Integrated Decision Support for Energy/Water Planning in California and the Southwest

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Abstract: Policy makers and resource managers need to understand the interconnections between energy and water use and production—the energy–water nexus—to make well-informed decisions regarding long-term system planning. Planning and assessment issues include the development of strategies for reducing the vulnerabilities of water and energy systems to climate change while also reducing greenhouse gas emissions. To provide useful decision support for climate adaptation policy and planning, it is important to understand the regionally-specific characteristics of the energy–water nexus, and the history of the current water and energy supply systems serving an area. This will help decision makers understand the extent to which past choices have determined the nature of current adaptive capacity, and how those choices may have reduced certain vulnerabilities, while perhaps increasing others. We present an integrated water-energy modeling platform that can facilitate tailored water-energy analyses based on a detailed representation of local conditions. The modeling platform entails linking the Water Evaluation and Planning (WEAP) integrated water management modeling system with the Long Range Energy Alternatives Planning (LEAP) system to create fully-coupled modeling capabilities. This will allow analysts to consider feedbacks between energy system development and changes in water policy or infrastructure in order to better represent the long-term consequences of decision-making in either sector. Preliminary results are presented from an effort to create this coupled modeling system for the U.S. Southwest and California. This region is marked by large-scale regional integration of both the electric power and water sectors. The linkages between water and energy planning and policy questions in this region are described along with early insights from applications of the coupled modeling system.

Keywords: Climate Impacts, Integrated Modeling, Hydrology, Water Systems, Electricity, Adaptation Planning

INTRODUCTION

Water and energy policy and management decisions will figure prominently in efforts to adapt to and mitigate anthropogenic climate change. If policy makers and resource managers are to make well-informed and mutually compatible decisions about legislation, program development and long-term system planning, they need to understand the interconnections between energy and water use and production—the energy–water nexus. More specifically, they need to be able to incorporate information about the regional and local-scale characteristics of energy and water sector interconnections, and their sensitivity to climate variations in order to develop effective and robust mitigation and adaptation strategies. This will require the development of appropriate modeling tools that can facilitate a fully integrated assessment of the interactions and feedbacks between actions taken in either sector. It also will require further development of transparent and interactive decision processes through which policies and plans can be effectively coordinated across sectors.
There has been growing attention to the need to understand the water–energy nexus and to assess the implications of a changing climate for the reliability of energy and water supplies. For example, the U.S. Federal government, several state agencies, and various non–governmental organizations (NGOs) have supported research on the use of water for energy production, especially for electricity generation (U.S. DOE 2006; U.S. DOE/NETL 2008; Averyt, et al. 2011; Cooley et al., 2011; EPRI 2011; Fisher and Ackerman 2011; Macknick, et al. 2011). These assessments have generated useful information by providing an overview of nation–wide and regional patterns of water use for electricity generation. They have, for example, documented large differences in the dependence of thermoelectric power generation on freshwater use and consumption as a function of the generation type (combustion turbine, combined cycle, etc), fuel used (coal, natural gas, nuclear, etc.) and the cooling system technology (once–through, recirculating, dry, etc.). Other analyses have focused on the consumption of energy by the water sector throughout a chain of functions including extraction, transport, delivery, pre– and post–use treatment, and user applications (Wilkinson 2000; Cohen et al. 2004; Hoover, 2011). Some reports and recent books have covered both sides of the energy–water nexus, but generally as loosely connected puzzle–pieces rather than as integrated components of a coupled resource–management system (Klein, 2005; Colby and Frisvold 2011; Kenney and Wilkinson 2011).

While the energy–water nexus information–base has been growing, there remains a dearth of modeling tools to evaluate long–term interactions and feedbacks between these sectors in the context of a changing climate. In particular, a spatially explicit coupled modeling system could facilitate a more complete and accurate evaluation of the workability and consequences of alternative climate mitigation and adaptation strategies.

