Potential impacts on hydrology and hydropower production under climate warming of the Sierra Nevada
Vishal K. Mehta, David E. Rheinheimer, David Yates, David R. Purkey, Joshua H. Viers, Charles A. Young and Jeffrey F. Mount

ABSTRACT
Watersheds of the Cosumnes, American, Bear and Yuba (CABY) Rivers in the Sierra Nevada, California, are managed with a complex network of reservoirs, dams, hydropower plants and water conveyances. While water transfers are based on priorities among competing demands, hydropower generation is licensed by the Federal Energy Regulatory Commission (FERC) and regulated by federal and state laws and multi-party agreements. This paper presents an integrated river basin management (IRBM) model for the CABY region, built to evaluate management and regional climate change scenarios using the Water Evaluation and Planning (WEAP) system. We simulated potential impacts of climate warming on hydrology and hydropower production by imposing a fixed increase of temperature (+2, 4 and 6°C) over weekly historical (1981–2000) climate, with all other climate variables unchanged. Results demonstrate that climate warming will reduce hydropower generation if operational rules remain unchanged, making the case for climate change induced hydrological change as a foreseeable future condition to be included in the FERC licensing process. IRBM tools such as the CABY model presented here are useful in deliberating the same.

Key words | climate change, hydrology, hydropower, Sierra Nevada

INTRODUCTION
Rivers draining the western slope of California’s Sierra Nevada provide critical water supply, hydropower, fisheries, recreation and ecosystem services to California. The Sierra Nevada range receives orographic precipitation, with much of this precipitation falling as winter snow at high elevations. Snowmelt runoff provides much of the water to the Sacramento-San Joaquin system, which is a major source of California’s irrigation and municipal water supply (Kondolf & Batalla 2005). High-elevation basins in the Sierra Nevada are responsible for almost 50% of California’s hydroelectric power generation (Vicuna et al. 2008) and nearly 20% of California’s in-state energy production (Cayan et al. 2008a). The watersheds of the Cosumnes, American, Bear and Yuba (CABY) Rivers drain into the Sacramento Valley. Except for the Cosumnes River (Booth et al. 2006), these watersheds are heavily managed for hydropower, water supply, recreation and environmental flows with infrastructure that stores and transfers water within and between river basins.

A number of water utilities and stakeholder groups exist in this region because of the high degree of management integration between these systems. The interest of these CABY-based groups is now largely focused on hydropower management as several major area projects are under
relicensure by the US Federal Energy Regulatory Commission (FERC), which will issue operational rules for a term of 30–50 years. Projects undergoing FERC relicensing in the CABY include the Yuba Bear Project managed by the Nevada Irrigation District (NID), the Pacific Gas & Electric (PG&E) Drum Spaulding Project and the Middle Fork Project managed by the Placer County Water Agency (PCWA). Recently relicensced projects include the Upper American River Project (UARP) operated by the Sacramento Municipal Utility District (SMUD) and Project 184 managed by the El Dorado Irrigation District (EID).

Stakeholders are also interested in assessing climate change impacts on these projects, given that the region is expected to warm significantly within the 30–50 year license periods (Maurer 2007; Cayan et al. 2008b). Climate models consistently forecast an increasing temperature trend through the twenty-first century for California, with end-of-century increases ranging from approximately +1.5°C under the low emissions (B1) scenario, to +4.5°C under the medium-high (A2) emissions scenario (Cayan et al. 2008b), and close to +6°C in the high emissions scenario (CCCC 2008). Ensemble projections of surface air temperature increases for California are consistently between 2 and 6°C by the year 2100 (Hayhoe et al. 2004; Dettinger 2006; Brekke et al. 2008). There is less agreement among models concerning precipitation trends into the future, although the current winter precipitation regime in California is not expected to change (CCCC 2008). Hydrologic impacts of climate warming consistently predict a shift in the centre of mass of the annual hydrograph to earlier in the year, due to a higher proportion of precipitation falling as rain instead of snow and earlier spring snowmelt (Knowles & Cayan 2002; Miller et al. 2003; Dettinger et al. 2004; Hayhoe et al. 2004; Stewart et al. 2005; Zhu et al. 2005; Vicuna et al. 2007; Cayan et al. 2008b). Medellin-Azuara et al. (2008) predict a decrease in hydropower generation for low-elevation powerplants associated with large reservoirs with climate warming, while Vicuna et al. (2008) and Madani & Lund (2010) found that in high-elevation systems the existing reservoirs could possibly compensate for earlier runoff by storing enough water for generation in the summer months.

