

High-Elevation Hydropower and Climate Warming in California

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Abstract

In California Climate warming is expected to shift the runoff peak from spring to winter from a reduction in snowpack. For high-elevation hydropower plants, this shift can have important effects on power generation and its economic value. With over 150 hydropower plants in California, estimation of climate warming effects by conventional simulation or optimization would be tedious and expensive. Two approaches are suggested to estimate climate warming effects on high-elevation hydropower in California. The first (No-Storage) approach neglects available storage capacity and produces an upper bound estimate of lost generation and hydropower revenues from climate warming. The second (No-Spill) approach estimates the available energy storage capacity assuming that existing capacity is enough to avoid spill from high-elevation reservoirs with historical mean flows, providing a lower bound estimate of generation and economic losses. The generation changes in dry and wet climate warming scenarios at different elevation ranges are simulated in aggregate for several climate change scenarios and compared to the historic generation.

Introduction

California relies on hydropower for 9 to 30 percent of the electricity used in the state, depending on hydrologic conditions, averaging 15 percent (Aspen Environmental Group and M. Cubed, 2005). Climate warming is expected to accelerate runoff in wet winter months, leaving less snowmelt runoff during spring. Such a shift might hamper California's ability to store water and generate electricity for the spring and summer months. Reservoir storage capacity reduces spill of inflows beyond the turbine capacity and allows more hydropower generation in the summer when energy price is greater. Currently, California's winter snowpack melts in the spring and early summer, replenishing water supplies during these drier months. The vast majority of reservoir storage capacity, over 17 million acre-feet (MAF), lies below 1,000 feet elevation, while most in-state hydropower generation capacity is at higher elevations (Aspen Environmental Group and M. Cubed, 2005) and mostly in northern California. Most low elevation hydropower plants (below 1,000 feet) benefit from relatively high water supply storage capacities which appear able to accommodate seasonal shifts with operational modifications (Tanaka et al., 2006; Medellin et al., submitted). Energy storage and generation capacities at high-elevation limit the adaptability of high-elevation hydropower systems to climate warming.

Several studies have examined climate change effects on hydropower generation, but such analyses have been largely restricted to large lower-elevation water supply reservoirs (Lund et al., 2003; Vanrheenen et al., 2004; Tanaka et al., 2006) or have inspected only a single hydropower system (Vicuña et al., 2005). There is still little knowledge of the climate change effects on statewide hydroelectricity generation for high-elevation facilities and the adaptability of California's high-elevation hydropower system to hydrologic changes. By focusing on the statewide high-elevation hydropower system, this study tries to complete a gap in the analysis of climate warming effects on water management in California. Moreover, the paper suggests an approach for storage estimation using the runoff and generation data which might be useful in future extensive regional studies.

Method

One hundred fifty-eight high-elevation (above 1,000 feet) hydropower plants are considered in this study. Since runoff patterns change by elevation, three different elevation ranges has been considered (1,000-2000 feet, 2000-3000 feet, and above 3000). Monthly hydropower generation information from U.S. Energy Information Administration Databases for the period 1982 to 2002 were used to calculate the average monthly hydropower generation and the maximum generation capacity of each power plant. The maximum value of monthly generation of each hydropower plant during this period was considered as the monthly generation capacity of the plant instead of using the name-plant capacity. This study investigates the climate change effects on the generation through two different approaches, a pessimistic No-Storage Approach and an optimistic No-Spill Approach.

a) No-Storage Approach: For this approach, storage capacity is assumed to be unavailable to shift winter flows (with climate warming) to summer months. Average historic monthly generation data were perturbed using monthly runoff perturbation ratios of two climate change scenarios, the Wet Warm Scenario (GFDL A2-39) and the Dry Warm Scenario (PCM A2-39) (Vicuña et al., 2005). Without storage capacity, there is a linear relation between the runoff and hydropower generation limited by the (known) generation capacities. The corresponding stream flow perturbation ratios were applied directly to estimate the new generation values, constrained by generation capacity (C_i). The hydropower generation of power plant i in month j under the scenario k ($G_{i,j,k}$) was estimated by multiplying the perturbation ratio of month j under the k scenario ($PR_{j,k}$) by× the corresponding monthly average historic generation of that power plant ($AG_{i,j}$) subject to its generation capacity (C_i) *(Equation 1)*.

