A Framework for Analysis of Energy-Water Interdependency Problems

Robert Jeffers, Jacob J. Jacobson

Idaho National Laboratory

2525 N. Fremont Ave

Idaho Falls, Idaho, 83415

208-526-3071

Kristyn Scott

Robert.Jeffers@inl.gov, Jacob.jacobson@inl.gov

Kristyn Scott

University of Idaho

krisscott@vandals.uidaho.edu

A Framework for Analysis of Energy-Water Interdependency Problems

ABSTRACT

The overall objective of this work is to improve the holistic value of energy development strategies by integrating management criteria for water availability, water quality, and ecosystem health into the energy system planning process. The Snake River Basin (SRB) in southern Idaho is used as a case study to show options for improving full economic utilization of aquatic resources given multiple scenarios such as changing climate, additional regulations, and increasing population. Through the incorporation of multiple management criteria, potential crosscutting solutions to energy and water issues in the SRB can be developed. The final result of this work will be a multi-criteria decision support tool – usable by policy makers and researchers alike – that will give insight into the behavior of the management criteria over time and will allow the user to experiment with a range of potential solutions. Because several basins in the arid west are dealing with similar water, energy, and ecosystem issues, the tool and conclusions will be transferrable to a wide range of locations and applications. This is a very large project to be completed in phases. This paper deals with interactions between the hydrologic system and water use at a basin level. Future work will include the interdependency between energy use and water use in these systems.

Key words: System Dynamics, Energy Water Nexus, Agent based modeling

A Framework for Analysis of Energy-Water Interdependency Problems

INTRODUCTION

Hydrologic systems around the world have been under pressure for the last century due to a number of economic, environmental, and social factors including increasing population, industrialization, agricultural runoff, climate and land use changes, poor water resource management practices and recreational use. Water scarcity in the western United States led to the development of the doctrine of prior appropriation to govern rights of water use. The doctrine – commonly summarized as "first in time, first in right" – partitions use of publicly-owned waters by those who first put the water to a beneficial use. The two primary uses of water in the western United States are for electricity generation and agricultural production. One of the weaknesses of prior appropriation is that it governs withdrawal but not consumption of water, resulting in a lack of a value-based system to maximize beneficial use. The conventional approach to water resource management has been to isolate the feedback dynamics of the human-technology-water systems in such a way that only the hydrologic components are closely modeled and managed. While this approach does help answer some important questions it fails to give a fully systemic long-term systems analysis of the problem. The modeling presented herein creates a framework to analyze the interconnected nature of water supply, withdrawal, and consumption for more equitable resource use and better informed management practices.

The state of Idaho is used as a case study to focus on real-world conflicts between water users. One of the primary conflicts in Idaho is between use of water for agricultural and energy purposes. The economy of Idaho is strongly dependent on both energy and water because of its heavy economic investment in hydropower and irrigated agriculture. However, there are complex limitations to energy and water supply in the state. To compound supply problems, concerns about ecosystem health and water quality have lead to additional constraints – such as minimum in-stream flow requirements and best management practices – on the management of energy and water systems. To grow economically the state over the coming decades will need to improve in efficient use of water and energy while accounting for ecosystem health. Balancing the needs of multiple users and a healthy environment is a problem in which complex spatial and temporal interdependencies are prevalent; however the majority of existing environmental process models applies varying unrealistic generalized assumptions or focus solely on a single system. As a consequence, the presence of these interdependencies significantly reduces the ability of these models to provide insights that are necessary to make proper decisions about the management of complex ecological–economic systems.[1] New modeling approaches are required to effectively identify, collect, and relate information that is relevant for understanding unconventional fuel development on human and natural systems.

Two principal research questions are the focus of this study:
1) How does the expected spatial-temporal distribution of water availability affect management decisions and in turn how do water management decisions impact: (1) the spatial-temporal distribution of water allocation and (2) water demand in a complex transboundary region?

2) What is the basis of validity for constructing a systems model of coupled natural and human relationships that form the basis of regional transboundary water resource management? How do we know such a model is sufficiently accurate and comprehensive for the purpose of fostering sustainable water resource management carried out over multiple spatial and temporal scales?

The broader objective of this work is to improve the holistic value of water use by integrating multiple planning criteria for water availability. Future iterations will include criteria for planning energy availability, water quality, and productive ecosystems. The Snake River Basin (SRB) in southern Idaho is used as a case study to show options for improving full economic utilization of aquatic resources given multiple scenarios such as changing climate, additional regulations, and increasing population. Through the incorporation of multiple criteria, potential crosscutting solutions to energy and water issues in the SRB can be developed. The final result of this work will be a multi-criteria simulation tool – usable by policy makers and researchers alike – that will give insight into the behavior of planning criteria over time and will allow the user to experiment with a range of potential solutions. Because several basins in the arid west are dealing with similar water, energy, and ecosystem issues, the tool and conclusions will be transferrable to a wide range of locations and applications. This is a very large project to be completed in phases. This paper deals with interactions between the hydrologic system and water use at a basin level given climate constraints. Future work will include the interdependency between energy use and water use in these systems.

APPROACH

Electric utilities often employ a process of end-to-end coupling in response to water-energy interdependency in which the outputs of hydrodynamic models are input to power system load flow models, but changes in generation and use of power may not directly affect the hydrodynamics. Our approach involves a more direct coupling, in which models of hydrodynamics and energy dynamics are running within the same environment. Energy and water are viewed as sub-models within one greater spatial environment. This object-oriented approach lends itself to define spatial and temporal resolution by sector instead of globally. More importantly, it allows for the representation of cross-sector feedback loops that would otherwise be lost. For example, withdraw and consumption of water depend heavily on climate and hydrology, which themselves are affected by electricity generation and consumption practices. In this paper we present a hydrologic model developed to reflect the dynamic tradeoffs between water uses in a basin such as the SRB. This model captures temporal and spatial processes on scales appropriate for both energy and water planning purposes.