Clearly, however, altering hydropower operations to compensate for lost generating capacity is potentially counter to FERC licensing conditions. Therefore, we present an integrated river basin management (IRBM) model for the CABY watersheds (henceforth CABY model, or model), which was built to provide a comprehensive toolset capable of analysing both water management and climate scenarios relevant to FERC hydropower relicensing. Although IRBM is not a new concept for regional stakeholders, the CABY model is the first IRBM toolset capable of integrating hydrology and operations for multiple, connected facilities. To date, efforts to analyse the impact of climate-mediated changes to hydrology and concomitant hydropower generation have separated hydrologic impacts from operations modelling, relying on perturbation of historical runoff data to simulate future climate conditions, which are then separately used in optimization routines (Medellin-Azuara et al. 2008; Vicuna et al. 2008). Additionally, these efforts are based on either single projects (e.g. Vicuna et al. 2008) or are statewide endeavours that understandably lack the finer resolution required for local to regional water resources planning applications (Medellin-Azuara et al. 2008). The CABY model was developed in Water Evaluation and Planning (WEAP) software with historical model simulations compared to the observational record, and its application to FERC relicensing is demonstrated by evaluating potential climate warming impacts to hydropower generation.

By using WEAP to develop the CABY model, our IRBM approach takes advantage of other ongoing efforts throughout the state, including those led by the California Department of Water Resources (DWR) and the California Climate Change Center (CCCC). WEAP includes a watershed hydrology module that is forced by input climate time series and integrated with a priority-driven water allocation routine (Yates et al. 2005b). In California, WEAP applications include evaluations of potential climate warming impacts on water management in the Sacramento and San Joaquin valleys (Purkey et al. 2007; Purkey et al. 2008; Joyce et al. 2009), on Chinook salmon runs in the Sacramento Valley (Yates et al. 2008) and on the hydrology of western Sierra Nevada watersheds (Young et al. 2009).

STUDY AREA

The watersheds of the Cosumnes, American, Bear and Yuba Rivers run from south to north in the region east of Sacramento, California (Figure 1). The Yuba and Bear Rivers are major tributaries to the Feather River, which flows into
the Sacramento River. The American River flows directly into the Sacramento River and the Cosumnes flows into the Mokelumne River, which drains into the Sacramento-San Joaquin Delta. These rivers provide a significant portion of California’s water supply, providing flows for the Central Valley Project and the State Water Project. Important reservoirs in the CABY region include: French Meadows, Hell Hole, Union Valley, New Bullards Bar, Englebright, Folsom, Combie, Fordyce, Bowman, Camp Far West, Spaulding and Rollins. There are also many small, natural
alpine terminal lakes at high elevation, which possess little connectivity to the fluvial system. Several of the larger lakes, including Jackson Meadows, Merle Collins, and Jenkinson Lake, have been modified to provide important flood control, water storage and electricity-generation capacity.

The study area encompasses a total area of 10,038 km² (Figure 1). Elevations range from 140 m at Folsom Reservoir to greater than 2750 m at the Sierra Nevada crest. The climate at lower elevations is Mediterranean, characterized by cool, wet winters and hot, dry summers. While this makes the aquatic ecosystems prone to distinct periods of extreme flooding and drought (Gasith & Resh 1999), the montane portions of the study area store precipitation as snowpack, ameliorating these effects with a predictable vernal snowmelt recession (Yarnell et al. 2010). The higher elevation Yuba and American watersheds receive greater precipitation overall, as well as greater snow accumulations compared to the lower elevation Bear and Cosumnes watersheds (Table 1). Precipitation ranges from 500 to 2000 mm, with the Yuba watershed receiving the most and the Bear watershed receiving the least (Table 1). Average temperature trends counter precipitation, decreasing from west to east with elevation. Yuba and American watersheds are snow-dominated, the Cosumnes is transient and the Bear watershed is rain-dominated.

The principal tributaries of the Yuba River watershed are the North Yuba, Middle Yuba and South Yuba in the upper portion of the watershed; the main stem of the Yuba is formed by the confluence of the North Yuba and Middle Yuba just downstream of New Bullards Bar Reservoir. Within the Bear River watershed, the Bear River is the only major river. The American River watershed contains the North Fork, Middle Fork, the North Fork of the Middle Fork and South Fork of the American River, as well as the Rubicon River. The North Fork, Middle Fork and South Fork of the Cosumnes River are the primary tributaries of the Cosumnes watershed.

