

# **A Framework for Analysis of Energy-Water Interdependency Problems**

**Boise Western Energy Policy Research  
Conference**

Robert Jeffers  
Jacob J. Jacobson

August 2011

The INL is a  
U.S. Department of Energy  
National Laboratory  
operated by  
Battelle Energy Alliance



This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint should not be cited or reproduced without permission of the author. This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this paper are not necessarily those of the United States Government or the sponsoring agency.

# **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

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

# **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 transferable to a wide range of locations and applications. This is a very large, multi-year 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

## INTRODUCTION

The continued economic health and security of the United States depends on sustainable supplies of both energy and water. Water and energy are closely linked, in that the production of energy requires large volumes of water while the acquisition, treatment, and distribution of water is often dependent upon readily available, low-cost energy.<sup>1</sup> The two primary uses of water in the United States are for electricity generation and agricultural production. Whereas electricity generation accounts for 41% of all freshwater withdrawal in the United States, it only makes up 3% of total consumption. Withdrawal of water implies only that which is diverted from its source, while consumption implies permanent loss through evaporation. In contrast to energy uses, agriculture is responsible for 37% of freshwater diversion, but approximately 80% of consumption.<sup>2,3</sup> Because the law of prior appropriation governs rights to water use in the driest sections of the country, there is not a value-based system in place to maximize beneficial water use, rather a first in time, first in right philosophy. The distinction between withdrawal and consumption is important because the prior appropriation system works on the right to divert, while consumption is governed by sector-specific laws against wasteful water use. As water demand increases while supply remains fixed, systems that have classically relied on available sources of water may be facing increased costs, production curtailment, and conflict among users.<sup>1</sup> 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.

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 evolving policy. Through the incorporation of multiple planning criteria within the analysis, potential crosscutting solutions to energy and water issues 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 overarching spatial environment. This object-oriented approach lends itself to spatial and temporal resolution definitions 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 in the agricultural sector is dependent on the price of electricity, which is affected by the generation of hydropower, itself dependent on upstream withdrawal and consumption of water. 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 utility planners often extend 20-30 years, so to capture impacts of decisions the model is able to quickly reflect hydrology over 10 to 50 year time spans. More importantly, the model will outline both the short term direct impacts and the long term indirect impacts of both electricity generation and water consumption. Management and planning practices for water resources occur at three different scales: year-ahead planning, month and week-ahead management, and day-ahead mitigation. This model aggregates day-ahead mitigation strategies into the monthly effects which allow 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, industrial complexes, 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 model complexity to a minimum, the 8-digit Hydrologic Unit Code (HUC) employed by the United States Geological Survey was chosen as the primary spatial element. Hydrologic behavior is aggregated to this scale, but generation of electricity is still modeled at the plant level. A medium-sized electric utility will span on the order of dozens of 8-digit HUCs, with a wide varying number of plants per HUC.

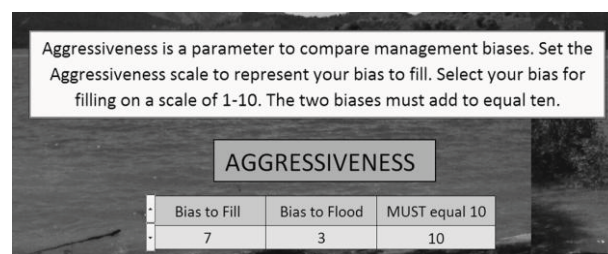
Recent work of Li et al. investigated the impacts of changing climate on performance of reservoirs in the North American Prairie.<sup>4</sup> Their model used system dynamics to link hydrologic processes with the inflow to a reservoir, and balanced the risk of flood and

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.<sup>5</sup> 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. 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.

## VISUALIZATION AND APPLICATION

An application of this modeling framework simulated the function of the Palisades Reservoir given multiple climate inputs. The purpose of the application is to describe the management practices of a single reservoir for multiple goals. The user has the option of setting the relative aggressiveness of the reservoir manager to either fill the reservoir during spring or to protect from flooding (figure 1). The



Aggressiveness is a parameter to compare management biases. Set the Aggressiveness scale to represent your bias to fill. Select your bias for filling on a scale of 1-10. The two biases must add to equal ten.