For planning purposes, electric utilities often extend 20-40 years, so to capture impacts of decisions the model is able to quickly reflect hydrology over 25 to 50 year time spans. Management and planning practices for water resources occur at three different scales: year-ahead planning, month and week-ahead management, and day-ahead mitigation. Aggregating day-ahead mitigation strategies into the monthly effects allows fast simulation of the 50-year window, while still capturing potentially conflicting weekly and monthly management policies. Therefore, the time resolution chosen for this exercise is on the order of weeks to months.

In order to address how energy system components such as individual generation plants, mines, wells, and waste facilities affect and are affected by water resources, the spatial scale was chosen to capture monthly dynamics of watersheds and aquifers. Energy systems are dependent on both surface water and groundwater for operation, so the model was designed to capture the interaction between these storage media. To keep complexity to a minimum, the 8-digit Hydrologic Unit Code (HUC) employed by USGS was chosen as the minimum spatial element. A medium-sized electric utility will span on the order of dozens of 8-digit HUCs.

Recent work of Li et al. investigates the impacts of changing climate on performance of reservoirs in the North American Prairie.[2] This model uses system dynamics to link hydrologic processes with the inflow to a reservoir, and balances the risk of flood and drought downstream of the reservoir by using rules curves to operate a single reservoir. The model assumes constant demand of water from the reservoir to simplify the operation, and therefore does not capture potential conflict over limited resource between demands. The method of defining a watershed and a reservoir in system dynamics, thereby abstracting their behavior into autonomous entities, is applicable in our case because it allows explicit definition of processes within a hydrologic unit and between the units as well.

Impacts of climate change on electricity supply and demand were discussed by Hamlet et al. for the hydro-dominated system of the state of Washington[3]. The authors employed a distributed hydrology model coupled with a model of the hydropower system to generate estimates of power dependence on climate. The results show a sharply increasing demand for water and a slight decrease in capacity in summer months under the full range of climate predictions. The assumption of perfect forecasting by energy managers, which allows the model to know summer flows several months in advance and plan accordingly, is a weakness of the modeling approach used because it ignores potential problems that arise due to imperfect foresight. Also, energy and water demand were a function of population, with no relationship between agricultural or industrial demand for energy and water. To examine potential failures in management practices given future operating scenarios, it would be beneficial to increase coupling and give the simulated reservoir manager only the information that would be obtainable in reality.

Often hydrology models simulate natural surface water processes only. The three greatest effects humans have on many western surface water are water storage, diversion and consumption (agriculture, thermal power, municipalities, industry), and artificial exchange with aquifers (added recharge minus pumping). In this paper, we will present the effects of reservoir management, and agricultural withdrawal and consumption.

METHODOLOGY

The model is implemented using an object-oriented system dynamics computer-aided modeling methodology, creating a backbone for future analysis of energy-water interdependency. The system dynamics methodology is based on a system of accumulators, or stocks, with flows which modify the quantities in the stocks, and feedback loops to describe temporally dynamic behavior.[4,5,6] The object-oriented approach is derived from agent-based modeling techniques, in which each autonomous entity, or "agent," is governed by a set of rules that define its behavior in certain situations.[4,5] In the case of multi-criteria energy-water modeling, the use of both system dynamics and object-oriented modeling can provide a framework for coupling multiple human and physical systems to autonomous and emergent behavior of components within these systems. In this way, the use of both techniques is as much a mindset as a methodology. The modeler is constantly forced to think of individual component behavior in conjunction with big-picture feedback loops involving multiple components.

With coupled energy-water systems, most entities have a set spatial reference and their interaction with each other is highly dependent on location. To represent this interaction, each entity in the model is treated as an object. In this way, the behavior of a single entity such as an individual reservoir can be aggregated and assigned parameters that calibrate it to historic record. That entity interacts in a pre-determined manner with other objects connected to it. This connection may be physical, as is the case with passage of water from a reservoir through a dam to a river, or it may be informational, as is the case with a management agency measuring the storage in that reservoir and making a decision based on that data. The object is assigned a visual representation in an interface, allowing the user to monitor its status and perhaps adjust its behavior. A schematic of how the system dynamic framework can be spatially aggregated by entity and linked via an agent-based framework is shown in Figure 1.

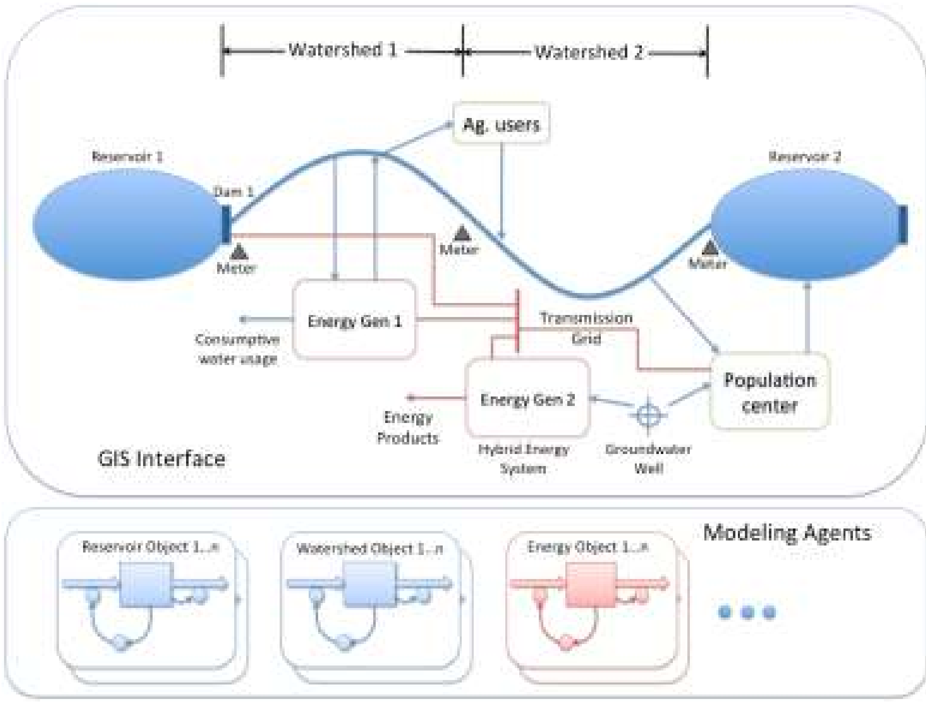


Figure 1: Concept diagram of energy and water system aggregation using system dynamics and object-oriented modeling.

