standardized snow index.

To gauge each policy's performance, I simulated the proposed policies individually and all of them together using the Cutthroat River Model spanning the three climate eras. In each simulation, the implementation of policy begins in year 2015, midway through the present era. First I evaluated only the springflow recovery from each policy, as shown in figure 10. Every policy improves springflows compared to business-as-usual. Managed recharge is the strongest individual policy for recovering springflows. With all suggested policies in place, long-term flow at Barley Springs completely stabilizes, while flow at King Springs is still in slight decline.

These three policies were designed to recover springflows, but to be truly comprehensive they should account for all five of the management criteria that I have discussed. To evaluate the success of each policy, I compared the performance metrics for the future era in each management category. These metrics are shown in table 5. Notably, the groundwater to surface water conversion policy is the worst performer in the agricultural delivery and hydropower categories, and it is the best performer in none of the categories. I used this information to weed conversion out as a potential “best” policy.

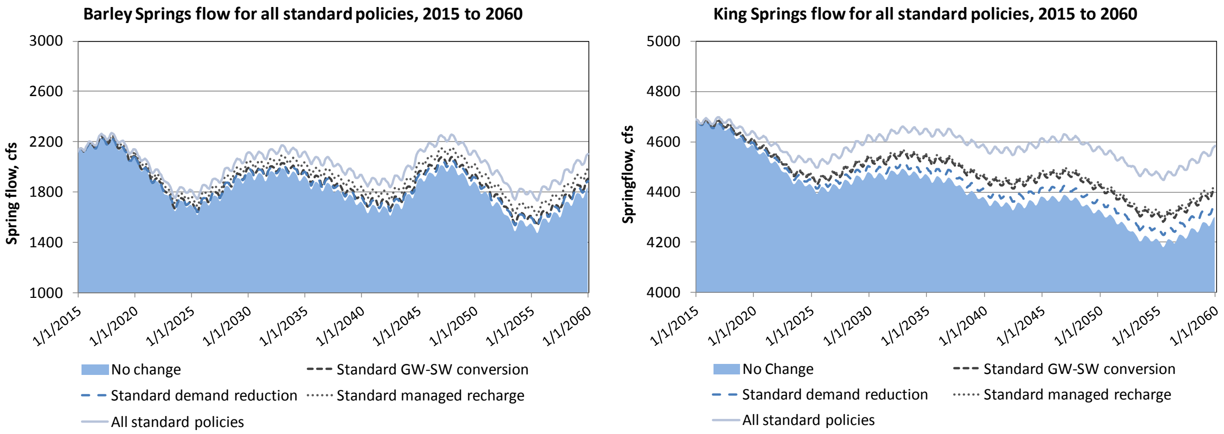

Figure 10. Springflow at least partially recovers with each policy, but only by enacting all policies together do springflows nearly stabilize by 2060.

After removing the conversion policy, I normalized the performance metrics by the business-as-usual case and plotted them all on the radar diagram shown in figure 11. The radar diagram is a helpful method for evaluating policies against multiple performance metrics because it translates numeric information into shapes. Values toward the edge of the radar diagram indicate desirable performance, while values toward the origin indicate undesirable performance. In this way, shapes with higher area are likely better at more criteria than shapes with smaller area. Notably, springflow recovery appears to be nearly as good as the sum of its parts, as indicated by the case with all policies in place. Agricultural deliveries become less reliable with any policy other than demand reduction. Demand reduction also improves environmental flow deficits and hydropower production quite well. Only managed recharge is able to curb flooding more than the business-as-usual scenario. The scenario with all policies in place appears to be a good middle ground between improving springflows and satisfying the hydropower interests.

Table 5. Performance metrics for the five management criteria: a comparison of each policy to the base case.