The CABY region is perhaps the most complex in California for the number and intricacy of inter-basin transfers. Many of these inter-basin transfers were first put in place during the California Gold Rush, during which water was shunted from place to place to hydraulically mine placer gold. The many flumes, canals and tunnels that were constructed have been reinforced and expanded to now move water through hydropower generation plants and to meet downstream urban demands. Some of the major inter-basin transfers are as follows. The North Yuba to South Feather water transfer is used in hydroelectric power generation – between 2000 and 2005, an annual average of $86 \times 10^6$ m³ of water was transferred. The Middle Yuba to South Yuba

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<td>Watershed (ID)</td>
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Note: $S$ – Ratio of storage capacity to watershed area; $P$ – Precipitation; $Q$ – Streamflow; $ET$ – Evapotranspiration; $SWE$ – Snowmelt in Snow Water Equivalent. Values in italics are modelled annual watershed scale aggregates from 1981-2000 model run. Values in normal type are from input data.
to Bear River transfers occurs under the Yuba Bear and Drum Spaulding hydropower projects. Under the licences, $76 \times 10^6$ m$^3$ of Middle Yuba water is transferred annually to the South Yuba watershed. Below Lake Spaulding the Drum canal transfers on average $457 \times 10^6$ m$^3$ of water annually out of the South Yuba to the Bear River, and the South Yuba canal transfers on average $73 \times 10^6$ m$^3$ of water annually out of the South Yuba to Deer Creek. Sly Park Reservoir (Jenkinson Lake), owned and operated by EID, transfers $28 \times 10^6$ m$^3$ from the Cosumnes River watershed to the South Fork American River system. Since inter-basin transfers move large volumes of water within the CUBY region, the development of a regional IRBM model is the best option for improved water management.

**METHODS**

WEAP consists of modules for simulating hydrology and infrastructure operations (Yates et al. 2005a; Yates et al. 2005b). The CUBY model integrates modules that simulate rainfall-runoff processes with routines that simulate water systems operations in the study area. The model, run at a weekly time step, uses climate, land cover, soils and elevation data within the CUBY watersheds to simulate the major terrestrial components of the hydrologic cycle, and subsequently uses these results to force the simulated water management of major reservoirs, hydropower facilities, diversions, demand sites, return flows and in-stream flow requirements within the region.

Model verification was performed by comparing simulated and observed streamflow from 1981–2000, and simulated and observed hydropower generation from 1991–2000. Hydrology and hydropower were then simulated under assumed warm climate scenarios, by forcing 2, 4 and 6°C increases over 1981–2000 temperatures, with all other climate inputs unchanged. The choice of uniform increases of 2°C to surface air temperatures in our climate time series are consistent with the projected end of the century mean departure of $+4$ C, with $\pm 2$ C alternatives to bracket climate model ensemble forecasts with different emission scenarios. Consequent changes in hydrology and hydropower are discussed here, along with implications for FERC hydropower relicensing in the CUBY region.

**Hydrology**

A summary of WEAP’s rainfall-runoff hydrology module is presented here. The module is conceptually simple enough to be computationally efficient, but specific enough to capture variability in the important terrestrial components of the hydrologic cycle and to address key water resource issues. This is accomplished via a one-dimensional, 2-storage soil water accounting scheme that uses empirical functions to describe evapotranspiration, surface runoff, sub-surface runoff or interflow and deep percolation (Yates 1996; Yates et al. 2005a). The unimpaired hydrology component of the CUBY model was extracted from WEAP models of unimpaired hydrology for the entire western Sierra Nevada developed by Young et al. (2009). Using Geographic Information Systems (GIS), watersheds were delineated (i) at Folsom Reservoir for the American watershed, (ii) at Michigan Bar for the Cosumnes watershed, (iii) at the confluence of Deer Creek and the Yuba River below Englebright reservoir for the Yuba watershed and (iv) at Camp Far West for the Bear watershed (Figure 1). Each CUBY watershed was first divided into sub-watersheds with outlets (pour points) placed where total flows in a stream are to be simulated. Placement of pour points corresponds to locations where the flow is either known (a gauged site) or managed (a dam or diversion). Sub-watersheds are further subdivided into elevation bands, which are in turn divided into $N$ fractional areas of unique soil and land cover characteristics. A water balance is computed for each fractional area, $N$. Each unique elevation band within a sub-watershed is referred to as a ‘catchment’ in WEAP, which is equivalent to the Hydrologic Response Unit (HRU). GIS data were acquired and used to define catchment units within the WEAP software. GIS-based elevation, soils and land cover data were used to discretize the study area into 324 catchments in the CUBY model. Elevation data were extracted from the Digital Elevation Model (DEM) provided by the US Geological Survey (USGS) (http://seamless.usgs.gov/). Soils information was sourced from the Natural Resource Conservation Service databases (http://soildatamart.nrcs.usda.gov/). Land cover information was obtained from the National Land Cover Dataset (NLCD) (Homer et al. 2004). Historical (1981–2000) weekly climate inputs for each catchment were
assembled from the interpolated daily weather dataset, DAYMET (Thornton et al. 1997).