HYDROLOGY MODEL

On monthly timescales and watershed spatial scales, hydrologists use what is known as a lumped-parameter monthly water balance model. Xu and Singh provide a detailed review of monthly water balance models with lumped parameters and a range of complexities.[6] The main advantages of these types of models are the relatively small number of parameters and ease of calibration. Of the six designated uses for aggregated monthly water balance models that Xu and Singh outline, two are applicable: forecasting of effects of land use and climate change, and synthesizing long-term basin records. Essentially, the approach is to synthesize what “normal” behavior looks like under a variety of climate conditions then project the hydrographs in each watershed given projected changes in climate conditions. The United States Geological Survey (USGS) has developed a monthly water balance model that fits a system dynamics framework and has proven useful for this purpose.[7] The system dynamics implementation of this model is shown in Figure 2.

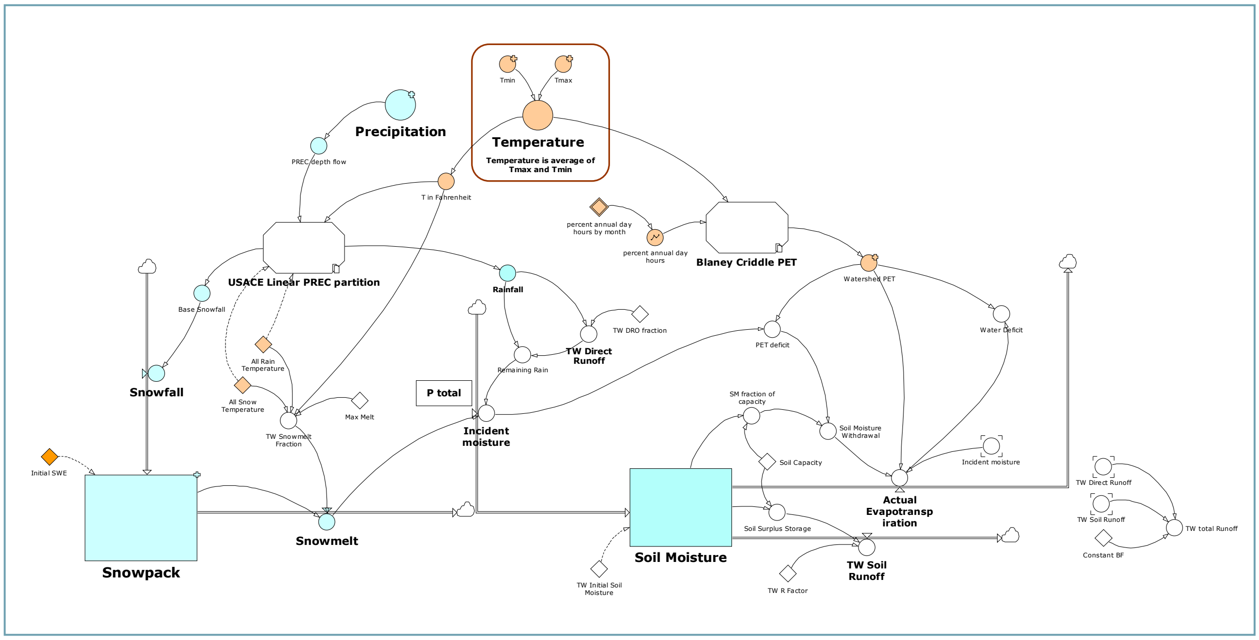


Figure 2: System Dynamic implementation of McCabe and Markstrom watershed model

The two major stocks for the watershed agent represent storage of water in snowpack and in the soil. All other natural surface water storage dynamics (such as that in the river itself) are too short-lived for the monthly time resolution. Mean monthly watershed precipitation and temperature are the only inputs require for this model. Using these inputs, the precipitation is partitioned into rain and snow using the United States Army Corps of Engineers linear method. Snow accumulates in the snowpack stock, and melts using a similar method to snow partitioning, multiplied by the volume of snowpack. A portion of rain is allowed to instantly run-off, and the remainder is combined with snowmelt to enter the soil moisture stock as net incident moisture. To calculate the evapotranspiration from this stock, we departed from the McCabe and Markstrom model and instead used the Blaney Criddle method that incorporates net solar radiation in addition to monthly temperature to calculate the potential evapotranspiration.[8] Potential evapotranspiration sets a maximum for actual evapotranspiration. Actual evapotranspiration is a function of incident moisture and soil moisture. If incident moisture is greater than potential evapotranspiration, then actual is equal to potential. Otherwise, actual evapotranspiration is linearly interpolated between incident moisture and potential evapotranspiration by an amount directly related to the fraction of soil moisture to its saturated value. Delayed runoff from the soil is also related to this fraction. The soil runoff is added to the instant runoff and a constant baseflow value to estimate the total runoff, which is the natural contribution to streamflow in that watershed.