AGGRESSIVENESS		
Bias to Fill	Bias to Flood	MUST equal 10
7	3	10

Figure 1: Aggressiveness Scale Interface

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 also indicate the user's intuition about how dry or wet the upcoming year will be based on the current level of snowpack and soil moisture. During a dry year a manager may be more 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.

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 a range between very dry and very wet. Using this methodology, the square root of accumulated squared residuals between observed and simulated storage over the course of one year was a maximum of 0.021% of the total reservoir's capacity, which is reasonable for long-term planning purposes.

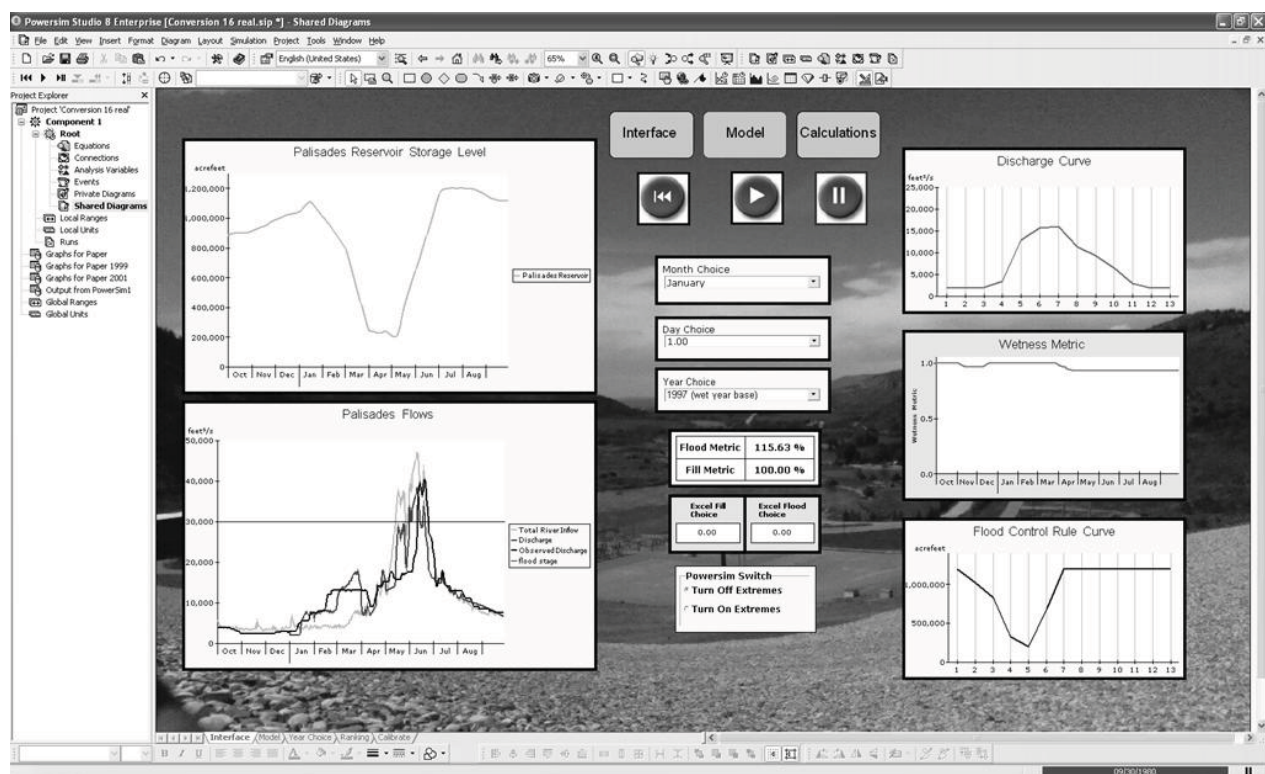


Figure 2: Illustration of the interface during simulation

Figure 2 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. The model will run on historic data from October 1 of the selected water year to the designated start date. At this point, the model calculates the five years most similar to the current water year based on a ranking index of surface water availability. It then simulates each potential year in succession, giving the user a clear view of a range of probable conditions given his or her chosen management strategy. If the user chooses to view extreme cases, the simulation will also run the wettest and driest years on record. In this example the user has chosen January 1 as the start date, 1997 as the base year, a neutral aggressiveness and did not choose to view extreme cases.

