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An integrated assessment of water-energy and climate change in sacramento, california: how strong is the nexus?

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Abstract

This paper is among the first to report on the full integration of basin-scale models that include projections of the demand and supply of water and energy for residential, commercial, industrial, and agricultural sector users. We link two widely used regional planning models that allow one to study the impact of rising climate variability on water and electricity use in Sacramento, California. Historic data combined with the current energy and water system configuration was used to assess the implications of changes in temperature and precipitation. Climate simulations suggest that electricity imports to the region would increase during hot dry spells, when regional power production is most constrained. In particular, regional imports of electricity would increase over 35 % in hot dry years, assuming a 4 °C increase in average temperature and a 25 % decrease in average precipitation.

Keywords

Thermal Power Plant Groundwater Depth Electricity Demand Hydropower Generation Thermal Generation

These keywords were added by machine and not by the authors. This process is experimental and the keywords may be updated as the learning algorithm improves.

Electronic supplementary material

The online version of this article (doi: [10.1007/s10584-015-1370-x](https://doi.org/10.1007/s10584-015-1370-x)) contains supplementary material, which is available to authorized users.

1 Introduction

In this paper, we develop a regional water-energy model with linkages for the use of water by the energy sector and the use of energy by the water sector. The linked water-energy model consists of the Water Evaluation and Planning system (WEAP) and the Long Range Energy Alternatives Planning system (LEAP). The choice of these models allows one to identify and analyze the interplay of key water and energy processes and linkages. We apply this model to study water and energy use in Sacramento, California over the period 1980–2001 with a weekly time step.

The demand for water and energy resources in California peaks during hot-dry spells when supplies of these resources are most scarce. This integrated approach is used to project the impact of climate change on regional water-energy systems. Following this introduction, the literature is briefly reviewed in Section 2, the case study region is described in Section 3 and the modeling platform, approach and performance are described in Section 4. In Section 5 the model is used to evaluate the impact of changes in temperature and precipitation, on regional electricity and water use. The paper concludes with a discussion of implications and future research in Section 6.

2 Review of water-energy modeling approaches

Energy and water supply modeling has been widely practiced since the early 1970s to develop strategies for dealing with climate variability. Energy models (e.g., EFOM (Energy Flow Optimization Model (Van der Voort et al. [1984](#))), MARKAL (Market Allocation Model (Loulou et al. [2004](#))), TIMES (The Integrated MARKAL - EFOM System (Loulou et al. [2005](#))), MESSAGE (Model for Energy Supply Systems and Their General Environment (Schrattenholzer [1981](#))), LEAP (Long Range Energy Alternatives Planning (SEI [2011](#))), OSeMOSYS (The Open Source Energy Modeling System (Howells et al. [2011](#))), and BUEM (Bottom-Up Energy Model, (Karali [2012](#))) typically mimic the dynamics and relationships of energy demand and supply. Similarly, water models (e.g., WATERGAP (Watery-Global Assessment and

Prognosis (Alcamo [2003](#))), WEAP (The Water Evaluation and Planning System (Yates et al. [2005a](#); [2005b](#))), MODSIM (Model for Distribution System Analysis ([Labadie 2000](#))), and WATERSIM (Water, Agriculture, Technology, Environment, and Resource Simulation (De Fraiture [2007](#)))) focus on water usage and availability and are used to develop sustainable water management policies.

However, even though these models may perform well separately, they typically ignore systemic interactions between water and energy components. Most prior studies treat water as a component of an energy model or energy as a resource within a water model. For example, Ould-Amrouchea et al. ([2010](#)) and Campana et al. ([2013](#)) investigated photovoltaic (PV) water pumping systems and Alawaji et al. ([1995](#)) analyzed desalination plant size with PV in Saudi Arabia. Similarly, Dubreuil et al. ([2013](#)) estimated the energy used to process and supply drinking water and Stillwell et al. ([2011](#)), Sattler et al. ([2012](#)), van Vliet et al. ([2013](#)), and Koch and Vögele ([2013](#)) estimated the water used to supply energy by coupling hydrologic with energy (e.g., thermal power plant) models.

