Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY-WATER INTEGRATED ASSESSMENT OF THE SACRAMENTO AREA UNDER SCENARIOS OF CLIMATE VARIABILITY

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NOVEMBER 2016
CEC-500-2016-064

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Contract Number: 500-09-017

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ACKNOWLEDGEMENTS

This work was supported by the California Energy Commission and Lawrence Berkeley National Laboratory. The authors would further like to express their gratitude to Joe O'Hagan, the Sacramento Municipal Utility District, SEI, Chile, Water Forum, and the Regional Water Authority for useful comments and discussions throughout the study.

PREFACE

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Energy-Water Integrated Assessment of the Sacramento Area under Scenarios of Climate Variability is the final report for the Linking Water and Energy for the American River System, contract number 500-09-017 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Water and electric utilities in California are uniquely vulnerable to climate change. Reduced precipitation and increased temperatures from climate change will likely lead to increasing demands for water and energy from both municipal and agricultural users. Surface water supplies quickly decline under such conditions, placing a greater emphasis on energy intensive groundwater supplies. At the same time, reduced precipitation leads to reductions in hydropower generation. These tight interactions among water, energy, and climate indicate the need for similarly linked water-energy models to forecast and manage the impacts of climate change on water and energy supplies and demand.

Researchers created fully integrated energy and water simulation models of the American River and Sacramento region to allow simultaneous analysis of the effects of climate change on water and electricity use in Sacramento, California. The Sacramento and American River region provides a good case study for modeling the linkages among water, energy and climate. Electricity utilities in the region use American River flows to generate hydropower and cool thermal power plants, while water utilities in the region use electricity to pump, pressurize, and treat water for residential, agricultural, and commercial users.

These basin-scale simulation models include projections of the demand and supply of water and energy for residential, commercial, industrial, and agricultural sector users. Historic data was combined with the current energy and water system configuration to assess the implications of changes in temperature and precipitation. The results of the case study for the Sacramento Area show that water and electricity demands and supplies are vulnerable to temperature and precipitation variability. The simulations suggest that, assuming a 4 °C (7.2 °F) increase in average temperature and a 25 percent decrease in average precipitation, electricity imports to the region would have to substantially increase.

Keywords: Water and Energy, Long-Range Energy Alternatives Planning Model, Water Evaluation and Planning Model, Sacramento Municipal Utility District, hydropower, electricity dispatch

Please use the following citation for this report:

Dale, Larry L.,Nihan Karali, Dev Millstein, Mike Carnall, Sebastian Vicuña, Nicolas Borchers, Eduardo Bustos, Joe O'Hagan, David Purkey, Charles Heaps, Jack Sieber, William D. Collins, Michael D. Sohn. Lawrence Berkeley National Laboratory. 2016. ***Energy-Water Integrated Assessment of the Sacramento Area Under Scenarios of Climate Variability.*** California Energy Commission. Publication number: CEC-500-2016-064.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction: The Water-Energy Nexus

Water and energy systems have historically been treated as separate realms, with little consideration of one another in planning and with little recognition of interactions between the two. In reality, these two systems are closely interlinked. Water is involved in all aspects of energy production, generation and use, while energy is essential for pumping, treating and distributing water. Efforts to address climate change have heightened awareness of these linkages—known as the "water-energy nexus"—and of the need to integrate water and energy planning and decision-making. A great deal of this has to do with water scarcity; in many places, conflicts are arising between water demand for energy production, urban use, agricultural irrigation, and to support environmental systems. At the same time, energy demand from the water sector—especially for irrigation, but also for desalination and water and sewage treatment—has emerged as a real concern; it cannot only strain already overtaxed energy systems, but also add significantly to greenhouse gas emissions.

Project Purpose

Even as recognition of these issues has grown, a lack of suitable tools has hindered efforts to address key questions about the water-energy nexus. For this project, researchers took two software systems used worldwide for water and energy analysis and linked them so they can be used together for an integrated, simultaneous analysis of water and energy research, planning and decision-making. Instead of building a new tool, researchers chose this approach to better meets the needs of water and energy users. By linking the two software systems, users could continue working with familiar, well-proven systems freely available to governments and nonprofits and avoid evaluating and learning new software.

Generally, hydrology models are used to understand how water flows through a watershed in response to hydrological events, while water resource planning models are primarily used to describe the allocation and use of that water within the context of water management decisions. The Water Evaluation and Planning (WEAP) system combines both the watershed hydrology model and the water management model into one model that can simulate a broad range of natural and engineered components of a watershed or basin, including snow accumulation and melt, soil moisture, runoff, stream flows, and groundwater recharge, as well as water demand by sector, reservoir operations, and hydropower generation. Several previous studies using WEAP addressed portions of this study area.

The Long-Range Energy Alternatives Planning (LEAP) system is a scenario-based modeling tool for integrated energy and environmental planning. Its scenarios are based on comprehensive accounting of how energy is consumed, converted, and produced in a given region or economy under a range of alternative assumptions on population, economic development, technology, price, and so on.

In this study, these integrated models are used to analyze the impact of climate change on regional water (WEAP) and energy (LEAP) systems in the Sacramento and American River Basins. Both tools feature mass balance accounting frameworks, simple dispatch rules for regulating resource supply, and climate sensitive functions for projecting resource demand and supply. Information transferred between the water and energy models include the following:

- Water requirements for energy production (such as water for hydropower generation and cooling of thermal power plants) are integrated into the energy model.
- Water supply characteristics that are needed to project energy demand (such as energy for pumping groundwater by urban and agricultural users and energy for treating water largely by urban water districts).
- Hydropower is modeled in WEAP and fed to the energy model.

With a linked WEAP and LEAP model of the Sacramento region, common modeling areas, scenarios, periods of analysis and timesteps are provided.

Project Approach

The electricity demand relations are user-defined equations of the Sacramento area WEAP-LEAP model. The authors developed the electricity demands for the period 1981–2001, according to population, working hours, temperature, stream flow, and groundwater depth information. Stream flow, groundwater depth, functions of temperature, and precipitation changes were calculated in the WEAP part of the modeling. Both stream flow and groundwater depth increase with precipitation and decrease with temperature. The other data used to project electricity demand was obtained through the SMUD (Sacramento Municipal Utility District) Planning Department, California Department of Transportation, and the United States Census Bureau.