After the user has selected the parameters and begins the simulation, the model simulates the 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 Microsoft Excel where the different years can be seen on a comparative graph (Figure 3). 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.

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.

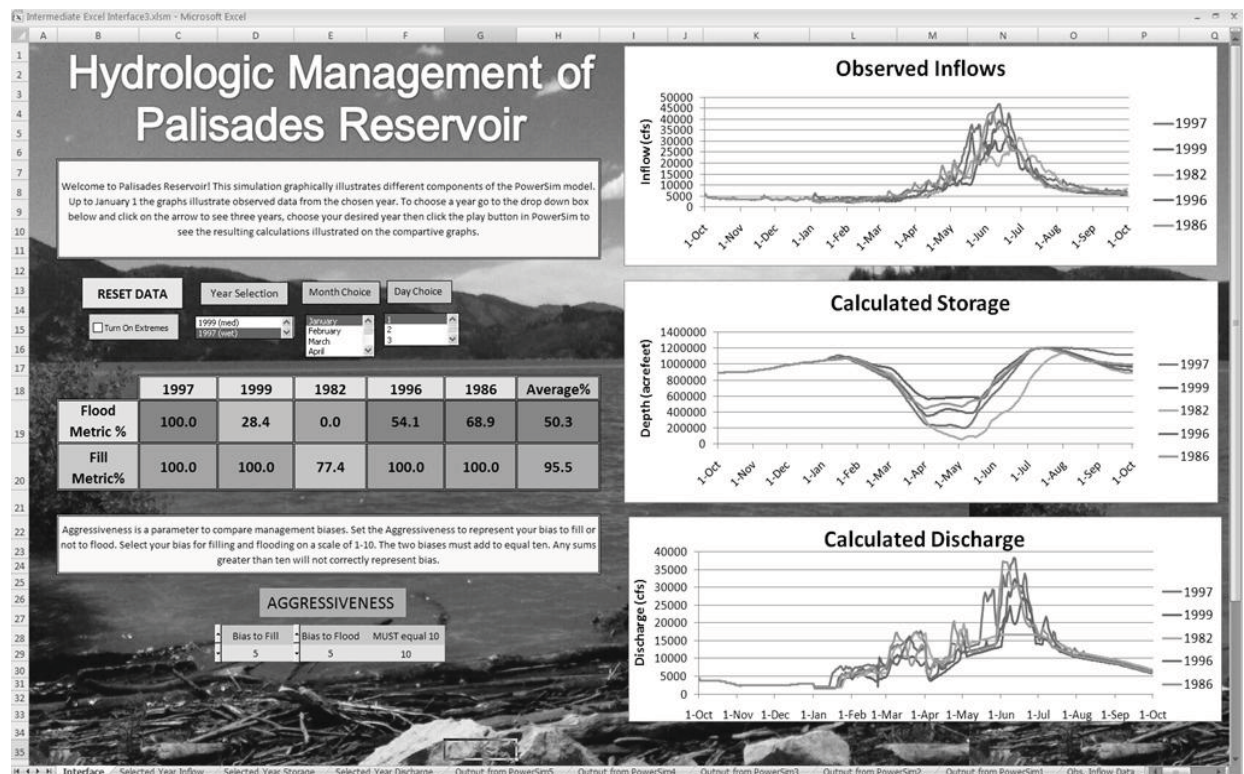


Figure 3: Diagram of the user interface with results.

## 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 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

---

<sup>1</sup> United States Department of Energy, 2006, "Energy Demands on Water Resources." Report to Congress on the Interdependency of Energy and Water.

<sup>2</sup> Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, "Estimated use of water in the United States in 2005." U.S. Geological Survey Circular 1344, 52 p.

<sup>3</sup> Solley, W.B., Pierce, R.R., Perlman, H.A., 1998, "Estimated Use of Water in the United States in 1995." U.S. Geological Survey Circular 1200.

<sup>4</sup> Li, L. Xu, H, Chen, X, Simonovic, P., "Streamflow Forecast and Reservoir Operaton Performance Assessment Under Climate Change", Water Resource Management, 2010.

<sup>5</sup> 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.