There have been fewer efforts to model regional scale interactions between water and energy across multiple economic sectors and zones. Bazillian et al. ([2011](#)) proposed an integrated climate-land-energy-water modeling framework, Climate, Land-use, Energy and Water Systems (CLEWS), which has been applied to case studies of Burkina Faso (Hermann et al. [2012](#)) and Mauritius (Howells et al. [2013](#)). The CLEWS framework integrates water (WEAP), energy (LEAP) and land use (Agro-Ecological Zoning) activities within an “externally linked” structure (Welsch et al. [2014](#); Howells et al. [2013](#)). The external linking is realized by manual flow of input-output data among the three models in an iterative fashion. The CLEWS studies include many of the same regional water energy interactions as our own study. An advantage of our modeling framework is that the regional water energy data are internally linked with supply and demand internally matched.

3 Introduction to the study region

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. In California, the American River basin and Sacramento area have some aspects of this ideal setting (Fig. [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.

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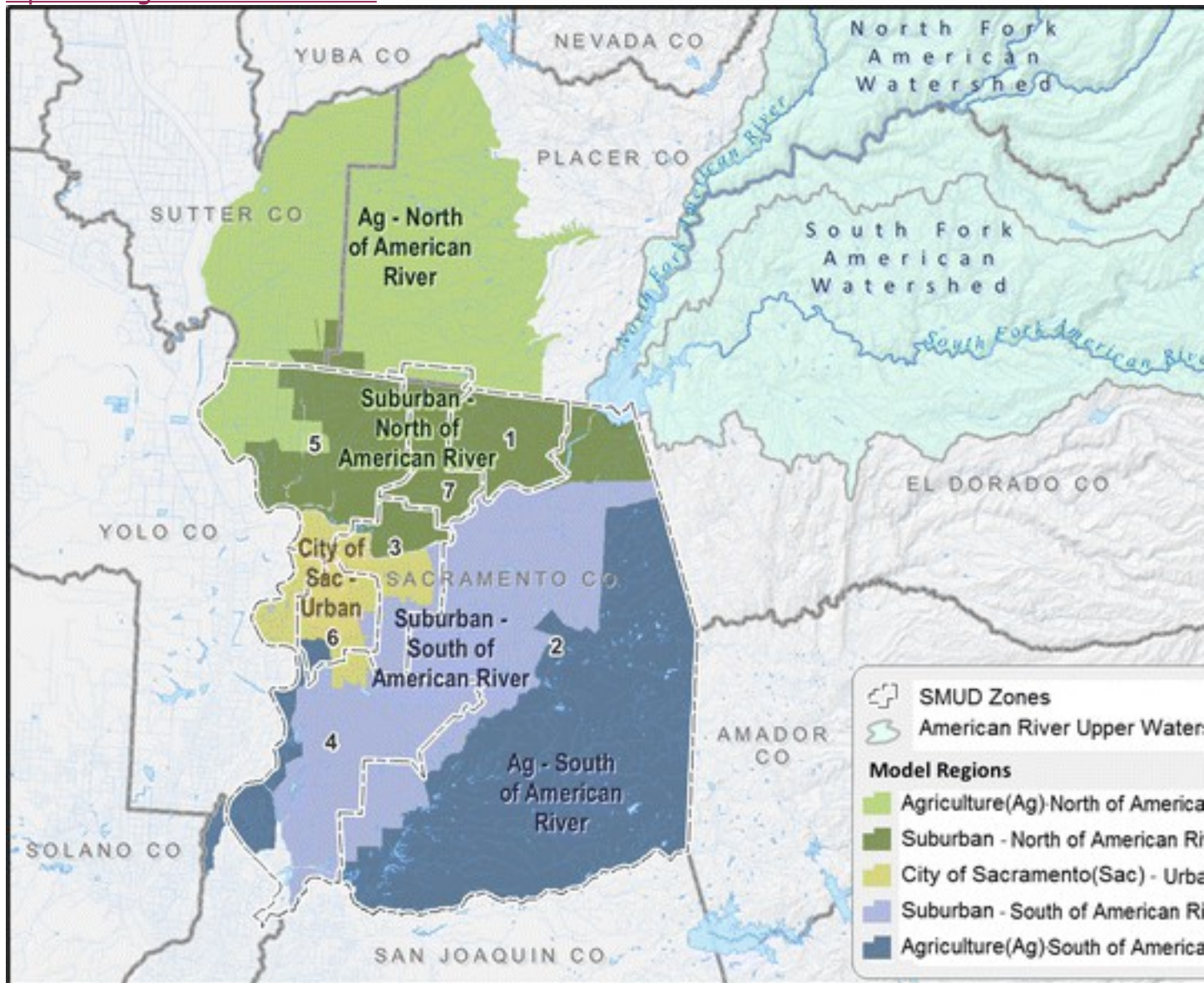


Fig. 1

Study area: American River Basin, Sacramento Municipal Utility District (SMUD) and Model Regions

3.1 Water system 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: 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 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. These water demand and supply patterns

contribute to a reliance on ground and reservoir storage. While groundwater and upstream surface storage are abundant in most years, drawdown in dry years can be significant in some places.