Four climate scenarios were created to represent the impact of future temperature and precipitation extremes in the region. These scenarios bracket the range of temperature and precipitation outcomes forecast for the region by some of the more widely used general circulation models. These scenarios, which are modifications to the base period temperatures and precipitation, are as follows:

Hot

1. 2 °C (3.6 °F) increase in temperature
2. 4 °C (7.2 °F) increase in temperature

Hot and Dry

3. 2 °C (3.6 °F) temperature increase and a 15 percent precipitation decreased
4. 4 °C (7.2 °F) temperature increase and a 25 percent precipitation decrease

Project Results

The results of the case study for the Sacramento Area show that water and electricity demands and supplies are vulnerable to temperature and precipitation variability. The modeled impact on electricity and water use suggests the vulnerability of the region to climate change. A 2 and 4 °C (3.6 and 7.2 °F) increase in temperature raises base period electricity demand by 1 and 3.3 percent, respectively. Electricity demand is less sensitive to decreases in precipitation, increasing only 4 percent over baseline in the hot-dry scenario, with a 25 percent drop in precipitation. This relative insensitivity reflects in part the region's secure access to abundant groundwater.

This study was performed as a preliminary test of the policy value of the water-energy perspective, where water use is accounted for in energy planning and energy use is accounted for in water planning. The results demonstrate the potential usefulness of a linked regional-scale analysis capability. In this case, we see that the water-energy system in the Sacramento, California region is particularly vulnerable to hot-dry scenarios, when electricity and water demands peak and electricity and water supplies decline. This vulnerability is indicated by changes in a series of water-energy stress variables, including regional electricity imports and electricity use per unit of water pumping. Currently, the region can cover any shortfall with increased electricity imports. Future availability of these electricity imports, including hydropower from the Pacific Northwest, is crucial to avoiding local electricity shortages and vulnerable to changes in the climate.

Ratepayer Benefits

This paper proposes a new modeling framework that links energy and water systems and provides a joint platform for detailed analysis of energy and water policies. In California, water and energy are especially closely linked. Long-term solutions to water and energy demands within the state are needed to be developed jointly to deal with climate change. The linkage between the two models improves our ability to track water demands for the energy sector and energy demands for the water sector.

CHAPTER 1:
Introduction

1.1 Water and Energy

Water and energy are inextricably linked resources: water is needed to extract and produce energy; energy is used to extract, treat, and distribute water. This interdependency, often called the "water-energy nexus" (Gleick, 1994, 2000), has been increasingly emphasized as an important issue for future planning and strategic policy considerations in the recent years. Historically, water and energy systems were treated independently. However, with increasing awareness of impending (potentially significant) changes in regional climate and water cycle, the interdependence between water and energy has received increasing attention. Long-term solutions to water scarcity and energy demand is needed to be developed jointly to deal with climate change.

1.2 Energy and Water Modeling

Energy modeling has been a commonly applied tool in energy planning since the early 1970s. Energy models, including the Model for Energy Supply Systems and Their General Environment (MESSAGE) (Schrattenholzer 1981), the Energy Flow Optimization Model (EFOM) (Van der Voort et al. 1984), the Market Allocation Model (MARKAL) (Loulou et al. 2004), the Long Range Energy Alternatives Planning (LEAP) (Stockholm Environment Institute 2011), and the Bottom-Up Energy Model (BUEM) (Karali 2012), typically mimic the dynamics and relationships of energy demand and supply. These dynamics and relations are often influenced by many outside parameters such as governmental policies, environmental enforcements, technological innovations, and physical resource limitations.

On the other hand, water models are largely used for the planning and operation of water supply, demand, and distribution systems. Water models, including Watery-Global Assessment and Prognosis (WATERGAP) (Alcamo 2003), the Water Evaluation and Planning System (WEAP) (Yates 2005a&b), the Model for Distribution System Analysis (MODSIM) (Labadie et al. 2000), and the Water, Agriculture, Technology, Environment, and Resource Simulation, (WATERSIM) (De Fraiture 2007), focus on water usage and availability, and are used to develop sustainable water management policies. However, even though those models perform well separately, they lack the data and systemic interaction between water and energy components. Energy models neglect the impact of climate changes on water systems and water models neglect the impact of climate changes on energy systems.

Most of the studies treat water as a component of the energy models and energy as a resource of the water models. For example, Ould-Amrouche et al. (2010) focused on photovoltaic (PV) water pumping systems with sustainable developments in Egypt, and Alawaji et al. (1995) studied on desalination plant size analyses with PV in Saudi Arabia. Another study showed that wastewater treatment and reuse options seem to be more energy and cost effective due to minimal transportation costs (Kajenthira et al. 2012). Moreover, recent analysis has focused on both energy and water consumption and environmental performance in the field of biofuel production (Fraiture et al. 2008). The development of the biofuel sector puts additional pressure on water resources while bringing an alternative source to energy sector.

Up to the present, there have been fewer efforts to model regional scale interactions between water and energy across multiple economic sectors and zones. The Climate, Land, Energy, and Water model (CLEW) is one of the modeling tools developed for regional scale (Bazilian et al. 2011). The development of this framework is based on soft linking of three models; WEAP for water modeling, LEAP for energy modeling, and Agro-Ecological Zoning (AEZ) (Fischer et al. 2002) for land-use. However, they are not linked in modeling structure and the soft linking is realized by manual transformation of the input-outputs among three modeling. Another recent modeling in this regard is the use of the TIMES Integrated Assessment model (TIAM-FR) (Loulou and Labriet 2008), combined with a water module. TIAM-FR model is a bottom-up energy optimization model, which is developed on TIMES modeling platform. Dubreuil et al. (2013) generated a water module in this bottom-up framework, including water supply options, key water processes, and water demand. Energy is treated as an input used in water processing systems that satisfies water demand in this model. However, water is not used in energy modeling modules. Thus, the hard linkage is not completed, works just one-direction, from energy modules to water module, and loses the feedback between energy and water modules.

Therefore, this study developed a linked WEAP-LEAP water energy model, which allows communication of water and energy in either direction. The development of this framework is based on hard linking of WEAP and LEAP modeling systems. Both WEAP and LEAP models provide a bottom-up perspective. The advantage of using a bottom-up approach for water and energy is to identify both key water and energy processes. A case study was carried out based on the weekly data from 1981 to 2001 in Sacramento Area, California. Energy and water linkages include power generation, water treatment, agriculture irrigation, and water pumping to residential, commercial, and industrial sectors. The study is focused on understanding potential climate variability (such as temperature increases and precipitation changes) impacts on water and energy processes in the case area.

1.3 Report Organization

The rest of the paper is organized as follows: Section 2 describes the study area. Section 3 describes the water-energy modeling framework and its application to some of the water-energy dynamics within the study area. Section 4 presents the study results and conclusions.