All Standard Policies - Future Era	Policy Name				
Performance Metric	No Change	GW-SW Conversion	Demand Reduction	Managed Recharge	All Policies
Mean Springflows, ft^3s^{-1}	6131	6276	6206	6358	6582
Undelivered Ag Obligation, %	0.177	0.273	0.082	0.222	0.217
Flooding, AF/yr	1926	1814	2120	1613	2057
Environmental Deficits, AF/yr	26098	25442	25555	26711	25147
Hydropower, aMW	699	698	704	698	702

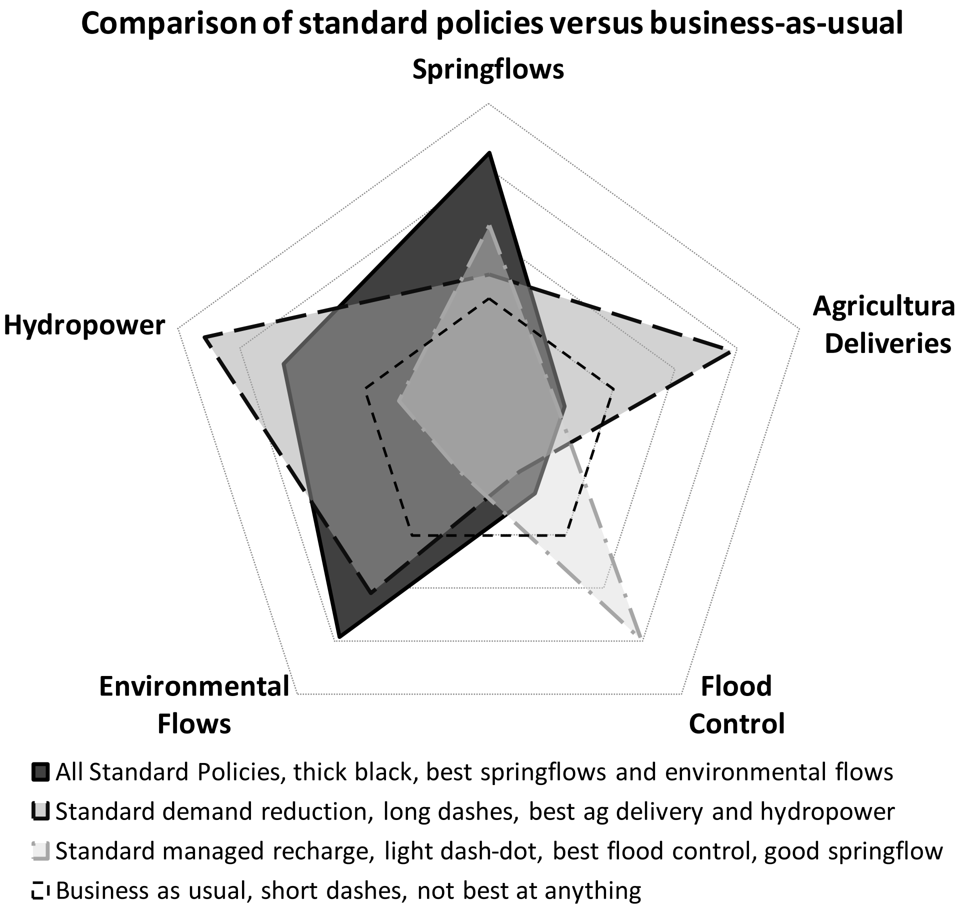

Figure 11. Radar diagram comparing three selected policies to the do-nothing scenario over five management criteria categories. The large dark polygon representing the combination of all CAMP policies benefits in three categories, yet performing only demand reduction benefits in four.

Perhaps some of the policies tested were either too aggressive or not aggressive enough to have beneficial impacts in all management categories. To test this theory, I increased the targets for each policy. Respectively, I named them the enhanced conversion, enhanced demand reduction, and enhanced managed recharge policies.

The enhanced conversion policy transfers 500 kAF/yr from groundwater pumping to surface diversions, split 60/40% between Barley Falls and Open Plains. This consists of converting 59,000 acres in Barley Falls and 40,560 acres in Open Plains. The reason for the bias towards Barley Falls is that previous simulations have indicated a greater capacity for increased surface diversions in this watershed. The enhanced demand reduction policy decreases withdrawals by 600 kAF/yr, split 40/60% between Barley Falls and Open Plains and 50/50% between surface and groundwater sources. I reduced pumping more in Open Plains than Barley Falls because the lower aquifer displays a higher flow deficit than the upper. The effective acreage taken out of production in Barley Falls using this method is approximately 10,000 acres and 23,600 acres for surface diverters and pumpers respectively. Open Plains loses 16,900 acres and 36,500 acres respectively. The enhanced managed recharge policy diverts an extra 600 kAF/yr from surface water flows into the aquifer with the added diversions being performed in April, May and October. Targets for spring managed recharge are 480 kAF/yr while targets for autumn managed recharge are 120 kAF/yr. These targets are split 50/50% between Barley Falls and Open Plains. The enhanced managed recharge policy begins to back off on these targets when the *Headwaters snow index* is below 0.5. A summary of the targets and snow index lookup is shown in figure 12.