The demand for water in the region is highly variable, with modeled summer peak use exceeding annual average use by a factor of 3 for the agricultural sector and a factor of over 15 for the urban sector (Table 1). 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 m³. Sacramento area shares Folsom storage with other downstream water rights holders and public trust requirements.

Table 1

Sacramento region weekly water demand in 2010

| | | Urban | Agriculture | Other |
|---------|-----------------------|-------|-------------|-------|
| Average | Mm ³ /week | 1.5 | 13.6 | 10.0 |
| Max | Mm ³ /week | 23.4 | 38.9 | 53.3 |

Source: Sacramento Regional Water Authority, 2012

3.2 Electricity system in the study region

The Sacramento Municipal Utility District (SMUD) (2013) 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 drive 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 |
| Max | 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 (Table 3). Hydropower generation also falls off dramatically during dry years.

Table 3

Observed SMUD regional monthly electricity demand and generation in 2010

| | Load | Hydro | Thermal | Imports |
|---------|-------------|--------------|----------------|----------------|
| Period | (MWh) | (%) | (%) | (%) |
| 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)

Percentages exceed 100 % in some months when exports are positive

SMUD's thermal generation facilities, including the Consumnes 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, (2 % 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.

3.3 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. Changes to reservoir operations are one method for mitigating downstream water shortages (e.g., for thermal cooling) not explored in the current version of the model.

4 Methodology

4.1 Water energy modeling framework (WEAP-LEAP)

In this study, we propose a new model integrating two popular planning tools—WEAP and LEAP. These tools are used to analyze the impact of climate change on regional water (i.e., WEAP) and energy (i.e., LEAP) systems. Both tools feature mass balance accounting frameworks, simple dispatch rules for regulating resource supply and climate sensitive functions, for projecting resource demand and supply (SEI [2011](#); Yates et al. [2005a](#)).

The linkages between model tools retain the underlying simulation capabilities of both models while improving run-time execution and numerical stability. 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.
- 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. The model integrates the water module with the energy model to match supply and demand automatically.

4.2 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 Consumnes, 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 RWA.¹

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 (i.e., based on natural gas), and renewable (i.e., 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 Consumnes thermal power plant; when flows are very low, the plant may be shut down.² 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 (Fig. 2).