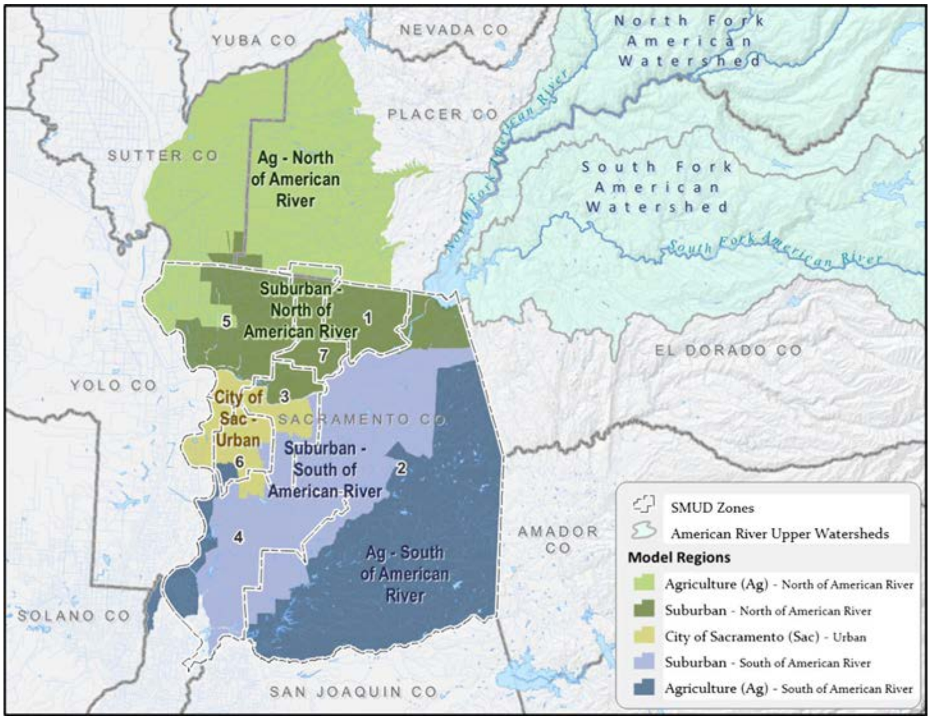
CHAPTER 2:
Study Area

2.1 Introduction

An idealized setting to demonstrate climate risks and management of a linked water and energy system would be a closed system with all water and electricity supplies generated and used in the same geographic study region. Such a setting presents stark management tradeoffs between water and electricity with no option for avoiding shortages with imports.

In California, the American River basin and Sacramento area have some aspects of this ideal setting (Figure 1). This region relies heavily on local hydropower and thermal generation resources and has important linkages between water and energy supply and demand. This is not a fully closed system, since the region has access to imported electricity and outside water.

Figure 1: Study Area—American River Basin, Sacramento Municipal Utility District (SMUD), and Model Regions



From this point of view, the Sacramento area is a good region for assessing how climate variability (such as temperature and precipitation) will affect electricity/water use and generation in an integrated water-energy model. In this region, the American River and associated Sierra watersheds provide water to hydropower and thermal power plants and residential, commercial, industrial, and agricultural users in the Sacramento area. Agricultural users are composed of farmers using surface and groundwater for irrigation, while residential customers are composed of single and multi-family residential water users supplied by water from regional water utilities. In sum, this area represents an interconnected system of streams, reservoirs, and groundwater for its water supplies and a mix of reservoirs, thermal power plants, and imports for its electricity.

2.2 Water Systems in the Study Region

The Sacramento area is fed by more than 60 rivers, reaches, and creeks, which join to form the major rivers included in the water system addressed in this study: the North Fork, the Middle Fork, and the South Fork of the American River. The American River flows are highly variable. Flow data indicate a characteristic pattern for California streams, with winter peak flows often several times the annual average.

The Sacramento region draws on two sources of stored water in dry periods: surface storage and groundwater. Surface storage in the region is concentrated in Folsom Reservoir, with a storage capacity of 1.2 billion m^3. Sacramento shares Folsom storage with other downstream water rights holders. Groundwater underlies the vast majority of the study region with depths below ground surface varying greatly throughout the study region.

The demand for water by urban and agricultural users is also seasonal, but, in this case, demand peaks in the summer months when surface water is least available. Table 1 shows the weekly average and maximum water demand in million cubic meters for urban, agricultural and others. These water demand and supply patterns contribute to a reliance on ground and reservoir storage. From 2005 to 2010, groundwater accounted for 44% of all water use in Sacramento County. There are 27 public and private water purveyors in the study area.

Table 1: Sacramento Region Weekly Water Demand in 2010

	Urban	Agricultural	Other
Average (Mm^3/week)	1.5	13.6	10.0
Maximum (Mm^3/week)	23.4	38.9	53.3

Source: Sacramento Regional Water Authority, 2012

2.3 Electricity System in the Study Region

The Sacramento Municipal Utility District (SMUD) is the Sacramento region's primary electric utility. The demand for electricity within the SMUD service area is quite variable by season. For example, the demand data indicate that maximum energy demands in the summer are 15% higher than the annual average (Table 2). The residential and commercial use of air conditioners drives the demand for electricity during the hot summer months.

Table 2: Sacramento region weekly Electricity Demand in 2010

	Commercial and Industrial	Residential	Total
Average (GWh/week)	117.4	84.1	201.7
Maximum (GWh/week)	130.1	104.2	232.5

Source: Sacramento Municipal Utility District 2012

SMUD supplies electricity using a mix of variable generation sources (hydropower and renewables), a stable generation source (thermal power), and imports. SMUD generates hydropower from a series of reservoirs and related facilities located on the upper American River, upstream of Sacramento. These hydropower facilities can provide as much as 40% of the region's electricity in spring and early summer but more typically provide only 10-20% of the electricity. Hydropower generation also falls off dramatically during dry years.

SMUD's thermal generation facilities, including the Cosumnes natural gas plant, provide the bulk of the region's local generation in most years. The renewable sector, including solar and wind facilities provide a growing yet, relatively small portion, (two percent in 2010) of the electricity. SMUD draws on electricity imports, primarily from the Pacific Northwest, to cover shortfalls, when regional demands exceed regional generation. In some months, SMUD sells small amounts of electricity to other regions. Table 3 shows observed SMUD regional monthly electricity demand and generation for 2010.

SMUD uses two regional water sources for generating electricity. SMUD draws down reservoir storage during the spring and summer for generating hydropower. In a typical summer, SMUD draws drown much of the available reservoir storage while generating hydropower. SMUD also withdraws water from the American river for cooling the Cosumnes natural gas plant. SMUD withdraws an average of 100 acre-feet per week from the American River for this purpose. In both cases, the withdrawals usually represent only a small fraction of the available water flow. However, during very dry periods, the withdrawals can be significant.

It should be noted that the residential and commercial and industrial demands for water and electricity are highly correlated—particularly during summer months when irrigation demands for water and air conditioning demand for electricity both peak. However, the relationship between electricity and water use in the region is apparently not a causal relationship. In other words, holding temperature constant, water demand is largely independent of electricity demand.

Table 3: Observed SMUD Regional Monthly Electricity Demand and Generation in 2010[1]

Period	Load (MWh)	Hydro (%)	Thermal (%)	Imports (%)
March	788,988	6	72	28
May	773,089	42	33	27
July	1,042,743	16	47	36
Average	858,998	19	53	31

Source: Sacramento Municipal Utility District, 2012.