Excluding the estimation of initial conditions, there are seven parameters in the watershed to set via calibration or estimation: all-rain temperature, all-snow temperature, maximum monthly snowmelt, direct runoff fraction, soil capacity, soil runoff factor, and constant baseflow. Several of these parameters have ranges suggested by McCabe and Markstrom.[6] To further simplify calibration, two parameters, constant baseflow and the direct runoff fraction have linear, mutually independent effects on the calculated runoff, and can therefore initially be set to fit observed data. An automatic calibration optimization routine was built to minimize the squared residuals between observed streamflow export and calculated streamflow export. To exclude effects of initial conditions, the first year's residuals are not accounted for in this calculation. A five year window was calibrated for all watersheds, and parameters were set automatically. Using these parameters, the watershed was validated against a separate five-year window. The results of validation for the Gros Ventre watershed, which is a headwaters watershed of the SRB with no irrigated agriculture, are shown in Figure 3.

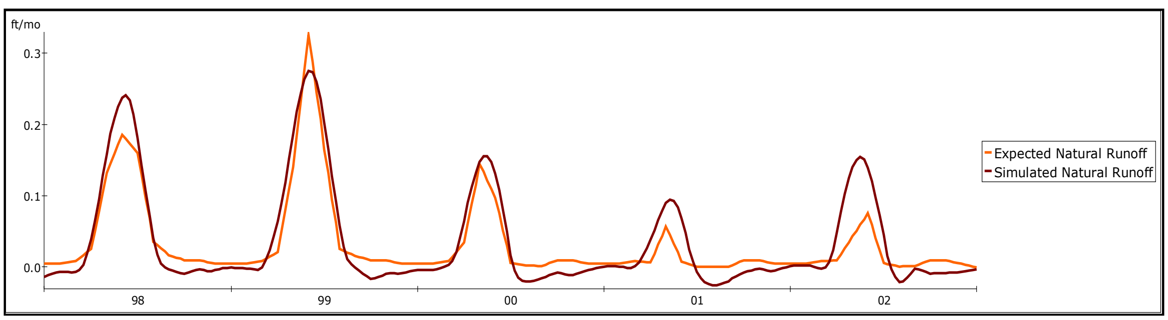


Figure 3: Simulated and reconstructed natural runoff from the Gros Ventre watershed in western Wyoming.

These results highlight some of the strengths and weaknesses of our refined system dynamics implementation of the McCabe and Markstrom model. First, the model does an excellent job of replicating the overall behavior in a snowpack dominated watershed. Runoff is baseflow dominated through late summer and winter, and snowmelt dominated through spring and early summer. However, the model consistently underestimates runoff in wet years and overestimates runoff in dry years. This effect is exacerbated in watersheds where topographic relief is high, which is the case in Gros Ventre. Possible mechanisms to increase the wet-dry discrepancy are the inclusion of elevation bands in the snowpack section, or an investigation into whether snow sublimation plays a more dominant water balance role in dry years than in wet years.

The McCabe and Markstrom model does not include effects of major consumers within the watershed, nor the interaction with human-managed reservoirs. To solve this problem, separate classes of agents were developed using system dynamics to model the behavior of the natural watershed, the withdrawal and consumption of agricultural users, and the management of reservoirs for multiple uses. The watershed agent class uses precipitation and temperature from the PRISM (Parameter-elevation Regressions on Independent Slopes Model) database as input, and calculates the streamflow export from that watershed as output.[9] The irrigated agriculture agent class uses calculations of surface water supply as input, withdraws water from a watershed, and consumes a part of that water, returning the remainder after a delay. The reservoir agent class uses the inflow from upstream and management input from an agency as input, and calculate discharge from the dam as output. Once one generalized hydrologic agent is developed and validated, it may be reproduced and calibrated for additional watersheds/reservoirs, and linked by hydrologic connection to create the entire system. The human management of reservoirs is simulated by modeling the agency that operates the particular reservoir, in this case the Bureau of Reclamation. Data for streamflow gauges and reservoir operation is compiled from the USGS National Water Information System and the Bureau of Reclamation HYDROMET database.[10]

RESERVOIR MODEL

The two dominant criteria for reservoir management in this model are flood control and summer refill. The reservoir object is modeled as an accumulation of water represented by a stock, with measurable inflow, measurable outflow, and remainder flow, which may include the effects of seepage, evapotranspiration, and other ungauged flows (Figure 4). In this way, the system mimics that of a simple bathtub. The remainder flow allows the modeler to calibrate measurable flows with observed data, but also ensure that the net flow is equal to the observed change in storage. While inflow is governed by the hydrology model for upstream watersheds, discharge is governed by a management algorithm. The developed management algorithm dynamically selects a curve of target storage (called a rule curve) for the upcoming year based on endogenous variables of snowpack and runoff in the system. This rule curve selection is updated in real time as conditions change, and is based on the amount of buffer needed for flood control by absorbing the high runoff period flows. Additional constraints are placed on the discharge based on the purpose of the dam. Agricultural entities may place a demand curve that sets minimum release. Power generation entities may place a scheduling curve in much the same way. Also if necessary, these curves can be selected based on endogenous energy and water system variables.