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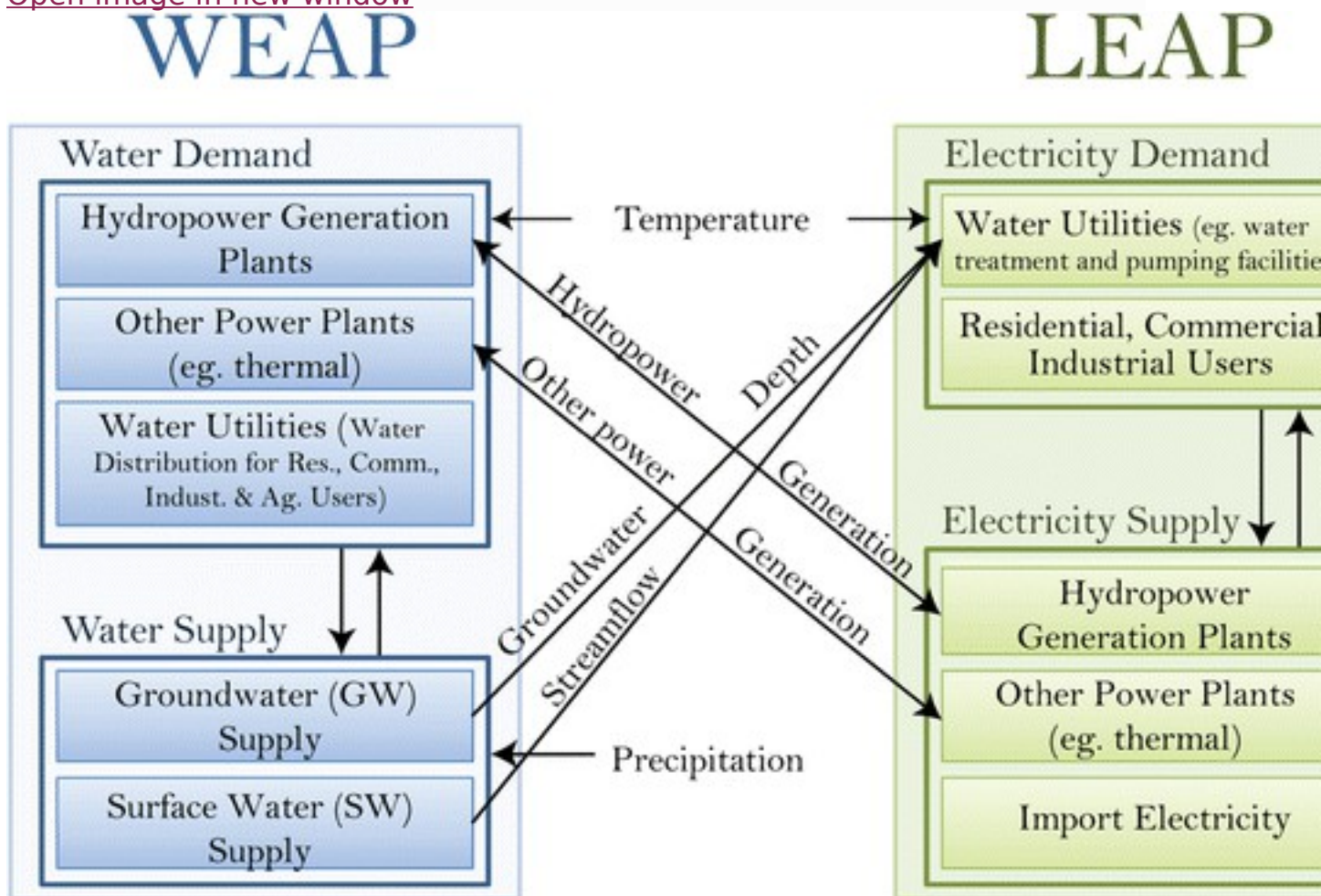


Fig. 2

Water-energy interactions in the Sacramento Area WEAP- LEAP Model

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.

4.2.1 Model to historic comparisons in the study region

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 (Fig. 3). (The correlation

coefficient is 0.87 for inflow and 0.71 for outflows). The lower fit for reservoir outflows suggests reservoir storage decisions not fully captured in the model.