The goal of this project is to take steps toward the development of a decision analysis framework that explicitly couples energy and water systems. Models built on this platform could be used to facilitate policy development and adaptation planning at appropriate geographical scales. For example, in order to evaluate a city’s alternatives for adapting to the loss of snowpack storage in its water supply source area, it will be important to represent the water side of a coupled modeling system in some detail. It also would be valuable to be able to simultaneously work through the energy use and carbon emission consequences of the city’s water adaptation alternatives, as well as the potential feedbacks of associated new energy system development on system–wide water demands. The work here described, can aid the development of tailored water–energy analyses based on a detailed representation of local conditions.

Background and Setting

Startling national–level statistics are often used to call attention to the potential vulnerability of electric power generation to droughts and to the impacts of anthropogenic climate change on water availability (e.g. Union of Concerned Scientists 2011). Indeed, at the national scale, electricity generation makes use of vast quantities of water–accounting for roughly 41% of all US freshwater withdrawals (Kenny et al. 2009). However most of that water is used for once–through cooling of thermoelectric plants east of the Mississippi River, and all but a small percentage of that water is returned immediately to the source stream–although at a higher temperature (Averyt et al. 2011).

The picture in California and the Southwestern states is quite different from that national–average snapshot. Electricity producers in these states have adapted to their arid and semi–arid climates by adopting cooling ponds, recirculating systems or even dry cooling towers for their thermoelectric power plants that result in relatively parsimonious freshwater use. Such systems consume a larger fraction of the water withdrawn than do once–through cooling systems (Macknick, et al. 2011), but when compared to the consumption of water by irrigated agriculture, power generation is clearly not the major water consumer in these states (Cooley et al.
2011; Avery et al; 2011; Fisher and Ackerman 2011). In fact, for the Western Electric Coordination Council (WECC) region as a whole, water consumption for thermoelectric power generation accounts for an estimated four–tenths of one percent of total consumption, while irrigated agriculture accounts for 95% of consumptive water use (Tidwell et al. 2011). This statistical outcome results both from California’s dependence on natural gas (which uses relatively little freshwater) as the primary fuel source for thermoelectric generation, and the overwhelming share of irrigated agriculture in total water consumption in the interior west where more water-intensive coal–fired generation dominates.

That does not mean that power generation is not vulnerable to climatic disruption in this region. Low water conditions or high water temperatures can constrain thermoelectric power plant operations at specific locations. In addition, hydropower is regionally–important and highly sensitive to changing runoff conditions, especially where storage capacity is limited. It is estimated that hydropower accounts for approximately 28% of electric generation in the Intermountain West—a region bounded by the Cascade and Sierra Nevada Mountains on the west and by the Rockies on the east (Cooley et al., 2011). In 2007, hydroelectricity accounted for 14.5% of the electricity consumed in California, of which 62% was produced in–state, and the remainder imported from the Pacific Northwest and from the Colorado River Basin in the Southwest (CEC undated). However, 2007 was a relatively dry year in California, the Southwest and other western states. In fact, the availability of hydroelectricity to California utilities is quite variable from year to year, ranging from a high of close to 30% of the total electricity supply in a regionally wet year like 1983 to less than 10% of the total in dry years like 1991 and 2001 (CEC undated; NCDC, 2012). Other forms of electric generation, therefore, must be available to supplement the varying supplies of low–cost hydroelectricity.

On the energy–for–water side of the ledger, long–distance interbasin water transfer projects servicing Southern California and parts of Arizona result in significantly higher energy costs for urban water supplies in those locations than are required for cities served by abundant local water resources (Wilkinson, 2000; Cohen, et al., 2004; Eden, et al., 2011; Hoover, 2011). For example, the energy–cost of delivering water to coastal Southern California cities through the State Water Project (SWP), and other long–distance conveyance facilities is estimated to be approximately 8,900 kilowatt hours per million gallons (kWh/MG), while only 150 kWh/MG would be needed to supply and convey the same quantity of water to a typical city in Northern California (Klein 2005). In dollar terms, water imported through the SWP is especially expensive for Southern California urban water providers because that water must be lifted approximately 3,000 feet over the Tehachapi Mountains. The contract price per kWh for the electricity to pump this water is roughly six times higher than the very low contract price for the power used to pump Colorado River water into the Los Angeles Basin (MWD undated).