Hydrologic parameters for the CUBY model were extracted from calibrated WEAP models of unimpaired hydrology that have been developed for all western Sierra Nevada watersheds. Hydrologic calibration was achieved against full natural flows at watershed outlets calculated by the DWR, and validation was performed using observed streamflow records at 19 locations within the watershed (Young et al. 2009). Goodness of fit metrics (bias, and the Nash–Sutcliffe Efficiency Index (Nash & Sutcliffe 1970)) were computed for each set of simulated and observed time series. These are computed respectively as:

\[
\text{BIAS} = 100 \cdot \left[ \frac{\sum_{i=1}^{n} (Q_s,i - Q_o,i)}{\sum_{i=1}^{n} Q_o,i} \right] \]

\[
\text{Nash–Sutcliffe} \ E_f = 1 - \frac{\sum_{i=1}^{n} (Q_s,i - Q_o,i)^2}{\sum_{i=1}^{n} (Q_o,i - \bar{Q}_o)^2}
\]

where \(Q_s,i\) and \(Q_o,i\) are simulated and observed flow rates for each timestep, \(i\).

### Infrastructure and operations

The CUBY model simulates operations of major reservoirs, hydropower plants and conveyances in the CUBY watersheds. The model includes 25 reservoirs, 36 hydropower plants, 39 diversions, 14 transmission links, 13 water delivery points and 68 in-stream flow requirement locations covering several projects (Table 2). The total storage capacity of modelled reservoirs is \(1662 \times 10^6 \text{ m}^3\) in the Yuba watershed, \(2288 \times 10^6 \text{ m}^3\) in the American watershed up to the gauge measuring inflows into Folsom Reservoir, and \(217 \times 10^6 \text{ m}^3\) in the Bear watershed. The Yuba watershed has the greatest storage capacity per watershed surface area of 0.5 m, followed by the Bear watershed (0.3 m) (Table 1). Although the American watershed has the greatest storage capacity, its storage capacity per watershed area is lower, at 0.2 m. The Cosumnes watershed has no reservoir storage.

Reservoirs in the CUBY region are generally operated to temporarily store runoff that is available from spring and summer snowmelt. This stored water is gradually drawn down during the dry summer and fall months to meet in-stream flows, and to provide for hydropower generation and consumptive water demands. In the CUBY model, simulated storage in reservoirs and transfers to hydropower plants and delivery points are based on assigned priorities. Priorities in the model follow FERC regulatory requirements and contractual agreements. In general, water allocation was prioritized in the following order: (i) safety, (ii) regulatory requirements including maintaining minimum in-stream flows below diversions, (iii) satisfying irrigation and domestic consumptive water demands and (iv) power generation. In addition to these general priorities, each facility was also constrained by rules specific to each operator’s rights, licences and permits.

Regulatory requirements impose further constraints on operations depending on the type of water year – hence project operations can be substantially different among dry, normal and wet water years. Water Year Types (WYT) are based on indices determined by the DWR. Based on these indices, WYT are assigned to different hydropower projects. In the CUBY model, a simplified version of this has been applied, by choosing a single index (the Folsom index) to determine WYT across the entire modelled region. The implicit assumption here is that when it is a relatively dry year in the American watershed, it is also a relatively dry year in the other CUBY watersheds. Where up to five WYT types were listed for a watershed or

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<tr>
<td>Yuba River</td>
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<td>Upper American River</td>
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<td>Drum-Spaulding</td>
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<td>Narrows</td>
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<td>Middle Fork</td>
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<td>Combie</td>
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<td>Folsom</td>
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<td>Other reservoirs</td>
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1 SSWD = South Sutter Water District; 2 BOR = Bureau of Reclamation.
project, these were reclassified to three WYT – 1 for dry, 2 for normal and 3 for wet water years.