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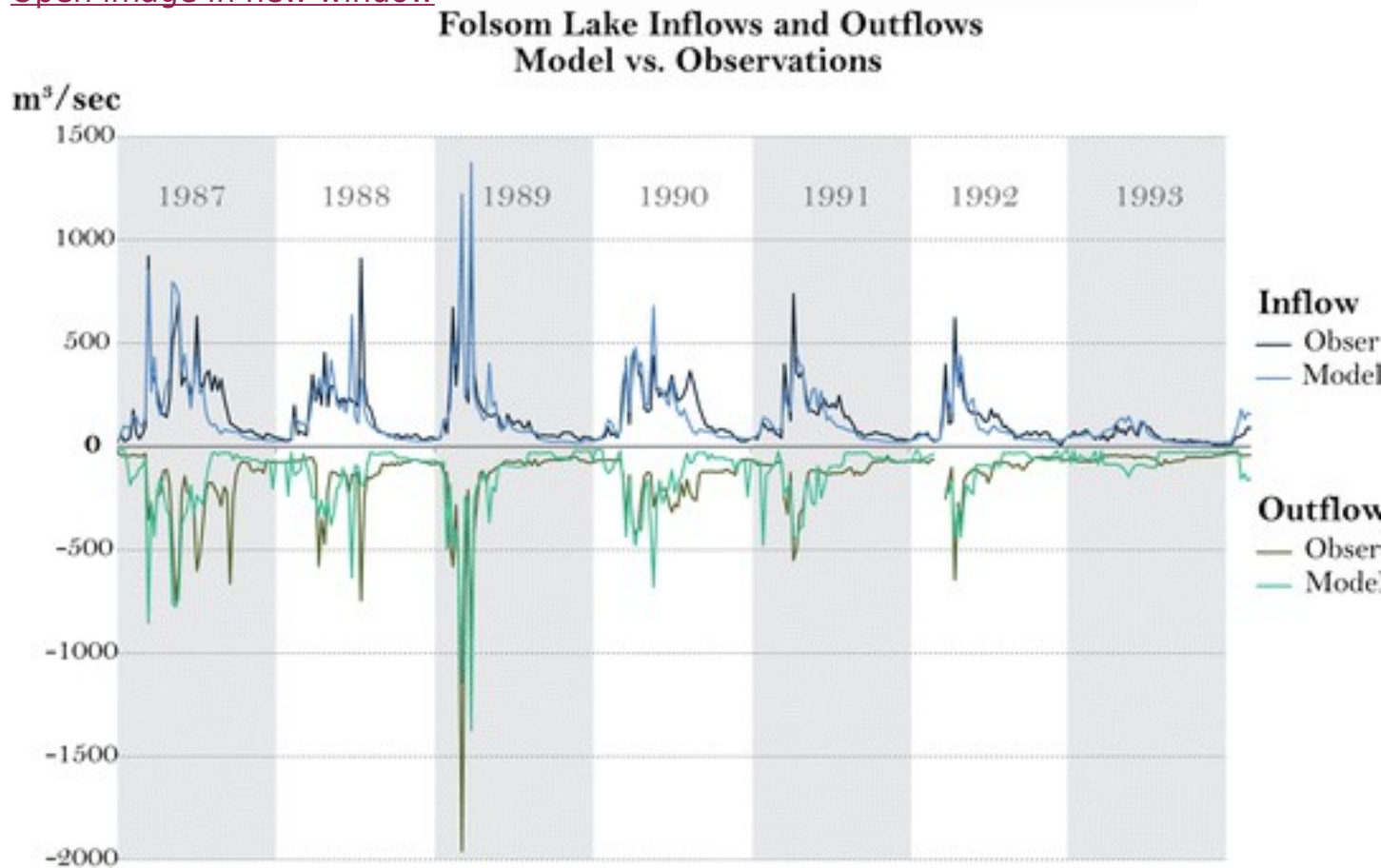


Fig. 3

Measurement and Model Prediction of Inflows and Outflows for Folsom Reservoir

Modeled hydropower generation also tracks observed generation closely (Fig. 4). The correlation coefficient in this case is 0.92.