In Arizona, it requires about 497 kWh to convey a million gallons of Colorado River water to the Phoenix area through the Central Arizona Project (CAP), and pumping that water the full distance to Tucson requires an estimated 1,023 kWh (Eden et al. 2011)¹. Pumping for the CAP is entirely dependent on a single coal–fired electric generating plant, the Navajo Generating Station. Eden notes that: “…CAP is simultaneously Arizona’s largest supplier of water and its largest single consumer of electricity. Since 2000, CAP has supplied roughly 20 percent of Arizona’s total annual water use. The project annually uses 2.8 million megawatt–hours (MWh) of energy—approximately 4 percent of all the energy consumed in the state—to deliver 1.6 million AF of water to central and southern Arizona” (Eden et al. 2011, p. 111).

Total energy consumption for urban water and waste water services has generally increased with the region’s rapidly growing population—although at different rates for different cities. Energy use also depends on average household water use, which varies considerably between cities as a result of differences in local climate, price structure, lot size and outdoor watering

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¹ Author’s computations converting figures reported by Eden et al in kWh/Acre-foot to kWh/MG.
practices (e.g., Mayer, et al. 1999; Brookshire, et al. 2002; Western Resource Advocates 2003; Olmstead et al. 2007; Colby and Tanimoto 2011). When the full cycle of water provision, treatment, end user heating and wastewater management is considered, it is estimated that 19% of the electricity and 30% of the natural gas consumed in California is water–related (Klein 2005). Most of that energy is consumed for end–use heating, cooling and treatment (Klein 2005; MWD undated), meaning that water conservation programs and distributed renewable energy investments, such as roof–top solar systems could reduce water–related energy use and related greenhouse gas emissions.

Southern California is an especially interesting case for analysis because the region is heavily dependent on imports of both energy and water from other areas. A California Energy Commission report notes that: “Southern California imports about 50 percent of its water supplies from the Colorado River and from the State Water Project (SWP)—each of which is more energy intensive than any single source of water supply used in Northern California.” (Klein 2005, p. 11).

Energy imports are also important, both generally and specifically for operation of the region’s water supply system. The Metropolitan Water District of Southern California (MWD), the regional wholesale water provider for utilities serving approximately 19 million customers in coastal Southern California, has historically benefited from very inexpensive hydroelectricity generated at Hoover dam on the Colorado River to supply a large share of the electricity that it uses to transport, treat and deliver water to its customers (MWD undated). Because its long–term contract with the Federal Government for purchase of that power expires in 2017, MWD expects its power costs to increase significantly after that date. The District is therefore engaged in a major long–term energy planning process, through which it hopes to reduce electricity purchases on the retail market and to largely eliminate greenhouse gas emissions associated with its water operations by 2030.

The feasibility and cost of such a program and its impacts on region–wide water and energy systems will likely depend on the characteristics and pace of climate change in coming decades. For example, extended droughts might reduce the availability of hydroelectricity from Hoover Dam, while also reducing potential generation from the various hydropower investment options that MWD is now considering. Such a scenario would affect the net benefits to MWD of that set of options while increasing the likely net benefits from alternative non–water dependent solar and wind power projects. Hot and dry conditions associated with such a scenario also might lead to increased water demands in the agricultural districts from which MWD now buys supplemental water, and to increased water and power demands throughout southern California (Mayer et al. 1999; Aroonruengsawat and Auffhammer 2009; Blue Ribbon Committee 2011). The future quantity and quality of water available to southern California through the State Water Project from the Sacramento–San Joaquin Delta is also a concern, especially if continued sea level rise degrades the quality of that water or requires that additional water be left in–stream to keep the saline water away from the Delta pumps (Blue Ribbon Committee 2011).

**Structured Decision–Making and the Role of Models**

A coupled modeling tool, described here, may be especially helpful for informing decisions and for facilitating coordination across multiple planning entities. However, the modeling system itself is only one tool to be used in the climate adaptation planning process. The process itself needs to be structured to provide informative guidance on the robustness, resilience and flexibility of alternative courses of action in the face of real uncertainties about the details of future climate change at specific time periods and places.

