



# Climate Warming and Adaptability of High-Elevation Hydropower Generation in California



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## Abstract

California's high-elevation hydropower system is composed of more than 150 power plants. Most of the associated reservoirs have relatively small storage capacities compared to water supply reservoirs downstream, and have been designed to take advantage of snowpack. With climate warming shifting the runoff peak from spring to winter, the adaptability of high-elevation hydropower system to new climatic conditions is in question. A simple optimization model has been developed to estimate the potential effects of climate warming on statewide hydropower generation from high-elevation plants. For three climate warming scenarios the model estimates the possible changes in hydroelectricity generation. The model's predicted generation data are compared with the historical generation to investigate the adaptability of the system to climate change.

## 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.

## 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 have 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. With over 150 hydropower plants in California, estimation of climate warming effects by conventional simulation or optimization would be tedious and expensive. Thus, this study suggests No-Spill Approach to investigate the climate change effects on generation.

## 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. 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.

$$runPercent(i) = \frac{average\_Runoff(i)}{average\_Annual\_Runoff} \quad genPercent(i) = \frac{average\_generation(i)}{average\_Annual\_generation}$$

In percentage terms, the total difference between the two curves for a year period (12 months) must be zero.  $\sum_{i=1}^{12} (runPercent(i) - genPercent(i)) = 0$   
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).  $\sum_i (runPercent(i) - genPercent(i)) - \sum_j (genPercent(j) - runPercent(j)) = 0$   
Therefore, the storage capacity as a percent of total inflow is:  $StorCapPercent = \sum_i (runPercent(i) - genPercent(i))$   
or:  $StorCapPercent = \sum_j (genPercent(j) - runPercent(j))$

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. 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 hydropower plant, a linear optimization model was developed to investigate the adaptability of the system to different types climate warming (Dry Warming, Wet Warming, No-Wet/Dry Warming). Six different objectives were considered:

- 1) Maximization of Revenue
- 2) Minimization of Shortage
- 3) Maximization of Revenue with Shortage Penalties
- 4) Minimization of Spill
- 5) Maximization of Revenue with Spill Penalties
- 6) Maximization of Revenue with Shortage and Spill Penalties

## Limitations

The No-Spill Approach overestimates storage capacities and adoptability. However, this method was used because of lack of energy storage capacity data. Perhaps later studies can incorporate such information.

California is big and variable in hydrology. Assuming the same hydrology for an entire elevation range will cause some inaccuracies. Also, it is more accurate to consider more than a few gauges at each elevation range.

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.

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

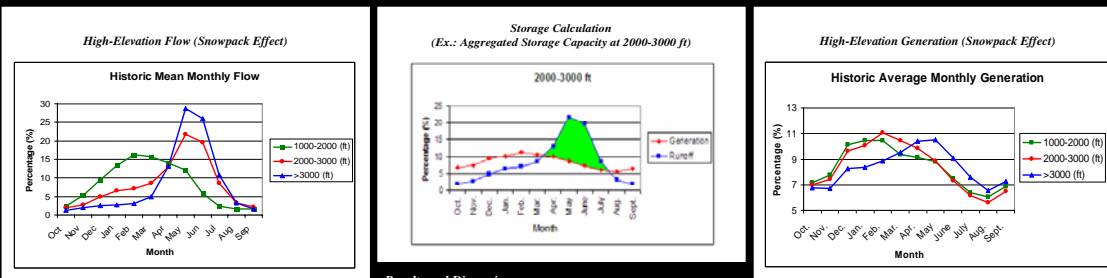
In absence of good information about energy storage capacities at high-elevation in California, this study suggested a simple approach for estimating the adaptability of high-elevation hydropower generation to climate warming. With climate warming, California loses snowpack which has functioned historically 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 winter. However, reservoirs can move some shortages to months with lower energy prices to reduce the economic losses.

Since there is no energy spill, similar results were obtained when aggregated storage and generation capacities at each elevation range were considered rather than individual reservoirs. This makes the modeling process much simpler and less costly.

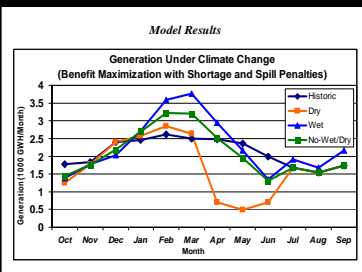
## Acknowledgements

We thank Maury Roos and Omid Rothani for their help. This work was supported by the California Energy Commission's Public Interest Energy Research (PIER) program.



## Results and Discussion

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. Revenue under the No-Dry/Wet climate warming is always less than the base and wet cases and more than the dry case.



| Run  | Revenue (Million \$) |              |              | No-Dry/Wet Scenario |
|--|----------------------|--------------|--------------|---------------------|
|  | Base Scenario        | Dry Scenario | Wet Scenario |                     |
| Benefit Maximization                                   | 607                  | 500          | 629          | 592                 |
| Shortage Minimization                                  | 567                  | 437          | 531          | 525                 |
| Benefit Maximization with Shortage Penalties           | 567                  | 474          | 611          | 536                 |
| Spill Minimization                                     | 515                  | 403          | 529          | 495                 |
| Benefit Maximization with Spill Penalties              | 607                  | 500          | 628          | 592                 |
| Benefit Maximization with Shortage and Spill Penalties | 579                  | 485          | 625          | 575                 |