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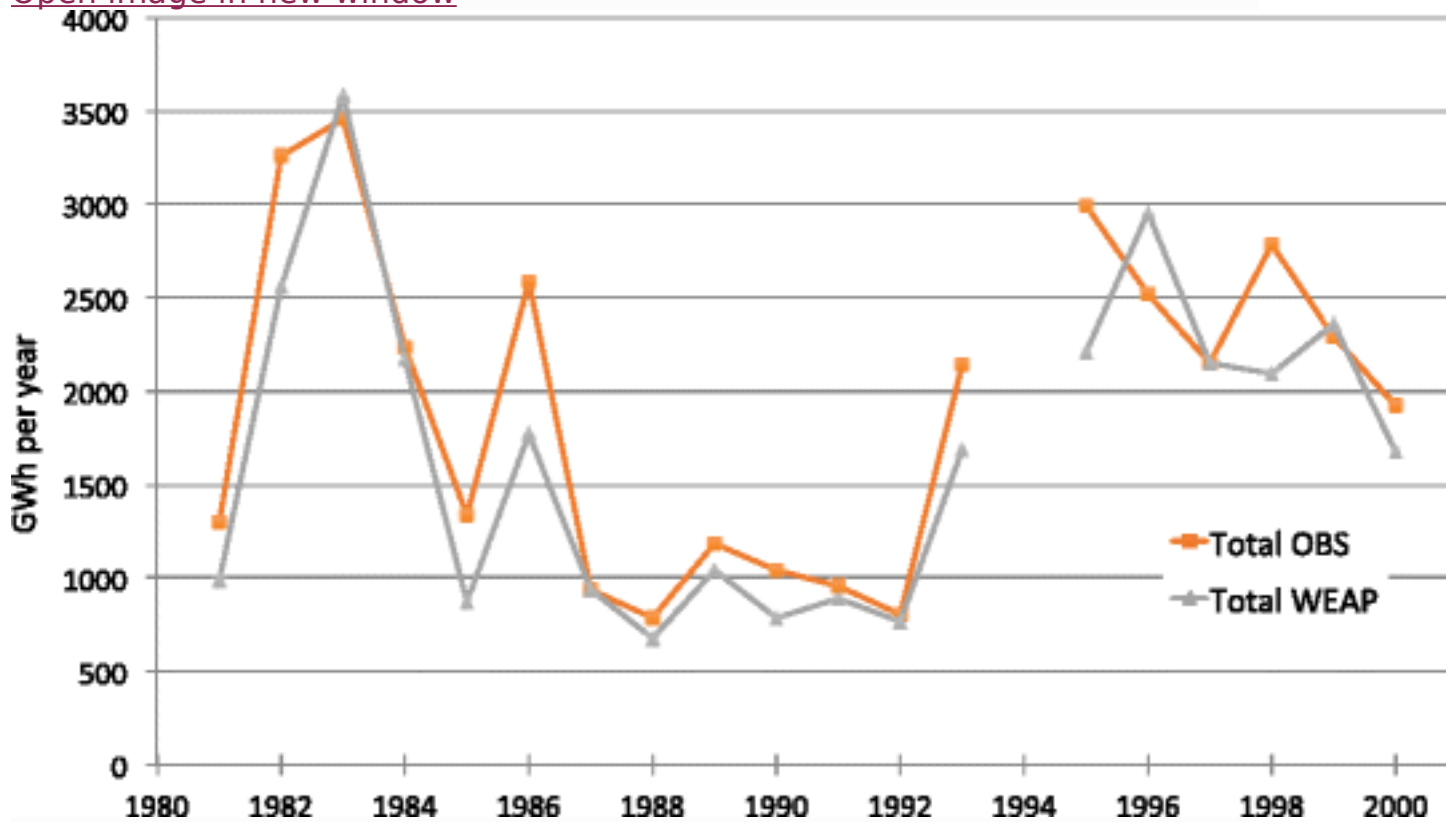


Fig. 4

Measurement and Model Prediction of American River Hydropower Generation

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 (Fig. 5).

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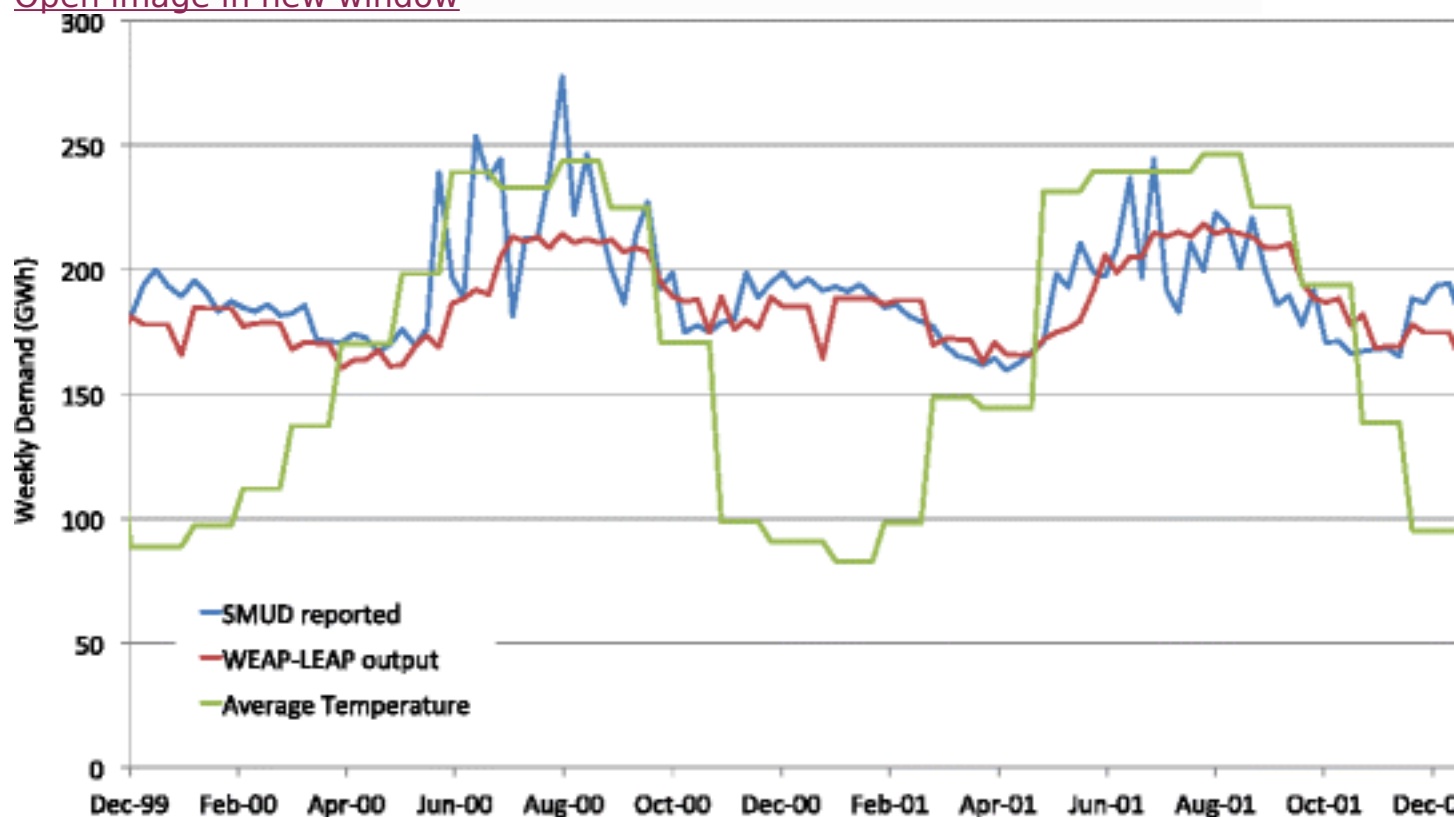