$$G_{i,j,k} = Min \{ [(PR_{j,k}) \times (AG_{i,j})], C_i \} \qquad (1)$$

b) No-Spill Approach: In this approach the basic assumption is that storage capacity at high elevation has been enough to accommodate the historical mean runoff without water spill from the reservoirs. Therefore, all mean-year water could have been stored behind the reservoirs during months when the demand for electricity was low and released later when energy prices are higher. This assumption will be helpful in estimating the aggregated energy storage capacity at each elevation range. However, for case of preliminary estimation we aggregate all storage capacity in each elevation range, probably overestimating the storage capacity actually available. With this No-Spill assumption, the available energy storage capacity can be estimated by finding the area between the monthly historical runoff and monthly generation curves when they both are expressed in percentage terms. In month i, the runoff percentage (*runPercent(i)*) and generation percentage (*genPercent(i)*) can be calculated by dividing the average monthly runoff in month i (*average runoff (i)*) and the average monthly generation in month i (*average generation (i)*) to the average annual runoff and the average annual generation, respectively.

$$runPercent(i) = \frac{average\_Runoff(i)}{average\_Annual\_Runoff} \qquad (2)$$

$$genPercent(i) = \frac{average\_generation(i)}{average\_Annual\_generation} \qquad (3)$$

In percentage terms, the total difference between the two curves for a year period (12 months) must be zero.

$$\sum_{i=1}^{12} (runPercent(i) - genPercent(i)) = 0 \qquad (4)$$

In the 12 month period there are months i when the runoff percentage exceeds the generation percentage value (e.g. when runoff is stored in the reservoir) and months j when the generation percentage value exceeds the runoff percentage value (e.g. when hydropower is generated by releasing stored water).

$$\sum_i (runPercent(i) - genPercent(i)) - \sum_j (genPercent(j) - runPercent(j)) = 0 \qquad (5)$$

Therefore, the storage capacity as a percent of total inflow is:

$$StorCapPercent = \sum_i (runPercent(i) - genPercent(i)) \quad (6)$$

or:

$$StorCapPercent = \sum_j (genPercent(j) - runPercent(j)) \quad (7)$$

Multiplying the storage capacity percentage by the average annual generation gives the energy storage capacity. Multiplying the storage capacity percentage by the average annual runoff gives the volumetric water storage capacity which is directly used for hydropower generation. Since the relation between power generation and water storage is not linear (generation depends on turbine head which changes nonlinearly with storage), this study employed calculations in terms of energy to avoid the linear assumption as was made in the No-Storage Approach and other studies (Vicuña et al., 2005). Turbine head in high-elevation hydropower facilities result mostly from penstock drops, rather than storage elevations.

Here, the runoff data were obtained from several U.S. Geological Survey's (USGS) gauges representing selected elevation ranges. These sample gauges were selected in consultation with the California Department of Water Resources' chief hydrologist. For each elevation range, the mean monthly discharge and mean annual runoff were estimated.

After estimation of available energy storage capacity and average monthly energy runoff at each elevation range, a linear optimization model was developed to investigate the adaptability of the system to different types climate warming. Three different objectives were considered, revenue maximization, energy shortage minimization, and revenue minimization for shortage penalties.

1) Maximization of Revenue: Most high-elevation hydropower plants are operated by firms or agencies interested largely in net revenue maximization (energy prices from Ritzema, 2002). Hydropower plants have almost no variable operating costs (at a monthly scale), so a surrogate for net revenue maximization would be revenue maximization.

2) Minimization of Shortage: To see if the available facilities could support the historical generation pattern with a changed hydrology, historic generation of each month was considered as the target generation of that month. This objective is considered for the system to address the main concern for the electricity shortage with climate warming which would increase electricity prices and decrease the consumer surplus if demands are the same.

3) Maximization of Revenue with Shortage Penalties: To address concerns of both electricity consumers and generators, a combined objective function is defined. This objective should maximize generators' revenue and minimize energy shortage, in a weighted combination. The overall objective is in energy units, with shortages penalized at the monthly price for hydropower.