2.4 Water-Energy Linkages in the Study Region

This regional overview suggests three prominent and direct energy-water linkages for this area. The most important linkage is hydropower, which supplies electricity and can affect the timing of some water supplies. The second is the use of electricity for pumping and treating water by the region's urban water and agricultural irrigation districts. The third is the water used for cooling thermal power plants. The process use of heated water by urban customers is an indirect, subcategory of total urban electricity use in our model. Some residences (about 15 %) use electricity to heat water, which amounts to another category of electricity use in the model. The model assumes reservoir releases based on historic practices, giving priority to hydropower generation in some cases and reliable water supply in others. Changing to reservoir operations as a means of lessening downstream water shortages (such as for thermal cooling) was not explored in this study.

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[1] Percentages exceed 100 % in some months when exports are positive.

CHAPTER 3:
Methodology

3.1 The Water-Energy Modeling Framework

In this study, a new model integrating two popular planning tools, WEAP and LEAP, for evaluating water-energy interactions is described. Both WEAP and LEAP are designed for analyzing the impacts of climate change on regional scale water and energy systems. These platforms feature a basic mass balance accounting framework, simple dispatch rules for regulating resource supply and climate sensitive functions, for projecting resource demand (Yates et al. 2005a; SEI 2011).

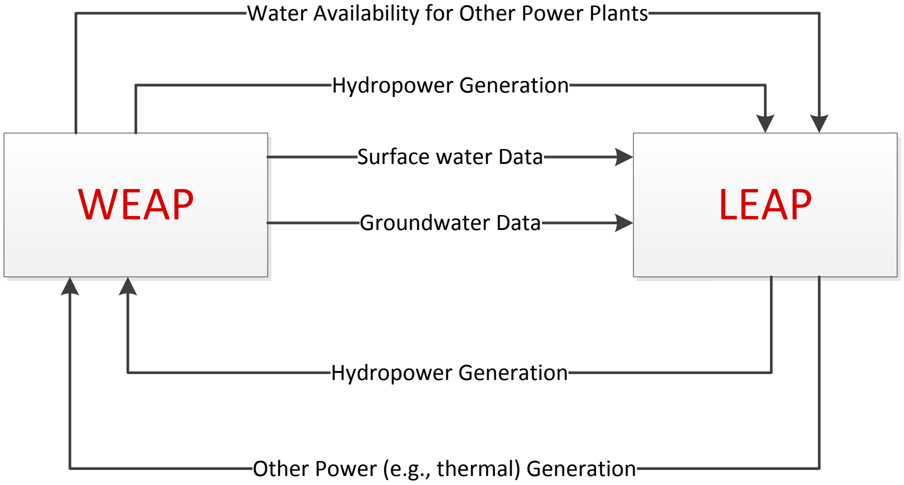
Both platforms are designed to simulate the effect of changes in climate and climate policy on water and energy systems. LEAP has been used widely for exploring the implications of reducing energy consumption and greenhouse gas emissions on energy systems (Huang et al. 2011, Tao et al. 2011, Park et al. 2013, Cai et al. 2007). For example, Ozer et al. (2013) analyze the CO_2 emission mitigation potential in the Turkish electricity sector with a LEAP model application. Bose and Srinivasachary (1997) use an India-specific application to evaluate energy use and environmental emissions from the transport sector. Wang et al. (2011) studied the Chinese energy system's supply and demand strategies and corresponding impacts on the environment using a LEAP model.

Similarly, WEAP is widely used to inform state and national water policy (Levite et al. 2003, Bloom et al. 2013, Yates et al. 2013, Mehta et al. 2013a&b). Swiech et al. (2012), for example, analyze the impacts of a reservoir for improved water use in irrigation in the Yarabamba region, Peru with a WEAP model application. In another WEAP modeling application for Benin, Höllermann et al. (2010) focus on Benin’s future water situation under different scenarios of socio-economic development and climate change until 2025.

3.2 Developing the WEAP-LEAP Application

The authors built an integrated WEAP-LEAP application to simulate the water and electricity systems in this region, including their interactions and sensitivity to climate variation. The application includes the water system based on WEAP components, the electricity system based on LEAP components, and the water-energy interactions, represented by linkages between WEAP and LEAP. The water and energy systems and the water-energy interactions of the application are illustrated in Figure 2.

Figure 1: Basic Relationships in the WEAP-LEAP Linked Framework



As Figure 2 shows, the WEAP application generates information on 1) the amount of energy that will be required as a water utility seeks to balance water supply and demand and 2) any ancillary energy that can be generated through the management of water. The LEAP application addresses the electric utility service area within which this water management takes place provides information on the energy availability, costs, efficiencies, and environmental impacts associated with these water management activities.

The first step in this effort was to identify linkage points where WEAP could provide useful water-specific insights to LEAP, and where LEAP could provide useful energy-specific insights to WEAP, including:

1. Energy demands from water management, including energy for pumping groundwater by urban and agricultural users, and energy for distributing and treating water largely by urban water districts.
2. Water demands for electricity management, including water flows for hydroelectric power production, and water for cooling thermal power plants.

SEI focused integration efforts on preparing the WEAP and LEAP software platforms for compatibility with Application Programming Interfaces (API's); progress here includes researching and implementing 1) a new file format enabling LEAP to run concurrently with WEAP, and 2) a new and more flexible approach for LEAP to incorporate seasonal and time-of-day variation into annual, user-designated time-slices.

SEI also created an array of unique API's to enable communication functionality between the WEAP and LEAP software platforms. This required core software changes to the LEAP model to ensure compatibility between LEAP and newly planned features.

SEI also modified the programming language to allow LEAP and WEAP to communicate with API's. The work focused on establishing the parameters for communication between the time period structure of WEAP (52-week hydrologic year), and the user-defined time slice structure of LEAP (for example, summer/winter or days/nights). SEI enhanced LEAP's capacity to model seasonal and time-of-day variations by creating a more flexible approach for dividing annual data into weekly time slices, achieved by linking user-defined LEAP time slices to an annual load curve. To ensure compatibility with future API's, SEI devised a user-interface element within LEAP to allow users to define weekly time slices rather than simply forcing users to define and link time slices to annual load curves.