Fig. 5
Measurement and Model Prediction of Weekly Sacramento Electricity Demand

5 Results

5.1 The impact of changes to annual average temperature and precipitation

We 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 ((+)2 °C),
2. temperatures increased 4 °C ((+)4 °C),
3. temperatures increased 2 °C and precipitation decreased 15 % ((+)2 °C & (–)15 % prec.),
4. temperatures increased 4 °C and precipitation decreased 25 % ((+)4 °C & (–)25 % prec.).

These scenarios 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 and precipitation changes between –25 and +5 % cover likely outcomes projected for the Sierra mountains and Sacramento Valley after 2060 (Pierce et al. [2012](#); Cayan [2014](#)). Actual climate change impacts will be more complicated than 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 increase in temperature raises base period electricity demand by 1 and 3.3 %, respectively. Electricity demand is less sensitive to precipitation—rising 4 % over baseline in the hot-dry scenario, following a 25 % drop in precipitation. 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](#)).

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 % prec. | 1.0 % | –3.2 % | –0.2 % | –13.2 % | 11.8 % |
| (+)4 °C (–)25 % prec. | 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”

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 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. Thermal generation declines 3.2 % below baseline in the hottest, driest scenario, with limited streamwater for cooling. The impacts on the regional electricity system are illustrated in Fig. 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 to hot-dry scenarios 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.