In the present context, it might be important to consider interactions and feedbacks among actions taken by multiple parties. That would be the case if the outcome of decision options available to an individual planning entity (e.g. an individual water utility) could be substantially
altered by the effects of decisions taken by other entities. For example, the feasibility of one water provider’s proposed strategy to increase its reliance on reuse of treated wastewater might depend on how the price of electricity is affected by another utility’s decision to build (or not) a major new renewable energy project. A structured decision process typically begins by articulating underlying goals and identifying problems to be addressed. Subsequent steps include the development of data, models, and methods of analysis for evaluating alternative proposed actions. Our focus, here, is on the development of appropriate system modeling tools, which are described next.

WEAP–LEAP Integration

A project supported by the NOAA Sectoral Applications Research Program (SARP) has been working to develop an integrated water and energy modeling platform by linking two previously separate modeling tools. These are the Water Evaluation and Planning (WEAP) system, developed by the Stockholm Environment Institute (SEI) in close collaboration with the National Center for Atmospheric Research (NCAR), and the Long-range Energy Alternatives Planning (LEAP) system, also developed by SEI.

WEAP (http://www.weap21.org) is an integrated water resource planning and management modeling tool. WEAP is a user–friendly system that uses an object–based approach to allow the model–builder to represent the physical processes governing the availability and movement of water as well as interactions among all of the water use and management activities in a watershed. The objects include such features as sub–catchments, surface water bodies, dams and other infrastructure elements, and the locations of specific water demands. WEAP can track the movement of water through a river basin starting with exchanges with the atmosphere–i.e. precipitation and evapotranspiration as well as interactions between groundwater and surface water systems.

LEAP (http://www.energycommunity.org) is a long–range integrated energy planning and greenhouse–gas mitigation modeling system. Its outputs are an integrated cost–benefit analysis of different energy portfolios along with the environmental effects of each portfolio in terms of pollutant loadings and other environmental externalities. It is a highly flexible tool that supports a wide range methodologies for both demand–side and supply–side model development.

Figure 1 is a schematic of the coupled WEAP–LEAP system, showing some of the interactions between the two sides of the energy–water nexus.

Linking the models entails passing data for specific variables between the models. For example, WEAP passes to LEAP at each time step, an estimate of the electricity demand associated with a given water management pattern, including the treatment and transmission of water. LEAP then responds to this demand for electricity by the water sector and all other demands for electricity by dispatching its power mix. This mix contains all sources of electricity generation in the time step, including WEAP’s estimate of available hydropower as well as the other electricity sources such as coal, natural gas, nuclear, etc. Information on the evolving conditions in the energy system (as simulated by the dispatch of electricity by LEAP) is then passed back to WEAP in the form of water demands for thermoelectric cooling. A fully integrated WEAP and LEAP model would converge on a consistent set of water management demands for energy, energy supplies, and opportunities to create energy in conjunction with managing water (e.g. biogas generation at waste water treatment facilities). This would allow the feedbacks between the water management and energy management sectors to be fully captured.
Focusing on the Water–Energy Nexus in US Southwest