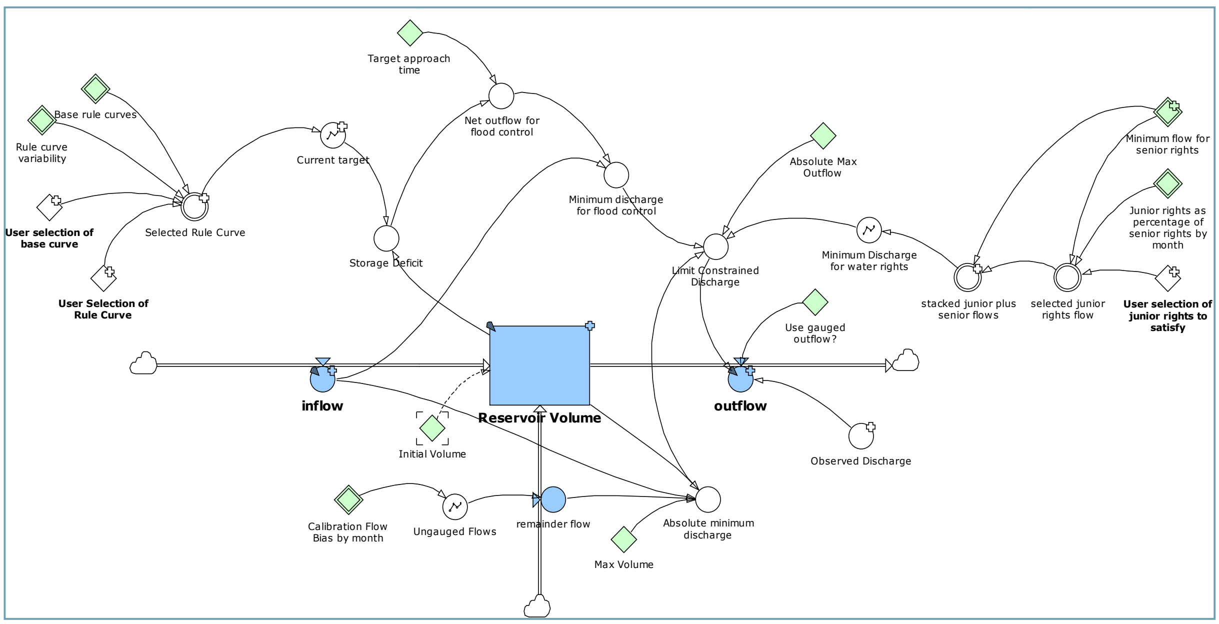
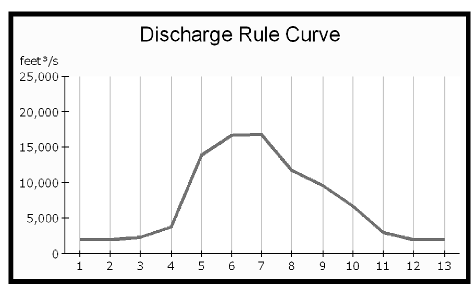


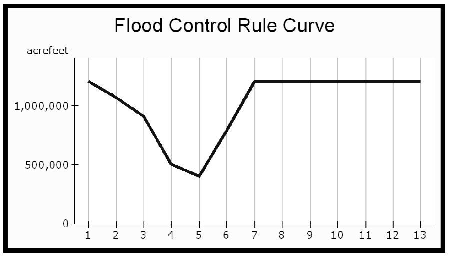
Figure 4: Diagram of the reservoir model.

The Palisades reservoir in eastern Idaho was simulated independently from other reservoirs in the system to calibrate and validate the reservoir model. Net inflow, discharge, and storage volume were all obtained from the Bureau of Reclamation Hydromet database. Plotting discharge patterns provided some interesting insight into reservoir management. In the absolute driest years, there was consistently a minimum discharge pattern, which could be dynamically adjusted based on a calculation representing the basin's relative moisture content. This suggests that there are exogenous flow requirements that must be fulfilled each year (figure 5). In the absolute wettest



ge Rule Curve for

years there was a large draw-down of the reservoir apparent in spring that set the storage target for the maximum level of flood control (figure 6).



e

To determine how to adjust the rule curve, the relative moisture metric was created which ranks a moving average of inflow over the current period versus the range of historic data. In the SRB, the wettest year was 1997 and the driest was 2001. The flood control rule curve and required summer discharge curve are adjusted based on a non-linear dependency on the moisture metric to prevent flooding downstream, to reach target storage level, and to satisfy downstream users.

IRRIGATION MODEL

The coupling of dynamic agricultural demand with the hydrologic system was accomplished by recognizing that agricultural users behave regularly and somewhat predictably when aggregated to watershed scales and monthly time resolutions. In an effort to better predict and define this behavior, Scott et al. noticed that agricultural diversion correlates well with the surface water supply index (SWSI), which is a synthesis of local moisture availability.[11] We used this method to develop correlations for diversion versus SWSI by month for three agriculturally predominant watersheds in the USRB. Consumption was calculated by assuming that the field application is related to withdrawal, and that this behaves as additional rain on the irrigated acreage. All water that is not consumed is returned to the originating aquifer. This assumption should be further tested and improved in the future by investigating the amount of return flow that leaches to groundwater or transfers to downstream watersheds.

The implementation of the agricultural model uses one stock to represent agricultural field moisture (Figure 9). It is assumed that all diversions are applied to this stock, and that a portion of this moisture evapotranspires, while the remainder returns to the stream from which it originated after a mean return time. The evapotranspiration is a function of the potential evapotranspiration from the watershed in which the agricultural entity resides as well as a crop coefficient corresponding to the relative consumption of the crop mixture. Return flow is directly computed from the field moisture and decays with a rate constant corresponding to the average return time for the diversion system.