While regulatory requirements and contractual agreements provide a good modelling framework and data source, the specific operating policies were often unavailable or are not explicit. For example, the Yuba-Bear (YB) and Drum-Spaulding (DS) Projects use proprietary Socrates forecasting models to conduct operations planning and schedule energy needs, flow releases and water demands (Jacobs et al. 1995). Thus, incomplete knowledge of operational rule sets posed particular challenges for Caby model development, such as (i) operating rules that released water for hydropower generation and (ii) operating rules that simulated the occasional spills from conveyances into stream reaches (henceforth called conveyance spills). In response, operating rules for hydropower were developed from empirically based functional relationships (described below). We obtained reservoir physical characteristics (storage capacities, volume-elevation curves), in-stream flow requirements and hydropower plant characteristics (turbine ratings, penstock capacities and operating heads) from publicly available documents, including project relicensing documents of the Yuba Bear, Drum Spaulding, Middle Fork Project and UARP. Reservoir rule curves (flood control, minimum pool and conservation guide) were also obtained from the same public documents.

Hydropower operations

Since explicit hydropower operating rules were not available, we analysed historical penstock flow data to derive hydropower flow requirements (HFR). We sought to develop HFR that were specific enough to adequately represent historical penstock flows, yet were general enough to be useful for alternative scenario-modelling. This was accomplished in two steps. First, we calculated flow exceedances of 10, 50 and 90% from the historical penstock (or other inflow conveyance) flow records for each week. Second, we associated each flow exceedance with a WYT. For example, flows with a 10% exceedance generally only occur during wet years, while flows with a 90% exceedance generally only occur during dry years. These steps result in a relationship between flow quantities and WYT. The HFR time series is then generated by an ‘operating rule’ that consists of a series of if-then statements that are applied each week during the simulation, as follows:

If WYT = 1 : HFR = Q1; Else if WYT = 2 : HFR = Q2; Else if WYT = 3 : HFR = Q3

where Q1 represents flow from the quantile associated with WYT = 1 for that week. The hydropower flow requirements were calibrated by comparing resulting simulated hydropower generation with observed hydropower generation. The flows associated with each WYT for each time step were adjusted on a per-powerplant basis. The result of the calibration was that each powerplant had its own separate operating rule scheme. Each calibrated HFR-based operating rule could then be used to simulate hydropower generation under alternative climate scenarios, assuming no change in hydropower operating rules. Hydropower simulation was calibrated for a total of 20 powerplants – 15 from the YB-DS and 5 from the MFP projects (Table 2). Wise 2 powerhouse in the YB-DS, which was poorly defined because of lack of data availability and operational logic, is not included in this analysis. Irrigation, municipal and industrial water demands have been included only for the Yuba-Bear and Drum-Spaulding Projects and for Wheatland Irrigation District demands since they were available from public documents. Note that we were unable to develop operating rules for modelling conveyance spills in a manner similar to powerhouse flows. Conveyance spills have not been modelled in the Caby model.

Climate warming scenarios

Down-scaled climate projections for California are consistent in projecting warmer temperatures; however, these same projections contain much more inter-model variability in precipitation, with changes expected to be modest (Dettinger 2005). We used simple temperature forcing to create climate warming scenarios similar to that employed by Miller et al. (2003) and Young et al. (2009). Model responses were evaluated to fixed increments of 2, 4 and 6°C to historical weekly temperatures from water years 1981–2000, keeping all other climate inputs constant. These increments cover the range of warming of down-scaled climate projections for California described earlier, and are treated here as low, medium and high warming scenarios respectively. Further, the historical time period used, while relatively
short in duration, captures a 5-year drought (1987–1992), the wettest year on record (1983) and flood year of record (1997). It is highly representative of observed extremes.