Results and Discussion

a) No-Storage Approach Results: Figure 1 compares the modeled monthly generation of high-elevation hydropower plants under the dry and wet climate warming scenarios with historic (base) monthly generations. These values have been estimated using the perturbation ratios in the No-Storage Approach. In this approach, energy spill occurs during the March-June period as a result of peak in runoff and lack of storage capacity. The total estimated amount of energy spill for high-elevation hydropower plans are almost the same under the different climate warming scenarios. This approach neglects the ability of high-elevation reservoirs to store water for more than a month and shift the generation from spring to summer when electricity demand and price is higher. For this method, snowpack loss shifts both peak runoff and generation from spring to winter. For a 3 months winter period, generation under new hydrology exceeds base generation. This period starts and ends a month earlier in the dry climate warming scenario than in the wet climate warming scenario. For the rest of the year, generation would be much less than the base case. Generally, annual generation will be less under dry warm climate than the historic and wet warm climates. Although precipitation under wet warm climate is higher than the historic climate, wet warm annual generation is just a bit higher than the historic annual generation due to the lack of storage capacity and a considerable amount of spill from the system.

Peak historic monthly generation occurs later at higher elevations. Most high-elevation power plants are constrained by their generation capacity in February, the peak runoff under new climatic conditions. The many units spilling energy (energy release greater than turbine capacity) highlights the value of storage capacity at high-elevation under new climatic condition. Without storage capacity, snowpack loss can hamper system performance.

b) No-Spill Approach Results: Energy storage capacities at each elevation range were calculated. Linear optimization models were developed and run with 3 different objective functions. First, optimization models were run at each elevation range without connection between the ranges. So generation targets were defined separately for each elevation range. Next, generation targets were summed to create system-wide monthly generation targets and the model was run for the second and third objectives (shortage minimization and revenue maximization with shortage penalties). When targets are not considered, the results are identical.

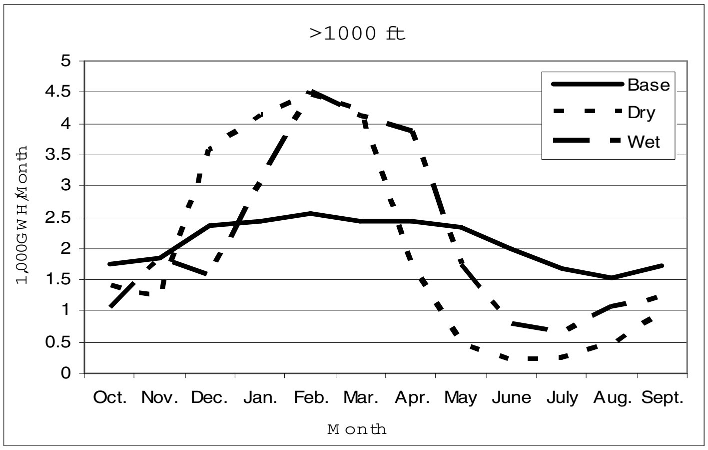

Figure 1.Monthly generation above 1000 ft range under different climatic conditions (No-Storage Approach)

Under any scenario, revenue is highest when the model only maximizes revenue. For all objective functions annual value is least under dry climate warming scenarios. Value will be the highest under wet warm climate if the model only maximizes the revenue (the first objective function). This indicates that the estimated storage capacity is enough to handle the extra runoff for the wet warm climate and can store water for when energy demand is higher. While maximizing the revenue, the model suggests no generation in months when the price is low and generation in months with higher prices. The model assumes that there is enough electricity demand and all generated power can be sold at the same price. In practice this operation might not be possible and electricity price will not be constant when supply is changing. Moreover, monthly demands will be also affected by climate warming which will affect energy prices.