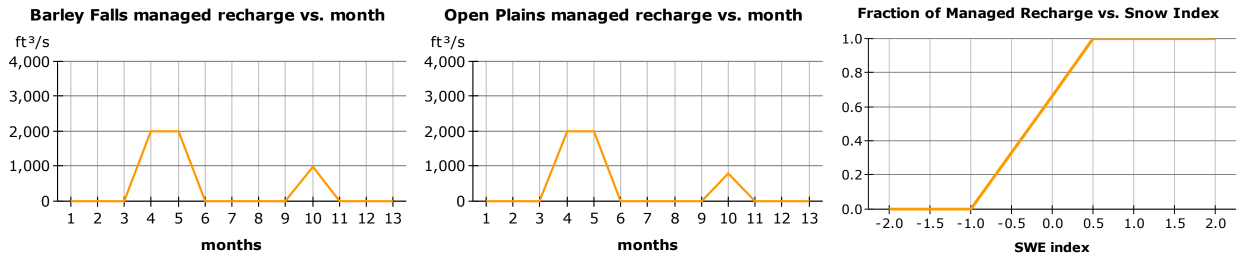

Figure 12. Enhanced managed aquifer recharge increases the targeted amount, but also increases the snowpack level at which managers attempt to achieve this amount.

I show the enhanced policies' springflow response in figure 13. I also ran one case with enhanced demand reduction and recharge together because they appeared to be a promising combination. Enhanced conversion and enhanced managed recharge do well to recover the aquifer, but the enhanced demand reduction seems to provide few springflow gains over its standard counterpart. This is because the demand reduction policy is split between surface water and groundwater reductions. Reducing groundwater demand results in a net increase to the groundwater aquifer's water budget, but reducing surface water demands results in a net *decrease*. It does however improve metrics for other criteria. Table 6 compares the three enhanced policies and the combined enhanced reduction and recharge policy. Many of the same themes from the standard policy comparison are apparent. Enhanced demand reduction has large beneficial impacts to agricultural delivery reliability and hydropower. Conversely, conversion is poor in these areas. Enhanced managed recharge continues to improve flood control throughout the basin.

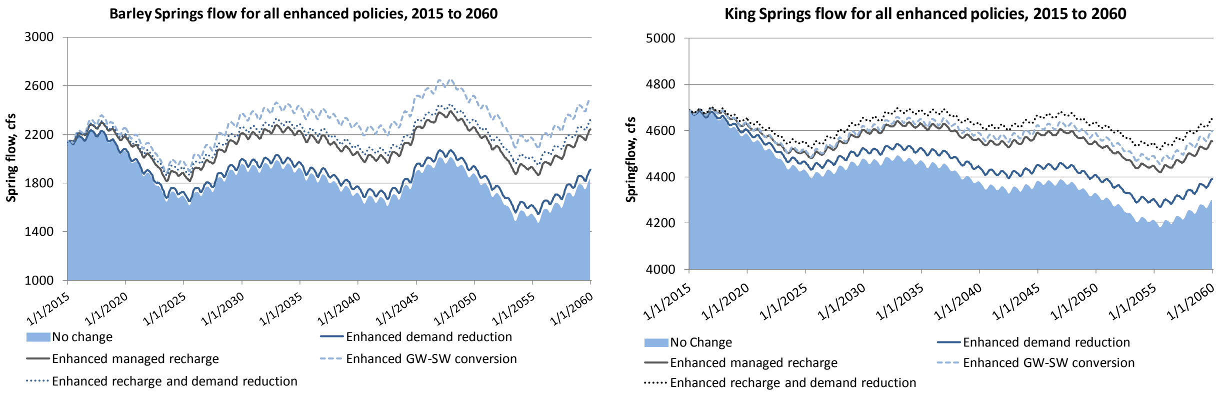

Figure 13. Most of the enhanced policies increase springflows nearly proportionally compared to their standard counterparts. However, the enhanced demand reduction policy reaches a point of diminished returns.