The initial focus of the coupled WEAP–LEAP modeling integration was an experiment for the Southwestern U.S., with a particular emphasis on California. In order to capture the dependence of California on imported water and electricity from the Colorado River Basin, a WEAP model was built covering the entire region. This is called the SwWEAP model (Figure 2). The SwWEAP model uses monthly climate data to simulate the hydrologic cycle, where WEAP catchment objects are used to represent the spatial and temporal attributes of climate in the watershed (Yates et al. 2005). The model includes more than 300 catchment objects based on elevation and broad land–use classes, including native, urban and irrigated agriculture types. The WEAP catchment object includes a conceptual hydrologic model that simulates runoff generation, which is passed to river objects that account for streamflow and groundwater–surface water interactions. The rivers in the SwWEAP model extend from the South Platte River in Colorado to the Coastal Rivers of California, the Salt River of Arizona, and the Klamath River of Southern Oregon—including 64 rivers. The river and transmission network of SwWEAP includes the primary storage reservoirs and water transfer projects, with 53 of the largest reservoirs and lakes that combine to total more than 100 million acre–feet of storage. These river systems generate from 20,000 to 60,000 GWh of hydroelectric power each year, depending on whether the water year is dry or wet.
There are five competing water demands represented in the SwWEAP model, each given an integer priority according to the WEAP allocation logic, with the highest priority assigned a value of 1. From Highest (1) to Lowest (5) Priority these are: environmental flows, such as required outflows in the Bay–Delta; thermoelectric cooling, urban indoor use, urban outdoor use, and irrigated agriculture. Under water short conditions, WEAP first allocates to the highest priority, then the second highest priority, and so on. Although these WEAP priorities are unlikely to accurately depict historically-established seniorities under the prior appropriation system, they may produce a reasonable approximation of actual use patterns when mechanisms exist to facilitate water transfers during drought periods (Miller, 2000; Hanak et al., 2010). These water demands are spatially explicit, and include the primary urban regions of the Southwest such as the Colorado Front Range, the Salt Lake Valley, the Phoenix Metropolitan Region, etc. In California, water demand is represented by more than a dozen of the largest municipal regions, such as the Bay Area, the Central Valley, San Diego, the LA Basin, the Santa Clara Basin, etc. In the current version of the regional model, indoor water demands are computed on a per-capita basis, while both agricultural and urban outdoor water demands are calculated based on acreage estimates and soil moisture deficits. In addition to hydropower production, SwWEAP estimates the electricity needed by water related activities, including conveyance; groundwater pumping; and municipal potable and waste water treatment.

The coupled modeling system was configured to simulate over the historic period 1979 through 2010, with 1979 through 2003 used for hydrologic calibration. Figure 3 shows observed and simulated inflows and releases at Lake Powell on the Colorado River, the inflows to Lake Shasta, and the Delta Outflows on the Sacramento/San Joaquin river system for the calibration period. Figure 3 includes the Nash–Sutcliffe (N–S) efficiency estimates\(^2\), with values around 0.9, suggesting that on an annual basis, the model has considerable skill in representing the streamflow volume and is able to adequately represent wet and dry periods. The model underestimated extreme wet periods, most notably the high flows on the Sacramento in 1983.

\(^2\) The Nash-Sutcliffe (N-S) efficiency is a measure of model skill with a value of 1.0 indicating the model is a perfect predictor of the simulated flow, while 0.0 suggests the observed mean is a better predictor than the model simulated values.
Figure 3: Annual Simulated and Observed Inflows to Lake Shasta on the Upper Sacramento River and Total Outflows at the Sacramento–San Joaquin Delta (Top), and Inflows and Outflows at Lake Powell on the Colorado River (Bottom). Numbers in Parentheses are the N–S efficiencies.
On the energy side of the ledger, the LEAP model focuses only on the electricity sector of California, and is referred to as CaLEAP. Household and commercial electricity use is estimated by regressing electricity demand on a KWh/household and KWh/ft$^2$ basis, against monthly maximum temperature to reflect regional and seasonal changes in electricity demand (Fisher and Ackerman 2011). Household and commercial electricity end-uses include water related activities, most notably electricity to heat water. Other water sector electricity uses include potable and wastewater treatment and water delivery (groundwater and conveyance pumping), which are estimated by the SwWEAP model and passed to CaLEAP at each time-step. These are estimated from electric intensity rates in KWh/m$^3$ of delivered water.