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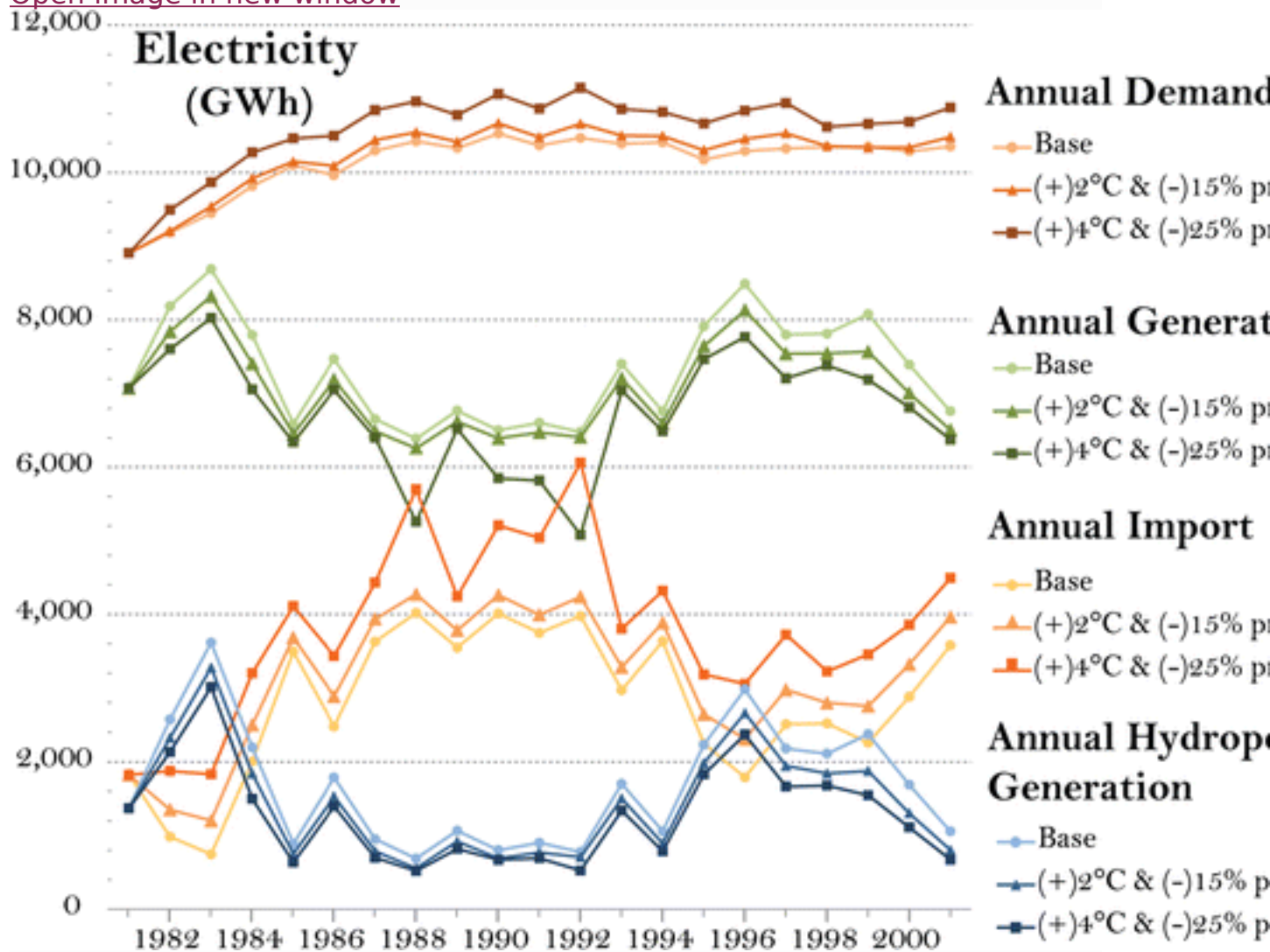


Fig. 6

Estimated Changes in Annual Electricity Generation and Demands in The Base, (+)2 °C & (–)15 % Prec., and (+)4 °C & (–)25 % Prec. Scenarios Table 5 summarizes the impact of a hot dry scenario, including 4-degree 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.

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) | Electricity (MWh) |
|--|------------------------------|--------------------------|
| Hydropower | 2,021,950 | 1,461,331 |
| Change from baseline (%) | –25.4 % | –13.8 % |
| Agriculture | 652,309 | 63,210 |
| Change from baseline use (%) | 5.5 % | 5.5 % |
| Residential, Commercial and Industrial | 387,465 | 302,698 |
| Change from baseline use (%) | 2.5 % | 5.6 % |
| Thermal cooling | 5,300 | 3,490,007 |
| Change from baseline use (%) | 0.0 % | –0.4 % |

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 %.

6 Conclusion

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 will cover 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. We also suggest applying the model to evaluate more fully closed water energy systems, including larger regions of the Western United States.

Footnotes

1. [1.](#)

Additional detail about resource demand and supply functions are included in a supplemental table.

2. [2.](#)

Consumes withdrawals and consumption average 5000 acre-feet per year.

Notes

Acknowledgments

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Supplementary material

[10584_2015_1370_MOESM1_ESM.xlsx](#) (19 kb)

ESM 1 (XLSX 18 kb)

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