Some of the major changes made to the WEAP and LEAP model platforms include the following:

LEAP:

- New file formats
- New time-slice data structures enabling variation of power supply and demand by season and time-of-day
- New communication structures supporting connections with WEAP
- New Application Programming Interface (API) features supporting both the revised time-slice data structures and expected communication points with WEAP

WEAP:

- New structure and methodology for API communication with LEAP
- New user-interface guide ensuring system consistency when linking WEAP and LEAP
- New data structures to hold linking information
- New calculation logic governing information flows between WEAP and LEAP in a given year model year, implemented as the models iterate towards convergence

Finally, the project team implemented the critical WEAP and LEAP connections via respective API's of the two models. This included mapping key features related to information exchanges. The process of connecting the models necessitated:

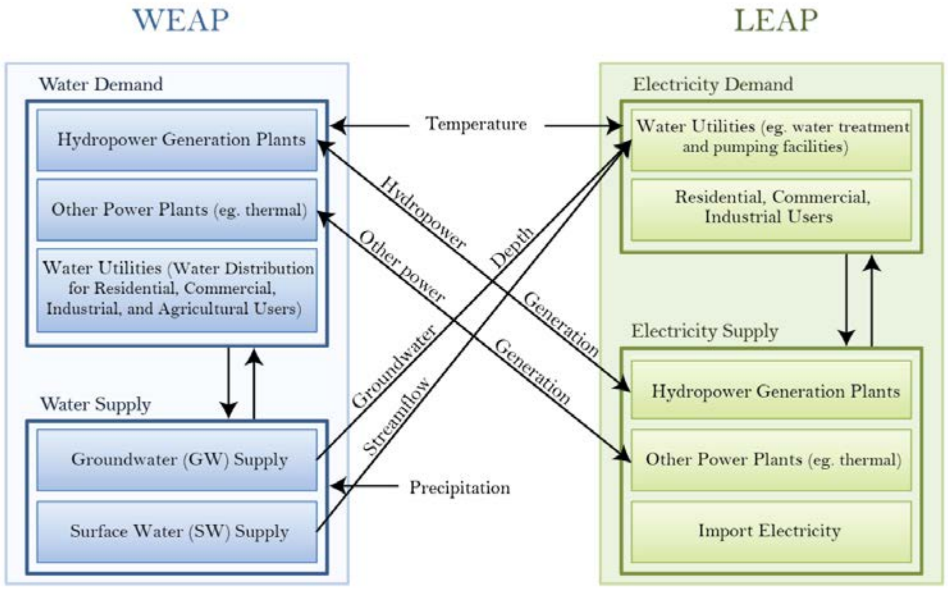
- Development of a software interface element to guide users and creation of an API programming code to make possible data transfers between WEAP and LEAP.
- Defining linkages between WEAP and LEAP.
- Creating the linkages for the American River WEAP LEAP Model.

The linkages between model tools retain the underlying simulation capabilities of both models while improving run-time execution and numerical stability. Since the purpose of this study is to study how temperature change as a proxy for climate change will affect electricity generation, in particular hydropower generation, and affect energy demand, in particular from increased groundwater pumping, information transferred between the water and energy models include the following:

- Integration of water requirements for energy production (such as water for hydropower generation and cooling of thermal power plants) into the energy model.
- Water supply characteristics that are needed to project energy demand (such as energy for pumping groundwater by urban and agricultural users and energy for treating water largely by urban water districts)
- Hydropower modeling in WEAP that is fed to the energy model
- Consistent weekly time step calculations

The main model water parameters/variables that are passed to the energy model module are hydropower generation, water for thermal power plants, and groundwater depth as needed to define the energy demand for pumping water (Figure 3.) The model integrates the water module with the energy model to match supply and demand automatically.

Figure 3: Basic Relationships in WEAP-LEAP Linked Sacramento Framework



3.3 Modeling of the Study Region

The water system in the WEAP-LEAP model includes the natural hydrology, storage and hydropower facilities, groundwater, and regional demand nodes. The natural hydrology and storage and hydropower facilities on the upper American River are simulated from earlier WEAP models, including Cosumnes, American, Bear & Yuba (CABY) and El Dorado Irrigation

District (EID) models (Yates et al. 2013). The water demands for the region's agricultural and urban users were estimated using data provided by the Regional Water Authority of Sacramento (RWA). These equations were estimated as functions of temperature and precipitation, as well as population and economic variables. The local surface and groundwater portions of the model, covering the region in and around Sacramento, were modeled using data provided by the Regional Water Authority.

Electricity supply was modeled in three main steps: estimation and integration of 1) electricity generation options, 2) power dispatch rules, and 3) electricity demand. The Sacramento area has three electricity generation alternatives: hydropower, thermal power (based on natural gas), and renewable (such as wind and solar) electricity generation. If electricity generation is insufficient to meet the demand (depending on the installed capacities and streamflow) at the end of a period, imported electricity is used to satisfy the remainder. Power dispatch rules determine the sources of electricity generation used to service electricity demand in the model. Hydropower plants, supplying largely base loads in the model, have the highest generation priority. Most of the electricity demand is met by local thermal and renewable plants, which have the next highest generation priority. The remaining electricity demand is supplied with imported electricity, which has the lowest generation priority.

Electricity demands in the region were modeled for the residential, commercial and industrial and water utility sectors. The demand relationships are calculated as functions of population, temperature, water deliveries, and groundwater depth. Electricity demand is particularly sensitive to temperature in this region; when temperatures exceed a comfort threshold, residential, commercial, and industrial demand for air conditioning increases. The data used to estimate electricity demands were obtained from SMUD, the California Department of Transportation, and the United States Census Bureau.

The three principal electricity-water interactions are incorporated in the model, including water for hydropower, water for thermal cooling, and electricity for groundwater pumping. Water used for hydropower is included as a function of reservoir storage and climate conditions. The approach estimates hydropower generation across a range of possible climate impacts similar to Madani and Lund (2010) and Vicuna et al. (2011). Withdrawals upstream of the reservoirs are rare. In terms of thermal cooling, American River withdrawals cool the Cosumnes thermal power plant; when flows are very low, the plant may be shut down. The smaller co-generation plants in the region use a variety of other water sources. Our application does not reflect the potential impact of changes in water temperature or plant technology that might impact surface withdrawals (van Vliet et al. 2013, Koch and Vögele 2013). Finally, groundwater withdrawals in one period affect groundwater availability and electricity requirements in later periods. Groundwater electricity demand is defined as a deterministic function of groundwater depth and average pump efficiency (Figure 3).

Electricity and water use in the model are linked in the sense that the supply for one resource is contingent on supplies of the other. For example, to increase water supplies in the model, the region needs to increase electricity (for pumping and treating water). Similarly, to increase local electricity supply, the region needs high water flows (for hydropower or cooling).

All energy-water interactions in the model are sensitive to climate inputs. During hot dry periods for example, water and electricity demands increase and hydropower and thermal generation decrease leading to an increase on imported electricity.

CHAPTER 4:
Model Verification

Model-to-historic data comparisons for the region suggest the general viability of our model. Modeled flows into and out of Folsom reservoir closely match the observed flows between 1994 and 2001 (Figures 4 and 5). (The correlation coefficient is 0.87 for inflow and 0.71 for outflows). The lower fit for reservoir outflows suggests reservoir storage decisions are not fully captured in the model.