Industrial electricity use is estimated by CaLEAP and is based on a simple estimate of KWh per millions-of-dollars of activity. Figure 4 shows SwLEAP simulated electricity demand for household, commercial, industrial and water sector activities. Electricity demand for household and commercial activity is the largest share of total electricity use. Estimates of electricity use in California in 2010 are about 280,000 GWh, with a SwLEAP estimate of 286,000 MWh for that year. Greenhouse gas emissions are relatively flat from 1990 to 2001, when hydropower production increased due to a sequence of wet years. Continued growth in electricity demand and a return to somewhat drier conditions in the early 2000’s increased the share of natural gas in electricity generation, with a corresponding increase in greenhouse gas emissions. The increase in industrial electricity use from 1998 to 2001 corresponds to increased economic activity, while the subsequent economic downturn shows up as a period of flat growth in electricity use. The bottom panel of Figure 4 shows the electricity portfolio mix for California, dominated by natural gas and imports, with hydropower making up from 10% to 15% of the total supply over that period. Hydropower is estimated in SwWEAP and passed to CaLEAP, and includes about 55% of the hydropower generated at Lake Mead on the Colorado River, supplying about 2,000 GWh annually. Figure 4 includes estimates of the associated greenhouse gas emissions in millions of metric tons of CO$_2$ equivalent of both in-state and imported electricity.
Figure 4: CaLEAP Estimated Electricity Demand by Sector in California (Top), and the Electricity Portfolio Mix (Bottom) for California, Including the Global Warming Potential of this Mix Given in Millions of Metric Tons of CO₂ Equivalent
Figure 5: Agricultural and Indoor and Outdoor Municipal Water Deliveries in Million Acre–Feet (Top) and Electricity use Associated with Water Delivery and Treatment to California for Municipal Treatment and Transmission and Agricultural use (Bottom)
Figure 5 shows SteWEP estimates of total delivered water for agricultural and outdoor and indoor municipal water demands (Top), and the electricity use associated with municipal water supply and treatment, long–distance conveyance, and agricultural supply and end use (bottom). Generally, electricity use by the agricultural sector is reduced in wet years like 1998, when agricultural water deliveries are primarily from surface supplies, and reduced groundwater pumping leads to a corresponding reduction in electricity use. High agricultural groundwater use is associated with high electricity use for pumping. In drought periods, it is assumed that the established practice of temporary agriculture–to–urban water transfers would stabilize municipal and industrial (M&I) water deliveries. During droughts, farmers will typically shift to groundwater, reduce their irrigation amount, change to less water consuming crops, or fallow land altogether.

We have demonstrated the utility of a linked Water–Energy model in exploring the relationship between water and electricity. Examples of questions that one could address with these models include assessing the implications of different population movement/growth scenarios for Southern California water and energy planning, evaluating the potential robustness of proposed Renewable Portfolio Standard strategies, and exploring the energy–demand and greenhouse gas emission implications of alternatives for improving water–supply flexibility. Many municipal water providers in Southern California are aggressively pursuing desalination and reuse as alternatives to imported water, and exploring the energy and CO₂ emission implications of these choices would be worthwhile. Future work will include further model development, and the creation of applications to examine the tradeoffs inherent in these issues.
REFERENCES


Dr. David Yates: David Yates is a Scientist in the Research Applications Laboratory at the National Center for Atmospheric Research and an Associate of the Stockholm Environment Institute’s US Center. Dr. Yates has been a part of the development team of SEI’s Water Evaluation and Planning (WEAP) system that seamlessly couples the physical hydrology of watersheds, agricultural systems, and water management infrastructure; and the Long range Energy Alternatives Planning system (LEAP), which is used to explore energy policy analysis and climate change mitigation assessment strategies. He has trained University, NGO, and government agencies around the world on water management, climate change and the application of WEAP and LEAP.

Dr. Kathleen A. Miller: Dr. Kathleen Miller is an economist who works with the Climate Science and Applications Program at the National Center for Atmospheric Research. Her research focuses on human exploitation of climate-sensitive natural resources, and the socioeconomic and institutional factors affecting resource management decisions in the context of uncertainty and competing interests. Among her publications is a co-authored book on the implications of climate change for urban water utilities: Climate Change and Water Resources: A Primer for Municipal Water Providers (Awwa Research Foundation, 2006). She is a lead author of Chapter 3, “Water Resources and Their Management,” in the IPCC Working Group II, Fourth Assessment Report: Climate Change 2007: Impacts, Adaptation and Vulnerability. She is also a lead author of the IPCC Technical Paper on Climate Change and Water. She received a B.A. in anthropology and M.A. and Ph.D. in economics from the University of Washington.
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