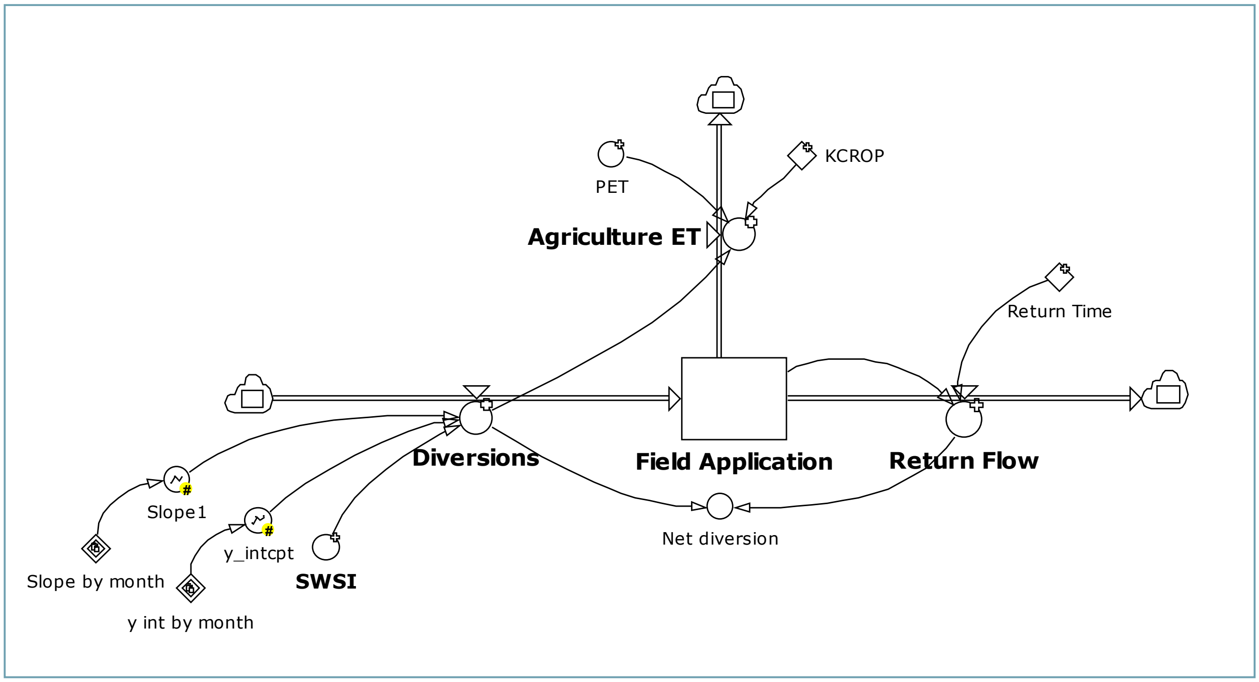


Figure 7: Diagram of irrigation object.

The irrigated agriculture object is coupled to its corresponding watershed agent as shown in Figure 8. This is done by endogenously calculating SWSI using a modified method that only accounts for precipitation and streamflow in the watershed.[12] Using the SWSI calculation and the potential evapotranspiration in the watershed, the agricultural agent calculates diversion and return flow. Diversions are subtracted and return flow is added to the net streamflow contribution of the watershed.

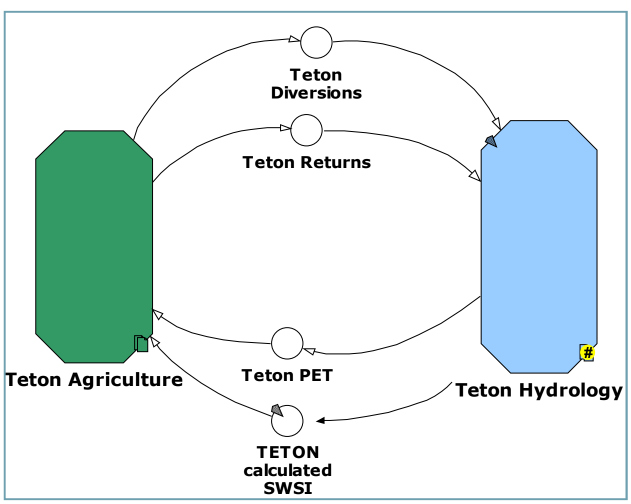


Figure 8: Coupling of agriculture to hydrology object

Two connected watersheds were simulated, the Teton and Lower Henrys, of which the Lower Henrys is the more downstream. The watershed and agricultural agent were calibrated in an iterative fashion by estimating the residual contribution of each to net observed streamflow. The calibration period was the years 1985 to 1994, and results for 1995 to 2004 are shown for validation (Figure 11). The watershed model contributes the timing and magnitude of peak flows, while the agricultural model is responsible for the summer dip and the fall peak in streamflow.

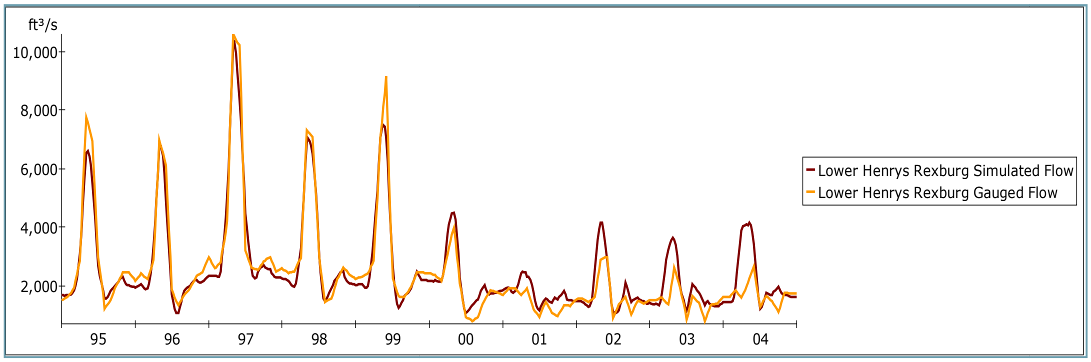
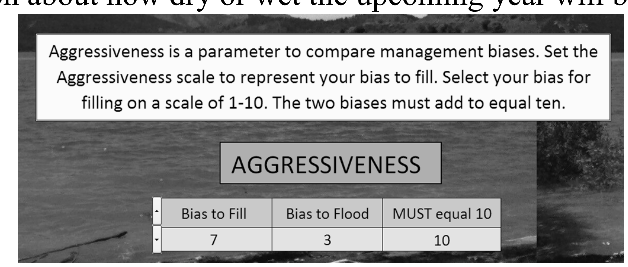


Figure 9: Calibration results of two watersheds.