RESULTS AND DISCUSSION

Hydrology

Unimpaired hydrology

The simulation of unimpaired historical hydrology is presented in detail in Young et al. (2009), who modelled the unimpaired hydrology of all western Sierra Nevada watersheds, including the CABY watersheds. Weekly streamflows were simulated with bias of 1% for the North Fork of the American River and –5, –3 and –1 for Yuba, American and Cosumnes rivers, respectively. Nash–Sutcliffe Efficiency Index values are 0.80, 0.85, 0.90 and 0.94, respectively, for these four locations. Note that in the case of the American river inflows into Folsom Reservoir, the comparison is against full natural flows, which are DWR estimates of river flows after withdrawals or storage in the watershed is back calculated out of the record. These results, along with other details in Young et al. (2009) confirm that the hydrology of the CABY watersheds was simulated well at a weekly time step by the CABY model.

Impaired hydrology

Calibration of unimpaired hydrology was the necessary step to ensuring the accurate modelling of existing (impaired) hydrology in the CABY watersheds. Figure 2 presents simulated and observed (impaired) annual flows at watershed outlets of the

Figure 2 | Observed and modelled flows at outlets of (a) Yuba, (b) American and (c) Cosumnes watersheds.
Yuba, American and Cosumnes rivers. A long-term, reliable record of stream flow in downstream Bear River reaches was not available. A summary of the historical (1981–2000) budget is also presented in Table 1. Reflecting the differences in elevations among watersheds, the Yuba and American watersheds receive a much greater proportion (∼25%) of precipitation as snowfall compared to the Bear and Cosumnes watersheds (only 3% and 9% respectively). On average over the simulation period, evapotranspiration represents less than 50% of precipitation in all but the low-elevation and southern-most Cosumnes watershed, where evapotranspiration accounted for 58% of precipitation. The impaired annual flows in Table 1 differ from unimpaired flows simulated by Young et al. (2009) due to inter-basin transfers. As a result of net Yuba basin to Bear basin transfers via the Drum Canal, annual Bear River flows are 23% higher, while annual Yuba River flows are 18% lower, than their respective simulated unimpaired flows. Flows from American and Cosumnes Rivers are changed relatively less (+3% and −4.5% respectively), because of smaller Sly Park canal water transfers from the latter to the former.

**Hydropower**

Observed monthly hydropower data were obtained from a United States Department of Energy database compiled by the Center for Watershed Sciences, University of California, Davis. We present simulated and observed hydropower from the period Water Year 1990–2000 at annual, seasonal and monthly scales (Figure 3). On an annual basis, the mean bias across all 20 powerplants was 6.1% and \( R^2 \) was 0.98 \((n = 200)\). Monthly data were grouped into four seasons – winter (Jan–Mar); spring (Apr–Jun); summer (July–Sept) and fall (Oct–Dec). Figure 3(b) and 3(c) show seasonal and monthly hydropower, respectively, along with observed power generation. Average seasonal hydropower was simulated with \( R^2 = 0.97 \) and a mean bias of 5.9% \((n = 40)\), while monthly hydropower was simulated with \( R^2 = 0.92 \) and a mean bias of 14.5% \((n = 240)\). These results indicate that the CABY model simulates hydropower well at annual to monthly time scales. Seasonal patterns are well simulated by the model with the month of April being a notable exception. April hydropower is over-predicted at several powerhouses, leading to the positive biases presented above. With the combined effect of previous winter precipitation, the beginning of snowmelt, and a relatively low power demand compared to summer and fall months, it is likely that April flows through powerhouses are running less than full capacity, with the excess occurring as conveyance spills in downstream reaches (Richard McCann, personal communication, July 25th, 2008). This would account for the apparent discrepancy between April simulations and observed hydropower generation.