Table 6. A comparison over the five performance metrics of the enhanced policies and the combination of demand reduction with managed recharge.

All Enhanced Policies - Future Era	**Enahnced Policy Name**			
Performance Metric	**Demand Reduction**	**Managed Recharge**	**GS-SW Conversion**	**Reduction and Recharge**
Mean Springflows, ft^3s^{-1}	6258	6682	6940	6824
Undelivered Ag Obligation, %	0.036	0.302	0.771	0.085
Flooding, AF/yr	2249	1085	1673	1456
Environmental Deficits, AF/yr	25539	26400	25767	25253
Hydropower, aMW	708	697	695	706

A radar diagram showing the normalized performance for the enhanced policies in every management category is shown in figure 14. I dropped the enhanced groundwater to surface water conversion policy because I believe its impacts on agricultural deliveries and hydropower generation are unacceptable. Enhanced demand reduction has strong performance in four out of five categories, so it appears to be a strong performer. Because enhanced managed recharge does well where demand reduction does poorly, I combined them into an enhanced reduction and recharge policy. This is the only policy tested to improve upon the business-as-usual scenario in all performance categories.

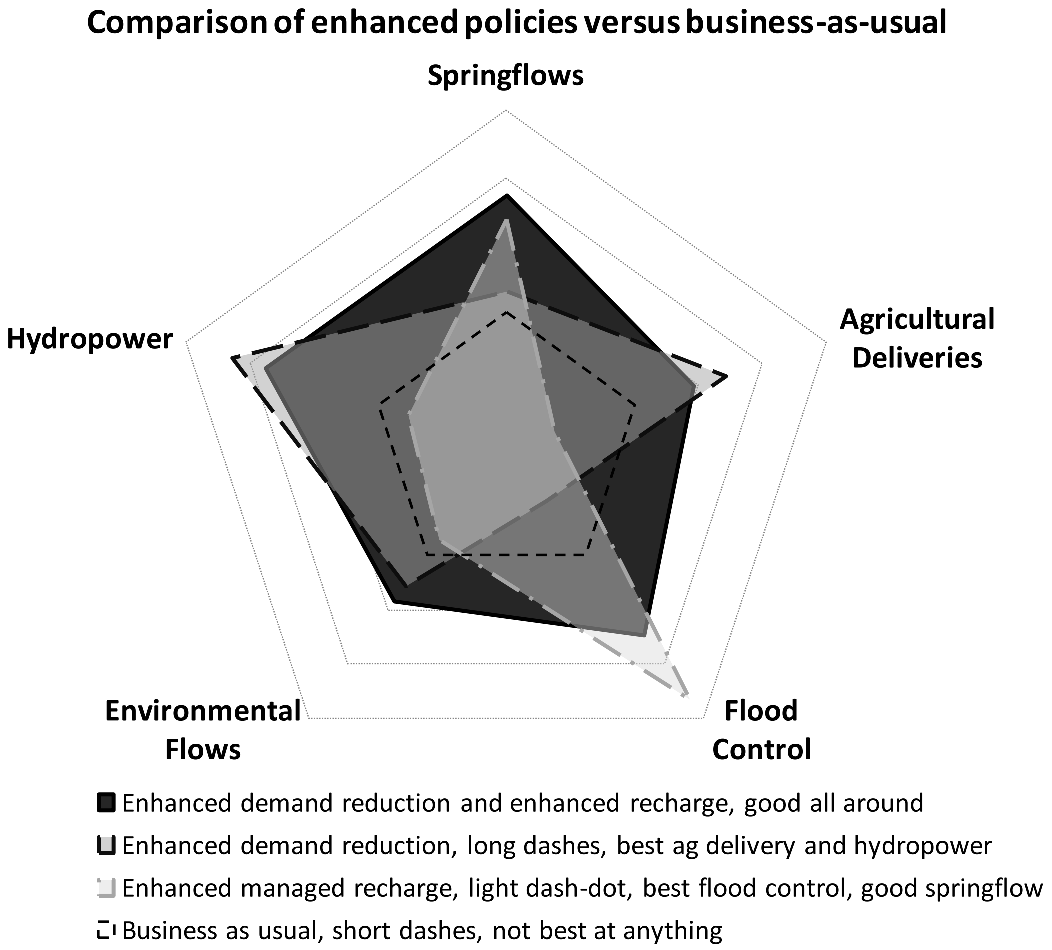

Figure 14. Radar diagram comparing three selected policies to the do-nothing scenario over five management criteria categories. The large dark polygon representing the combination of all CAMP policies benefits in three categories, yet performing only demand reduction benefits in four.