VISUALIZATION AND APPLICATION

An application of this modeling framework simulated the function of the Palisades Reservoir given multiple climate inputs. The user has the option of setting the relative aggressiveness of the reservoir manager (figure 10). The user may choose a management strategy on a scale of one to ten, one being an absolute bias toward refill and ten being an absolute bias for flood control. These biases should indicate the user's intuition about how dry or wet the upcoming year will be based on the current level of snowpack. During a dry year a manager may be biased toward filling the reservoir than during a wet year. This scale is beneficial for managers because they can test different management strategies and see the reaction and constraints of the system.



face

To validate the results of the model the calculated storage and discharge were compared to the historical records available. Three years are used as an example: 2001, 1999, and 1997, corresponding to the driest, a normal and the wettest years respectively. The accumulated squared residual between the observed storage and the calculated storage over the course of one year was a maximum of 50,000 square acre-feet. Since the capacity of the reservoir is 1.2 million acre feet the discrepancy was reasonable for educational purposes.

Figure 11 shows the model interface where the user selects a start date, a comparable inflow year, the aggressiveness scale and an option to view extreme cases. In this case study the user has chosen January 1 as the start date, 1997 as the year choice, a neutral aggressiveness and did not choose to view extreme cases.

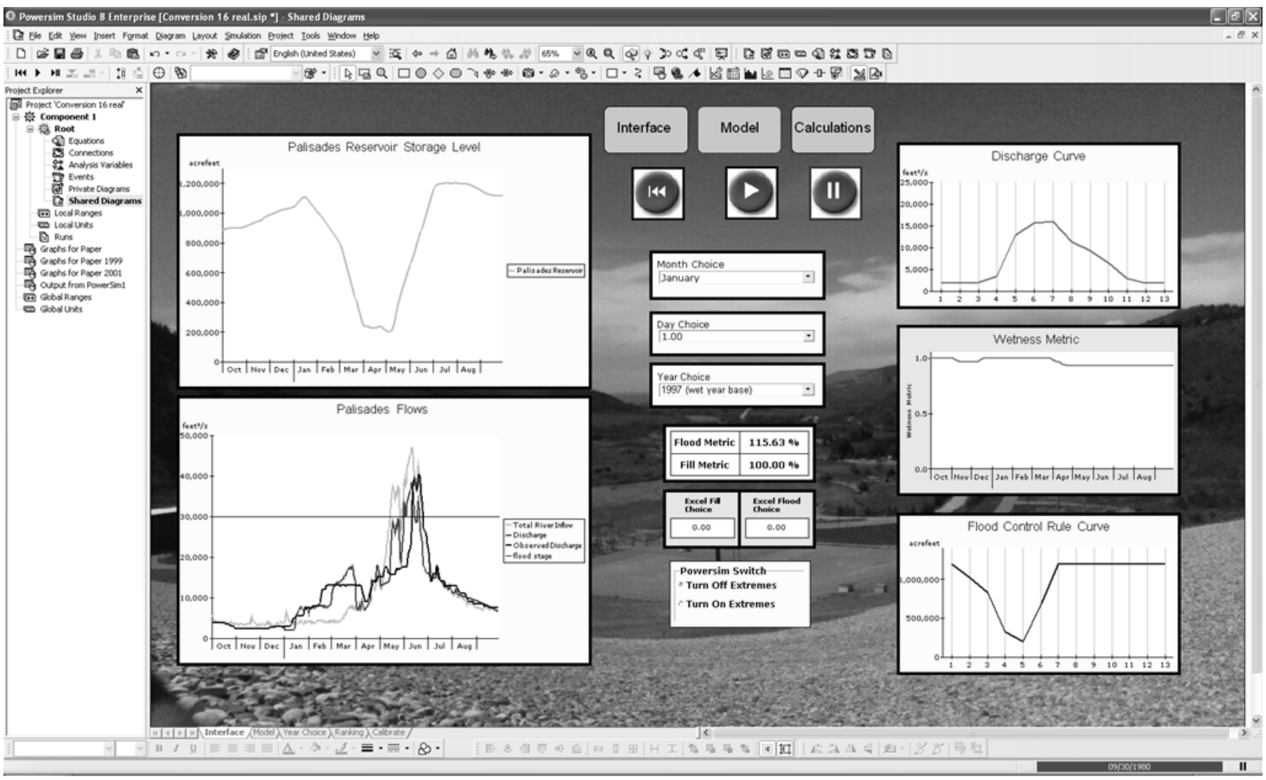


Figure 11: Illustration of the interface during simulation

After the user has selected the parameters and begins the simulation, the model simulates five consecutive years of inflow and discharge. The interface allows the user to see the results and observe interactions between the rule curves, wetness metric, discharge and storage levels. The model runs five one-year simulations and transfers the information to Excel where the different years can be seen on a comparative graph (Figure12). The user can simulate scenarios as many times as they like. This allows the user to observe the consequences of bias toward refill or flood control given changing climate conditions.