Under dry and wet warm climates, revenues are higher when revenue is maximized with shortage penalties than the case when shortage is minimized. The optimization suggests storing water and having shortages in months when the penalty is lower and selling it later when price is higher. When the model minimizes shortages, it considers no economic value for the stored water. So lower revenues result when shortage is minimized. The optimization over all elevations together always resulted in better objective values, except for pure revenue maximizing where results are identical with optimization for each elevation range. Overall system optimization increases revenue for the second and third objectives under climate warming. Despite the benefits of overall system operation, because hydropower plants are owned by different entities and because of the competitive nature of the power market, they night not be managed in this way and the results might differ.

Figure 2 presents comparison of estimated monthly generation for different climate warming scenarios by No-Spill and No-Storage methods. The values found under revenue optimization with penalties at the overall scale are used here as the No-Spill Approach's results. These estimates are based on simplifying assumptions and the reality might be between the two optimistic and pessimistic estimations. The difference between these estimates underlines the importance of high-elevation storage capacity in absence of snowpack as a result of climate warming in California. Availability of storage capacity neutralizes much snowpack loss for hydropower generation. Table 1 presents comparison of estimated annual revenue for different climate warming scenarios by No-Spill and No-Storage methods. It also shows how total generation revenue would change with the objective function and management scale.

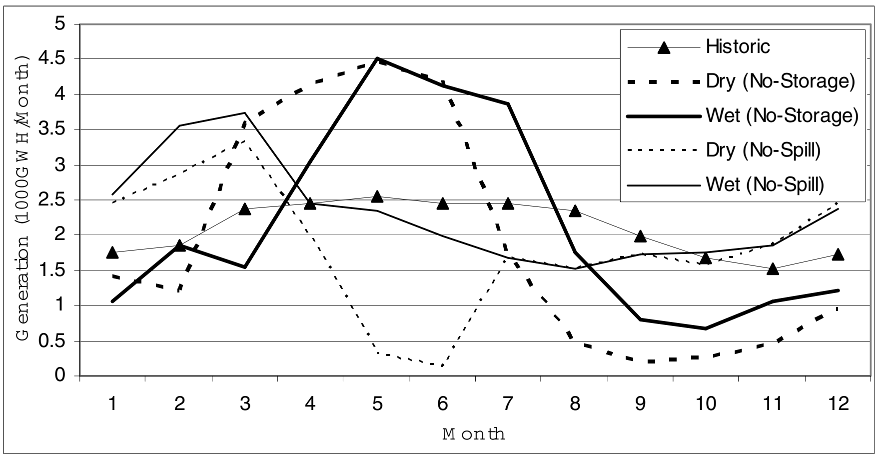

Figure 2.Comparison of monthly generations resulted from No-Storage and No-Spill methods (The generation values found under revenue optimization with penalties at the overall scale are used here as the No-Spill Approach's results)

Table 1.Hydropower revenue changes with different methods and model runs under various climate change scenarios

Method	Run	Revenue (Million $)		
		Base Scenario	*Dry Scenario*	*Wet Scenario*
No-Spill	Benefit Maximization at Each Elevation Range	*616*	*528*	*645*
	Shortage Minimization at Each Elevation Range	*585*	*439*	*556*
	Benefit Maximization with Penalties at Each Elevation Range	*585*	*517*	*621*
	Shortage Minimization in the Overall System	*585*	*445*	*574*
	Benefit Maximization with Penalties in the Overall System	*585*	*517*	*623*
No-Storage	--	*585*	*469*	*569*

Limitations

Models are not perfect and optimized results are optimized to their problem. During model development many simplifying assumptions are made which should be considered while interpreting the results. However, simulation and optimization models are useful tools in studying resources management problems. Here, the results, give same insights on how the system works and how it might adapt under different climate warming scenarios.

The No-Storage Approach neglects the available storage capacity and the No-Spill Approach overestimates storage capacities and adoptability. However, these methods were used because of lack of spill or energy storage capacity data. Perhaps later studies can incorporate such information. In the No-Spill Approach the reservoirs and the generation capacities of all the plants at same elevation range are aggregated and a for each elevation range the problem becomes a single reservoir, single plant problem. This aggregation might cause inaccuracies from under-predicted energy spills from some turbines and reservoirs.