Modeled hydropower generation also tracks observed generation closely (Figure 6). The correlation coefficient in this case is 0.92.

Finally, modeled total electricity load roughly matches the observed data at the end of the baseline period but tends to exceed observed subsector load data for some sectors (Figure 7).

Figure 2: Folsom Lake Weekly Inflows and Outflows Predicted in the WEAP-LEAP Model Versus Observed Statistics (m^3/sec)

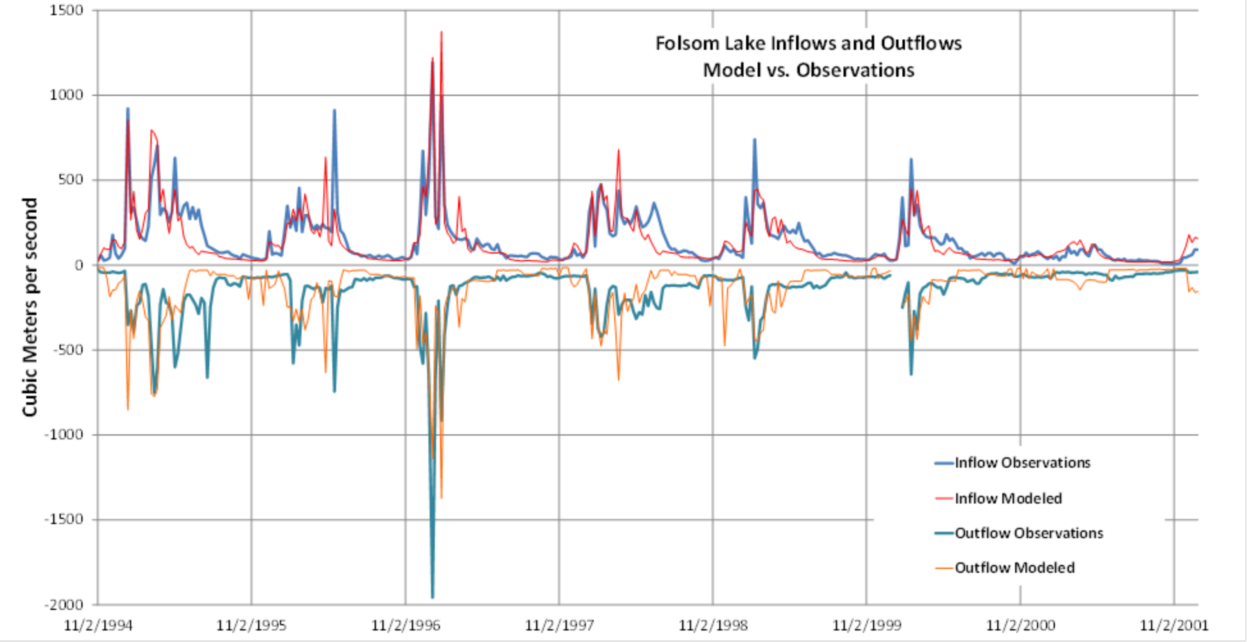


Figure 5: Folsom Lake Annual Inflows and Outflows Predicted in the WEAP-LEAP Model Versus Observed Statistics (103 m3/sec)

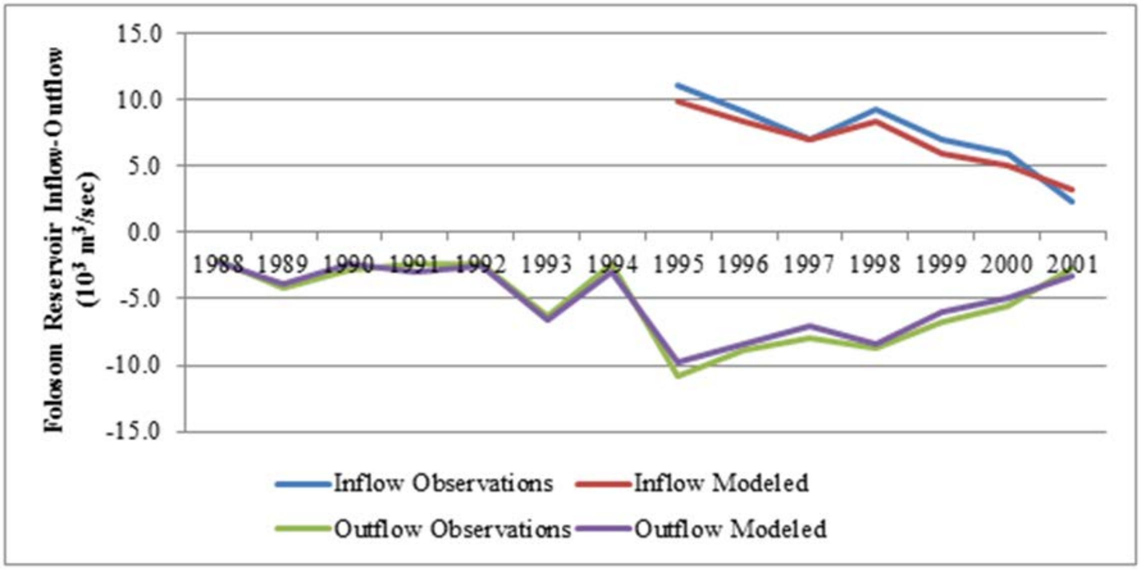


Figure 6. Measurement and Model Prediction of American River Hydropower Generation