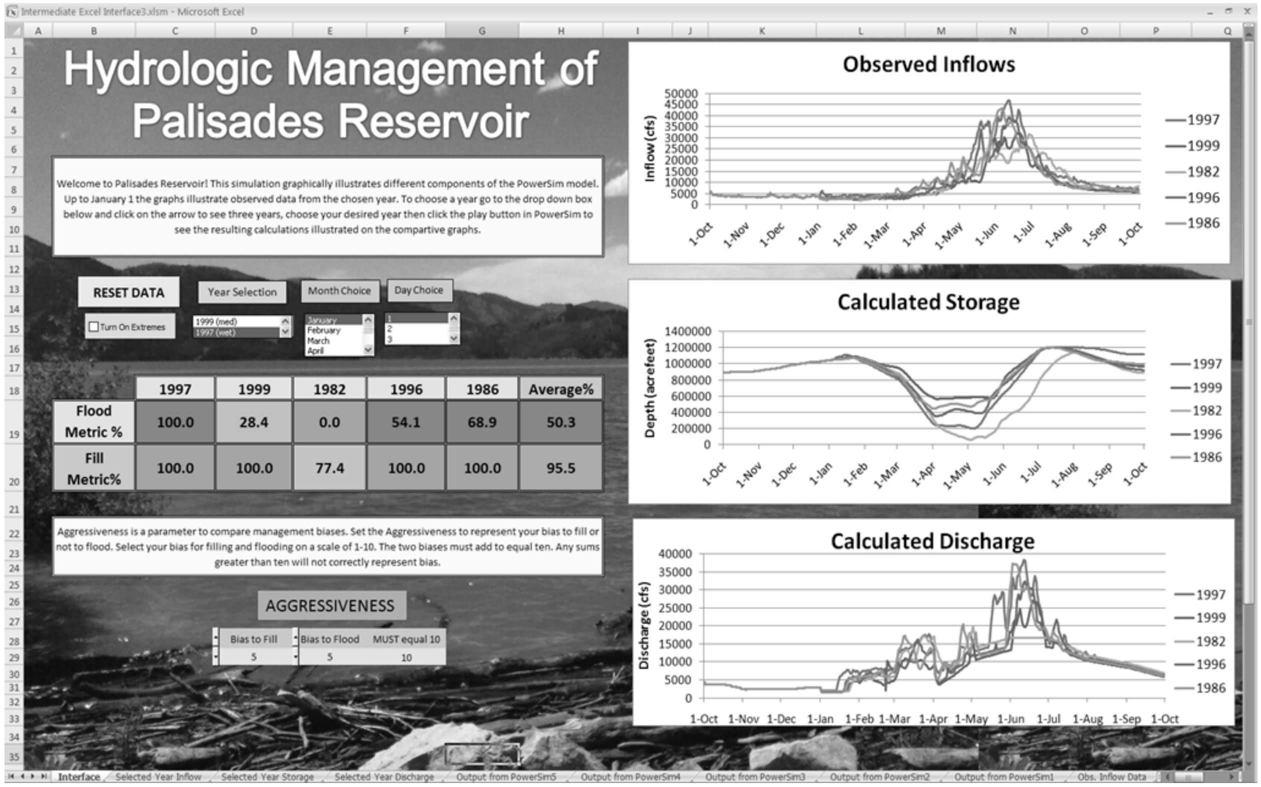


Figure 12: Diagram of the user interface with results.

This model is simple enough for people unfamiliar with system dynamics or hydrology to conceptualize the internal mechanics of a reservoir while allowing them to ask questions, learn about feedback loops and relationships within the system. They can then expand the current model to more accurately represent their circumstances and constraints. By allowing stakeholders to be involved in the modeling process the model becomes individualized and specific to their facility and the managers better understand why and how the model works. The model then becomes a more effective teaching and learning tool about the system.

CONCLUSIONS AND FUTURE WORK

This work has contributed to a framework for improving the holistic management of water resource systems by developing a modular and easily calibrated system dynamics water balance model that not only estimates the natural runoff schemes, but how they are coupled with the human withdrawal and consumption. A hydrologic watershed component was implemented in system dynamics that performs a monthly water balance for natural systems. The behavior of a major consumer – irrigated agriculture – was modeled and coupled to this watershed component. Management of water resources was analyzed through the creation of a simplified reservoir model that may be coupled with hydrology models in a modular fashion. This allows the modeler to develop a very large and complex linked hydrologic environment by calibrating and validating each individual component. Future work will integrate a groundwater component that can be linked to multiple watersheds, and groundwater pumpers. The end result of this linked model will investigate the coupling between surface and groundwater supply, withdrawal, and consumption. Finally, the model will be able to investigate potential solutions that attempt to balance energy, water, and ecological needs in water-constrained basins.

REFERENCES

[1] Costanza, R. and M. Ruth (1998). "Using Dynamic Modeling to Scope Environmental Problems and Build. Consensus." Environ. Management 22(2):183-195.

[2] Li, L. Xu, H, Chen, X, Simonovic, P., "Streamflow Forecast and Reservoir Operaton Performance Assessment Under Climate Change", Water Resource Management, 2010.

[3] 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.

[4] Bonabeau, E., 2002, "Agent-Based modeling: Methods and Techniques for Simulating Human Systems." Proceedings of the National Academy of Sciences, Vol. 99 (3) pp. 7280-7287.

[5] Brown, D.G., Riolo, R., Robinson, D.T., North, M., Rand, W., 2005, "Spatial Process and Data Models: Toward Integration of Agent-Based Models and GIS." Journal of Geographical Systems, Vol. 7 (1) pp. 25-47.

[6] Xu, C.Y. and Singh, V.P., 1998, "A Review On Monthly Water Balance Models for Water Resources Investigations." Water Resources Management, Vol. 12 (1) pp. 20-50.

[7] McCabe, G.J. and Markstrom, S.L., 2007, "A Monthly Water-Balance Model Driven by a Graphical User Interface." U.S. Geological Survey Open-File Report, Vol, 1088 (6).

[8] Blaney, H.F. and W.D. Criddle, 1950. Determining water requirements in irrigated areas from climatological and irrigation data. USDA/SCS, SCS-TP 96.

[9] PRISM Climate Group, Oregon State University. http://prism.oregonstate.edu.

[10] BOR regional Hydromet System at http://www.pn.usbr.gov/agrimet.

[11] Scott, K., "Modeling energy implications of water management decisions on the Eastern Snake River Plain." Master's thesis, University of Idaho, Moscow, Idaho, 2010.

[12] Shafer, B. & Dezman, L (1982). “Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas.” Annual Western Snow Conference Proceedings, Denver, Colorado, 710-82: 164-175.