California is big and variable in hydrology. Assuming the same hydrology for an entire elevation range will cause some inaccuracies. A 1000 feet range covers great variability in hydrology. Smaller elevation ranges might increase the accuracy of the estimation. Since many power plants are in the 3000-4000 feet elevation range, it might be worthwhile to study this range separately. Also, it is more accurate to consider more than a few gauges at each elevation range. Using the same perturbation ratios in both approaches to estimate the changes in generation and runoff patterns under climate warming scenarios will result in some inaccuracies. It is more accurate and difficult to justify such ratios for different elevation ranges.

Defining a reasonable objective function for an optimization model is always a big challenge. Although, different objectives have been defined here, they might all be far from the real objective. In the real electricity market, revenues are not linearly related to monthly generation as the electricity price changes all the time based on supply and demand. With climate warming, demands are likely to increase in warmer months from higher temperatures. This has some effects on the prices. Change in demand as a result of climate warming should be considered while defining target generations and energy prices.

Here the model optimizes generation based on perfect information about the future hydrological pattern and energy prices. This kind of management is unavailable in practice as there is always some risk associated with decisions in reservoir operation because of inability to forecast the future hydrological conditions perfectly. A stochastic optimization formulation might help with this problem.

Conclusions

In absence of good information about energy storage capacities at high-elevation in California, this study suggests two simple approaches for estimating the adaptability of high-elevation hydropower generation to climate warming.

With climate warming, California loses snowpack which has functioned historically as a natural reservoir. However, considerable energy storage capacity is available at high elevations. Model results indicate that most of extra runoff in winter months from climate warming might be accommodated by the available storage capacity at high-elevation sites. Lower-elevation reservoirs have already been to have substantial re-regulation capacity for season flow adjustments (Tanaka et al., 2006). However, operational rules must change to adapt the system to changes in hydrology (Medellin et al., submitted).

Hydropower generation revenue can increase with wet climate warming as increased total annual runoff more than compensates of an unfavorable seasonal shift. Dry climate warming reduces revenue and generation as a result of less runoff and less availability during drier seasons. Generation reductions occur mostly under dry climate change in summer. However, reservoirs can move some shortages to months with lower energy prices to reduce the economic losses. When the whole system is optimized rather than optimization only within each elevation range, better results are obtained since the system becomes more flexible. Increasing generation capacity at the lowest elevation range might help in increasing revenue but not reducing shortage.

This study required some simplifying assumptions. This leads to some limitations. Some of these shortcomings can be addressed in future studies.

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References

- Aspen Environmental Group, M. Cubed (2005). "Potential changes in hydropower production from global climate change in California and the western United States", *California Climate Change Center*, CEC-700-2005-010, June 2005.
- Lund, J. R., Zhu T., Jenkins M. W., Tanaka S., Pulido M., Taubert M., Ritzema R., Ferriera I. (2003). "Climate Warming & California's Water Future", Appendix VII, *California Energy Commission: Sacramento*. pp. 1–251.

- Medellín-Azuara J., Harou J. J., Olivares M. A., Madani-Larijani K., Lund J. R., Howitt R. E., Tanaka S. K., Jenkins M. W., Zhu T. (Submitted). "Adaptability and Adaptations of California's Water Supply System to Dry Climate Warming", *Climatic Change.*
- Ritzema R. S. (2002) *Appendix D-Hydropower in Calvin Model.* p.15.
- Tanaka S. T., Zhu T., Lund J. R., Howitt R. E., Jenkins M. W., Pulido M. A., Tauber M., Ritzema R. S., Ferreira I. C. (2006). "Climate Warming and Water Management Adaptation for California", *Climatic Change*; Vol. 76, No. 3-4.
- VanRheenen, N.T., A.W. Wood, R.N. Palmer, D.P. Lettenmaier (2004). "Potential Implications of PCM Climate Change Scenarios for Sacramento–San Joaquin River Basin Hydrology and Water Resources", *Climatic Change*; Vol. 62(1-3), pp. 257-281.
- Vicuña S., Leonardson R., Dracup J. A., Hanemann M., Dale L. (2005). "Climate Change Impacts on High Elevation Hydropower Generation in California's Sierra Nevada: A Case Study in the Upper American River", *California Climate Change Center*, CEC-500-2005-199-SD, December 2005.