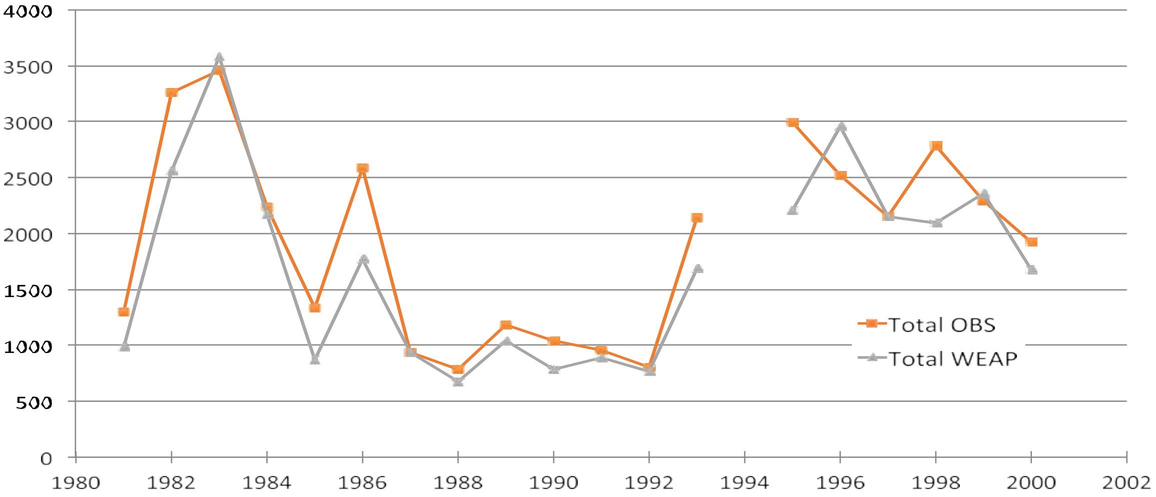
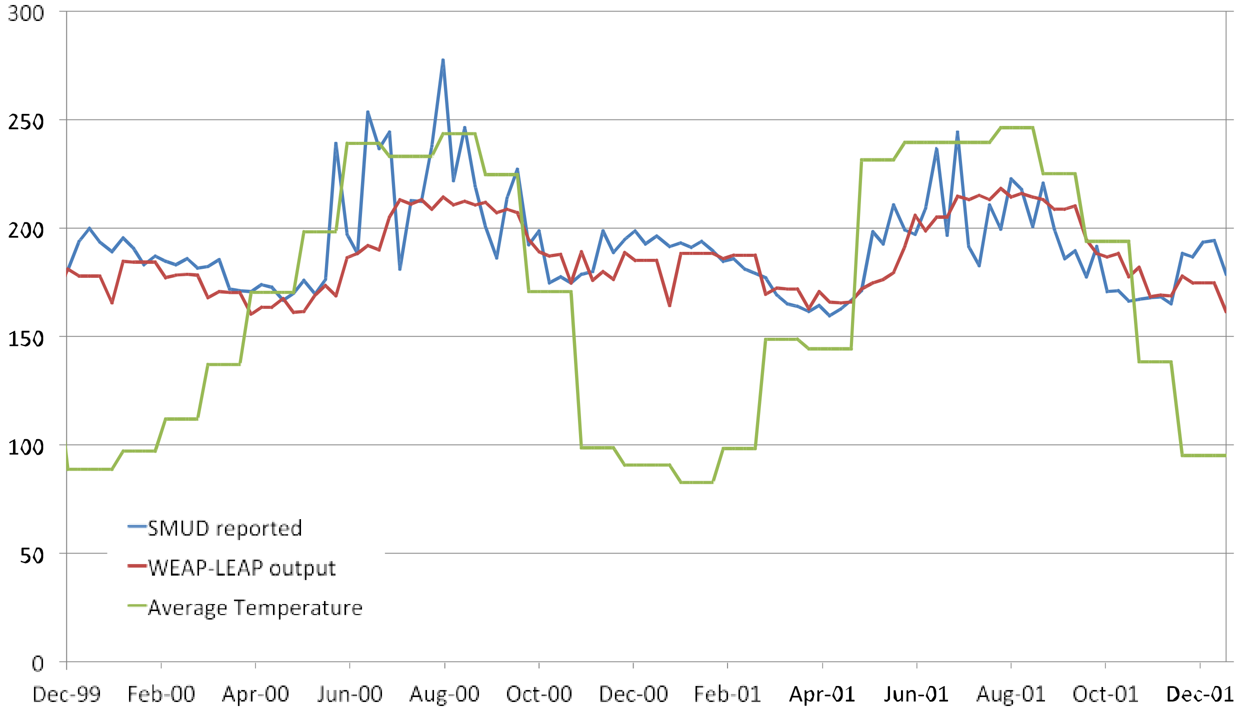


Figure 7. Measurement and Model Prediction of Weekly Sacramento Electricity Demand



CHAPTER 5:
Case Study Results—The Impact of Changes to Annual Average Temperature and Precipitation

5.1 Scenarios

The authors created four climate scenarios to represent the impact of future temperature and precipitation extremes in the region. In each scenario, the base period (1982–2001) climate pattern was modified as follows:

1. Temperatures increased 2 °C (3.6 ° F) ([+] 2 °C);
2. Temperatures increased 4 °C (7.2 ° F) ([+] 4 °C);
3. Temperatures increased 2 °C and precipitation decreased 15 %
4. Temperatures increased 4 °C and precipitation decreased 25 %

These scenarios do not illustrate specific climate scenarios and cannot show the effect of any shift in timing of precipitation, or seasonal differences in future warming, but they do bracket the range of temperature and precipitation outcomes forecast for the region by some of the more widely used general circulation models (GCM).

For example, averaged across model ensembles, temperature increases of 2–4 °C (3.6–7.2 °F) and precipitation changes between −25 and +5 % cover likely outcomes projected for the Sierra Nevada Mountains and the Sacramento Valley after 2060 (Pierce et al. 2012; Cayan 2014). Actual climate change impacts will be more complicated than are indicated by applying uniform scaling factors.

The modeled impact on electricity and water use suggests the vulnerability of the region to climate change. Table 4 shows that a 2 and 4 °C (3.6 and 7.2 °F) increase in temperature raises electricity demand above the base period by 1 and 3.3 %, respectively. Electricity demand is less sensitive to precipitation—rising only 4 % over baseline in the hot-dry scenario, despite a reduction in precipitation by 25 %. This relative insensitivity reflects in part the region's secure access to abundant groundwater. Electricity demand would be higher if the region had less abundant groundwater (Dale et al. 2013).

Production and demand for electricity are also impacted by swings in temperature and precipitation. Generation decreases most in the hot-dry scenarios—a 4 °C (7.2 °F) increase and 25% decrease in precipitation causes generation to fall about 8%. This reduction is unsurprising, as hydropower generation is everywhere vulnerable to changes in temperature and precipitation (Vicuna et al. 2011). Thermal generation may also be affected by climate extremes; in the hottest, driest scenario, with limited streamwater for cooling, thermal generation declines 3.2 % below baseline.

Table 4: Modeled Change in Electricity Demand, Generation, and Imports, Compared to the Base Scenario (%)

	Electricity Demand	Electricity Generation	Thermal Power	Hydropower	Imported Electricity
Hot Scenarios					
(+) 2°C	1.0%	-1.0%	-0.7%	-1.9%	6.0%
(+) 4°C	3.3%	-2.0%	-1.3%	-4.4%	17.1%
Hot-Dry Scenarios					
(+) 2°C (-) 15%	1.0%	-3.2%	-0.2%	-13.2%	11.8%
(+) 4°C (-) 25%	4.0%	-7.7%	-3.2%	-22.8%	35.9%

Please note that these rates represent any change (decrease/increase) within demand, generation, and import by itself. They are not relative changes. Thus, “Electricity Generation” and “Imported Electricity” do not necessarily sum up to “Electricity Demand”

The impacts on the regional electricity system are illustrated in Figure 6. It is apparent that electricity demand is significantly above baseline demand during hot-dry periods. On the other hand, electricity generation, particularly hydropower generation, is well below baseline during hot-dry periods, including the 1985–1994 period. The vulnerability of the system in the hot-dry scenario is perhaps best summarized by projected changes in electricity imports. Regional electricity imports increased somewhat during the baseline period, to make up for low generation between 1985 and 1994. However, hot-dry scenario imports increase dramatically during this time, as needed to match rising demand with falling supply. Table 5 summarizes the impact of a hot dry scenario, including 4 °C (°F) rise in temperature and a 25 % decrease in precipitation, on regional water and related electricity use.