12. Discussion and conclusions

The following narrative is my own take on what the Cutthroat River Model's results mean for the Snake River Basin, and has not been fully assessed by any agency. It notably ignores the impacts of changing climate which I am analyzing separately.

If the CAMP policies outlined in table 4 are not enacted, the results of the Cutthroat River Model suggest that springflows will continue to decline, but will eventually stabilize by around year 2080. This stabilized state would not be as productive in terms of agriculture and hydropower as the historic period of 1970-1999. Surface water irrigators, especially those in the Open Plains region, would find decreasing delivery reliability because they are more dependent on the upper Barley Falls Reservoir due to the decreased flow from Barley Springs. Because Open Plains surface water diverters have senior rights in general compared to Barley Falls diverters, this scenario could result in more calls for curtailment of groundwater pumpers and Barley Falls diverters. Courts would continue to face problems with futile calls and may need to curtail water users out of priority. At the same time, IPCo shareholders may notice the decrease in hydropower generation and call for even more water released from Open Plains Reservoir to meet the Swan Falls in-stream right. Environmental interests around the Deep Canyon Complex may also notice that less water is being released in spring and autumn for anadromous fish passage downstream because IPCo is trying to hold water back for peak electricity demand season. Flood control downstream of Open Plains will be more effective due to the decreased springflows. This may be the new normal if no CAMP policies are enacted.

If CAMP provisions are implemented as-is, they won't improve all water and energy management goals in the Snake River Basin. Namely, groundwater to surface water conversion policies help springflow substantially, but put additional stress on agricultural deliveries, hydropower, and environmental flows. Managed recharge also helps springflows substantially, but can negatively impact environmental flows and hydropower. Demand reduction helps the most criteria, but it also has the highest potential to decrease agricultural production and leaves more potential for downstream flooding. I believe surface water and groundwater demand reduction should be two separate policies because they have very different water budget outcomes. Surface water demand reduction has a negative impact on groundwater management and a short-term positive impact on hydropower. Groundwater demand reduction has a positive impact on groundwater management and a more long-term positive impact on hydropower. Enhancing demand reduction and combining it with an enhanced recharge policy has all around positive impacts and should be considered as an alternative by IDWR.

This analysis represents a targeted discussion around how IDWR should plan to manage water resources for multiple interests, including power. However, the results also are highly applicable to power system planners such as IPCo. The analysis suggests that, if allowed to continue, the average head difference overcome by agricultural pumps will increase in the Snake River Basin. This means that agricultural electrical load and peak summer load are likely to increase, all else equal. Additionally, I simulate a power decrease of nearly 5% from IPCo's major hydropower dam, the Hell's Canyon Complex. But there are several more dams on the Snake River that collectively double Hell's Canyon's capacity, and hydropower makes up about half of IPCo's total generation capacity. So, by extrapolation we may surmise that about 2.5% of IPCo's generation capacity may be lost if there is no action on declining springflows. This amount is significant, especially since load is changing in the opposite direction, and these results would likely change IPCo's portfolio plans in their IRP if it were included.

Using WEST, I have interactively demonstrated the Cutthroat River Model to stakeholders including the Idaho PUC as well as IDWR and the Idaho Department of Environmental Quality. Interaction with the model is nearly instant during these meetings, and they have greatly shaped my analysis. Going forward, I believe WEST should be used for intensive collaborative studies on potential human behaviors given changing climate, declining springflows, and changes in energy policy such as the push toward biofuels. I believe that without such an inclusive forum to collectively test individual assumptions, the energy-water planning cycle will fail to meet the challenges that are colliding before us.

1.8 References

Bebic, J., 2008, “Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics.” National Renewable Energy Laboratory Subcontract Report, NREL/SR-581-42297, Boulder, CO.

Committee on Assessment of Water Resources Research, 2004, “Confronting the Nation’s Water Problems: the role of research.” National Research Council, Washington DC.

