Modeling California's high-elevation hydropower systems in energy units

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[1] This paper presents a novel approach for modeling high-elevation hydropower systems. Conservation of energy and energy flows (rather than water volume or mass flows) is used as the basis for modeling more than 135 high-elevation high-head hydropower sites throughout California. The unusual energy basis for reservoir modeling allows for development of hydropower operations models for a large number of plants to estimate large-scale system behavior without the expense and time needed to develop traditional streamflow and reservoir volume-based models in absence of storage and release capacity, penstock head, and efficiency information. Potential applications of the developed Energy-Based Hydropower Optimization Model (EBHOM) include examination of the effects of climate change and energy prices on system-wide generation and hydropower revenues. An extensive comparison of the EBHOM with a traditional hydropower optimization model used in California produced similar results and indicated good reliability of EBHOM's predictions.

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1. Introduction

[2] Hydroelectric power's low cost, near-zero pollution emissions, and ability to quickly respond to peak loads make it a valuable renewable energy source. In the mid-1990s, hydropower was about 19% of world's total electricity generation [*Lehner et al.*, 2005]. Worldwide hydroelectric generation from 1990 to 2020 could grow between 2.3 and 3.6% per year [*European Commission*, 2000; *Lehner et al.*, 2005].

[3] Depending on hydrologic conditions, hydropower provides 5–10% of the electricity used in the United States [*National Energy Education Development Project*, 2007] and almost 75% of the nation's electricity from all renewable sources [*Energy Information Administration*, 2005, Table 18; *Wilbanks et al.*, 2007]. No major electricity generation source is cheaper; while it costs almost 4 cents and 2 cents for 1 kWh of electricity from coal and nuclear plants, respectively, hydropower generation typically costs only about 1 cent per kWh [*National Energy Education Development Project*, 2007].

[4] About 75,000 MW of hydropower generation capacity exist in the United States, equivalent capacity to 70 large nuclear power plants [*National Energy Education Development Project*, 2007]. More than half of U.S. hydroelectric capacity is in the western states of Washington, California and Oregon, with approximately 27% in Washington (Energy Information Administration, Energy kid's page, 6 November 2007, available at http://www.eia.doe.gov/kids/energyfacts/sources/renewable/water.html). Hydropower facilities in the United States are diverse. Facilities range from multipurpose dams with large reservoirs to small run-of-river dams with little or no active water storage [*National Energy Education Development Project*, 2007]. Plant elevations also vary. In California multipurpose dams are usually at lower elevations, with higher elevation plants operating primarily for hydropower.

[5] California relies on hydropower for 9–30% of electricity used, depending on hydrologic conditions [*Aspen Environmental Group and M. Cubed*, 2005]. California's high-elevation hydropower system is composed of more than 150 power plants, above 305 m (1,000 feet) elevation. This system, which mostly relies on snowmelt, supplies roughly 74% of California's in-state hydropower, although only about 30% of in-state usable reservoir capacity is at high elevations, above 305 m [*Aspen Environmental Group and M. Cubed*, 2005]. The high-elevation reservoirs are predominantly single-purpose reservoirs for generating hydropower [*Aspen Environmental Group and M. Cubed*, 2005; *Vicuna et al.*, 2008] with some secondary benefits such as flood control. These reservoirs are mostly privately owned, regulated by U.S. Federal Energy Regulatory Commission (FERC), and operated for hydropower revenues. The high-elevation hydropower plants are generally located below small (within-year storage) reservoirs with high turbine heads compared with much larger multipurpose reservoirs with lower head downstream (lower elevations).

[6] California's Mediterranean climate has one wet season and a long dry season; 75% of annual precipitation occurs from November through March. These single-purpose reservoirs (except for a few such as Lake Almanor) are emptied by the end of the hydrologic year (September) to capture fall and winter precipitation and spring snowmelt. Since electricity prices are high in summer, it is reasonable to generate and sell hydropower instead of risking energy spill in the wet

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