In this scenario, water flow through the hydropower facilities declined 25 %, demand for water by agricultural and urban users rose 6 and 3 % respectively and water use for thermal cooling remained roughly constant.

Hydropower generation during this time fell only 14 %. This suggests the importance of regional water storage facilities for maintaining relatively stable generation in the face of low flows. Electricity use by agricultural and urban users to move water rose a small amount during this period. Agricultural electricity use for pumping rose about 6 % and urban electricity use for pumping rose about 3 %.

Figure 8: Estimated Changes in Annual Electricity Generation and Demands in the Base, the +2 °C Temperature & the −15 % Precipitation and + 4 °C Temperature & −25 % Precipitation Scenarios

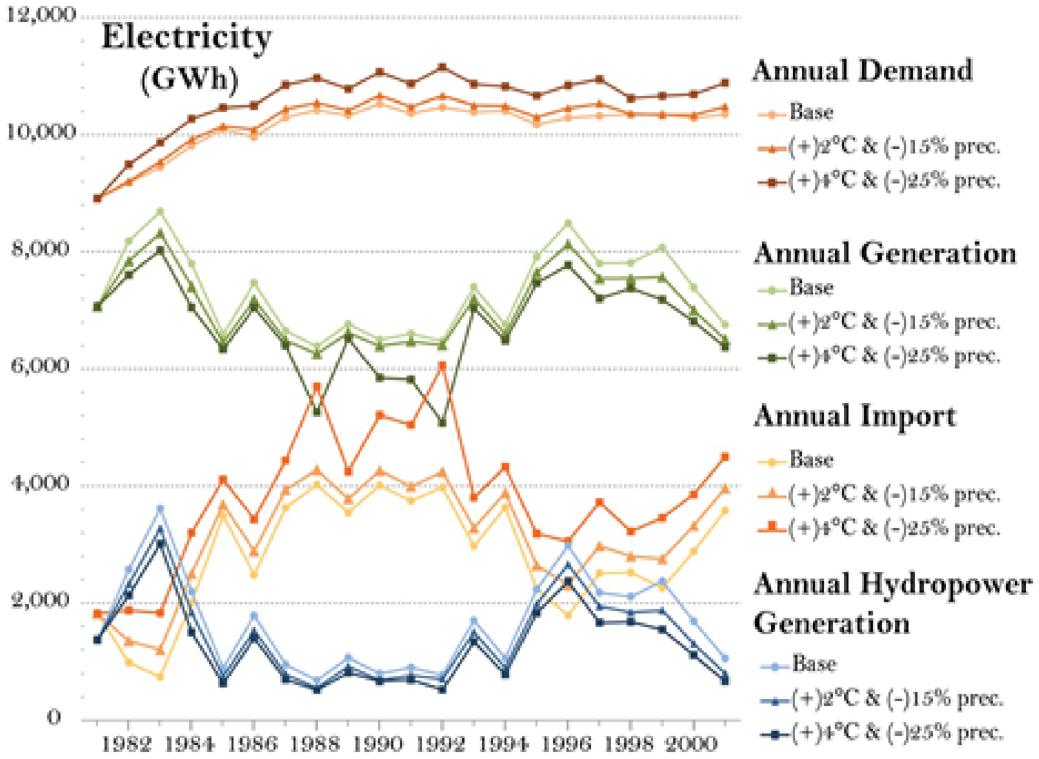


Table 5: Modeled Impact of the Hot (+4 °C) Dry (−25 %) Scenario on Baseline Average Annual Water and Related Electricity Use

	Water Use (Acre Feet)	Change from Baseline (%)	Electricity (MWh)	Change from Baseline (%)
Hydropower	2,021,950	-25.4	1,461,331	-13.8
Agriculture	652,309	5.5	63,210	5.5
Residential, Commercial and Industrial	387,465	2.5	302,698	5.6
Thermal Cooling	5,300	0.0	3,409,007	-0.4

It can be stated that these scenarios have fully illustrated the responsiveness of the Sacramento area WEAP-LEAP model to temperature and precipitation variability. The analysis produces plausible changes in the results. However, in view of the results, it should be noted that these discussions are made under a certain set of assumptions establishing a one-way (or single-direction) relationship from WEAP to LEAP. In this version of the WEAP-LEAP model, LEAP model does not communicate back to WEAP model. We built the relations in a way that water demand and supply produced in WEAP affect the electricity demand and generation in LEAP, but the reverse is not relevant. However, a full analysis of the results including feedback (or two-direction) relationships between WEAP and LEAP models (in other words, how water demand and supply affect the electricity demand and generation, as well as how electricity demand and generation affects water demand and supply) could reveal better insights into the Sacramento Area's climate variability and limitations within the capabilities of WEAP-LEAP model. Thus, future work on the Sacramento area WEAP-LEAP model is planned to include further design and analysis of the two-way feedback relationships between WEAP and LEAP modeling.

5.2 Conclusions

This paper proposes a new modeling framework that links energy and water systems and provides a joint platform for detailed analysis of energy and water policies. Long-term solutions to water and energy demands are needed to be developed jointly to deal with climate change. Development of this framework is based on hard linking of WEAP and LEAP modeling systems. The model matches the energy system planning capabilities of LEAP modeling with the water system detail and planning capabilities of WEAP modeling. The linkage between the two models allows us to track water demands for the energy sector and energy demands for the water sector.

Our study was performed as a preliminary test of the policy value of the water-energy perspective, where water use is accounted for in energy planning and energy use is accounted for in water planning. The results demonstrate the potential usefulness of a linked regional-scale analysis capability. In this case, we see that the water-energy system in the Sacramento, California region is particularly vulnerable to hot-dry scenarios, when electricity and water demands peak and electricity and water supplies decline. This vulnerability is indicated by changes in a series of water-energy stress variables, including regional electricity imports and electricity use per unit of water pumping. Currently, the region can cover any shortfall with increased electricity imports. Future availability of these electricity imports, including hydropower from the Pacific Northwest, is crucial to avoiding local electricity shortages and vulnerable to changes in the climate. Future work should address factors that are not demonstrated in the paper, including impacts of climate change on surface water temperature and the potential for selected mitigation options, including changes to reservoir operating criteria, to deal with these impacts. The authors also suggest applying the model to evaluate more fully closed water energy systems, including other regions of California.

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