Diamond, J., 2005, “Collapse: How Societies Choose to Fail or Succeed: Revised Edition.” Penguin Group, New York, NY.

Ford, A., 1996, “Testing the Snake River Explorer.” System Dynamics Review, Vol. 12 (4) pp. 305-329.

Ford, A., 2009, “Modeling the Environment: 2nd Edition.” Island Press.

Forrester, J.W., 1971, “Counterintuitive Behavior of Social Systems.” Theory and Decision Vol. 2 (2) pp. 109-140.

Hamlet, A.F., Lee, S.Y., Mickelson, K.B., Elsner, M.M., 2009, “Effects of Projected Climate Change on Energy Supply and Demand in the Pacific Northwest and Washington State.” Climatic Change pp. 1-26.

Hoekema, D.J., 2011, “A system dynamics approach for climate change impact analysis in the Snake River Basin.” Master’s Thesis, Boise State University, Boise, ID.

Idaho Department of Water Resources, 2009a, “Eastern Snake Plain Aquifer: Comprehensive Aquifer Management Plan.” Adopted the Idaho Water Resources Board, Boise, ID.

Idaho Department of Water Resources, 2009b, “Eastern Snake Plain Comprehensive Aquifer Implementation Committee.” CAMP implementation working group update, December 2009, Boise, ID.

Idaho Department of Water Resources, 2013, “Water Right Research.” Online spatial database. Accessible: <www.idwr.idaho.gov/apps/extsearch/wrajsearch/wrajsearch.aspx>

Idaho Power Company, 2011, “2011 Integrated Resource Plan.” December, 2011. Available online: <http://www.idahopower.com/default.cfm>

Jackson, R.B., Carptenter, S.R., Dahm, C.N., McKnight, D.M., Naiman, R.J., Postel, S.L., Running, S.W., 2001, “Water in a Changing World.” Ecological Applications Vol. 11 (4) pp. 1027-1045.

Lohmann, D., E. Raschke, B. Nijssen and D. P. Lettenmaier, 1998: “Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model,” Hydrol. Sci. J., 43(1), 131-141.

Meyer, B., 2000, “Object-Oriented Software Construction.” Prentice Hall, New York, NY.

Munson, E., 2005, “From Edison to Enron: The Business of Power and What It Means for the Future of Electricity.” Praeger Publishers, Westport, CT.

Otter, C.L., Keen, J.L., Wasden, L.G., 2009, “Framework Reaffirming the Swan Falls Settlement.” Boise, ID.

PRISM Climate Group, 2011, “Parameter-Elevation Regressions on Independent Slopes Model.” Accessed Online, Jan. 2011. < http://www.prism.oregonstate.edu/>

Slaughter, R.A., 2004, “Institutional History of the Snake River 1850-2004.” Climate Impacts Group, University of Washington, Seattle, WA.

Sovacool, B.K. and Sovacool, K.E., 2009, “Identifying Future Electricity-Water Tradeoffs in the United States.” Energy Policy vol. 37 (7) pp. 2763-2773.

Stoll, H.G., 1989, “Least-Cost Electric Utility Planning.” Wiley-Interscience, New York, NY.

Stone, R. 2009, “Divining Angkor: After rising to sublime heights, the sacred city may have engineered its own downfall.” National Geographic Magazine, The National Geographic Society.

Tidwell, V., Passell, H. Conrad, S., Thomas, R., 2004. “System dynamics modeling for community-based water planning: Application to the Middle Rio Grande.” Journal of Aquatic Sciences, 66, 357-372.

Tidwell, V., Malczynski, L., Kobos, P., Castillo, C., 2009, “Decision Support for Integrated Water-Energy Planning.” Sandia Report SAND2009-6521.

United States Department of Energy, 2006, “Energy Demands on Water Resources.” Report to Congress on the Interdependency of Energy and Water. Washington, D.C.

US Canada Power System Task Force, 2006, “Final Report on the Implementation of Task Force Recommendations.” Joint report to the US Department of Energy, Washington, D.C.

World Bank, 2010. “Sustaining Water for All in a Changing Climate,” World Bank Group Implementation Progress Report of the Water Resources Sector Strategy, The International Bank for Reconstruction and Development, Washington, D.C.