**Climate warming impacts**

**Impacts on stream flow, snowmelt and evapotranspiration**

In all four watersheds, greater warming leads to greater reductions in annual stream flow, partly attributed to corresponding increases in evapotranspiration (Figure 4). The Cosumnes and American River flows show greatest
reductions over historical annual averages, from 5 to 14% and 3 to 10% reductions, respectively (Figure 4(a)). At first glance, Yuba River flow seems to be least sensitive to climate warming (only 2 to 5% flow reductions), along with Bear River flow under 2°C warming. However, the different flow response of the Yuba-Bear cannot be attributed to differences in evapotranspiration response. All four watersheds show a similar annual evapotranspiration response, with increases from 3 to ~10% (Figure 4(b)). Rather, the difference in response of the Yuba-Bear flows compared to the American-Cosumnes flows was predominantly due to (i) large water transfers out of the Yuba watershed and into the Bear watershed and (ii) large storage capacity per surface area of the Yuba watershed. The Drum Canal is the major upstream conduit for transferring Yuba waters into the Bear through hydropower infrastructure of the YB-DS projects. The 1981–2000 average annual flows transferred by the Drum Canal, as measured by USGS gauge 11414170, was 462.3 × 10^6 m^3. This transfer accounts for as much as one-sixth of the annual Yuba watershed runoff. Approximately 90% of simulated Drum Canal transfers reach the Bear River through the Drum 1 and Drum 2 powerhouses, a volume that is as much as 70% of the Bear River flows into Camp Far West. Hence the climate warming responses for the Yuba and Bear Rivers as reported in Figure 4 are strongly mediated by the response of operations. Under the low-warming scenario (2°C), simulated Drum Canal flows were less than 3% below historical average flows, while maintaining all downstream Yuba River in-stream flow requirements. This accounts for the negligible reduction in annual Bear River flows (Figure 4) under this scenario. However, under medium- and high- (4°C and 6°C) warming scenarios, and in order to maintain downstream Yuba in stream flow requirements, Drum Canal flows were reduced by 12% and 18% respectively, from historical average flows; thus causing greater reductions in Bear River flows under these scenarios. Yuba operations maintain Bear River flows with low warming, but not with moderate or higher warming. For the Yuba River, reductions in flow are lower than the American and Cosumnes under all warming scenarios because of Drum Canal withdrawals as well as the large buffer provided by large reservoir storage capacities, as reflected by the highest storage capacity to surface area ratio (S = 0.5 m in Table 1).

By contrast, the flow changes for the American and Cosumnes Rivers can be primarily taken to be a climate response. First, despite the considerable infrastructure on the South and Middle Forks of the American River, the majority of this flow does stay within the American watershed and eventually flow into Folsom Reservoir. Second, a relatively small volume (4.5%) of the Cosumnes watershed’s runoff leaves the Cosumnes watershed before Michigan Bar. Since major quantities of flow do not enter or leave these watersheds, their flow response is interpreted as being driven primarily by climate warming.

Weekly hydrographs reveal the distribution of flow changes seasonally (Figure 5). In the snow-dominated Yuba and American watersheds, climate warming results in sharp increases in winter overland flow, as a result of higher temperatures causing more of the precipitation to fall as rain instead of snow, as well as earlier melt of the snow that does accumulate. These results are consistent with the general trends in recent decades across western states that have been attributed to warming (Knowles et al. 2006). Increases in winter flows are less substantial in the Cosumnes and Bear watersheds, since they are less snow-dominated. Spring and summer season reductions in flow are experienced in all four watersheds. The cumulative effect on the hydrograph is a shift in the centre of mass, with peak flows occurring earlier in the spring. The Cosumnes and Bear watersheds experience
the least shift in the hydrograph. The Yuba and American watersheds exhibit a shift between 2 and 4 weeks earlier depending on degree of warming (Young et al. 2009). The net result of these seasonal changes is an annual decrease in flows for all watersheds, as presented earlier.

All four watersheds show greater losses in snowmelt upon increased warming (not shown). The Bear and Cosumnes watersheds, with less snow accumulation to start with (Table 1), lose greater than 60% of their snowmelt contributions upon 2°C warming, and almost all of it under the high warming (6°C) scenario. More than 90% snowmelt losses are simulated for all four watersheds, upon 6°C warming. Yuba and American watersheds, which experience greater snowfall, lose about 45% of historical snow melt upon 2°C warming. These snowmelt losses upon warming, due to decreasing proportion of precipitation falling as snow and increased evapotranspiration, amount to 25% and 19% respectively of the annual flow of the Yuba River.

Figure 5 | Average weekly simulated flows under historical and warming scenarios.
(into Englebright Lake) and the American River (into Folsom Reservoir).

**Impacts on hydropower**

By simulating hydropower generation for historical conditions (1981–2000) and under warming scenarios, we found increasing temperatures successively reduce the annual hydropower generation – from approximately 5% reduction for a 2°C warming, to approximately 20% reduction under the 6°C warming scenario (Table 3). These decreases in annual hydropower generation follow from both the overall decreases in stream flow (Figure 4), as well as the changes in seasonal flows (Figure 5), assuming that the historical operating regimes continue unchanged. The seasonal patterns in hydropower changes reveal the linkages to seasonal changes in flow. Figure 6 shows the monthly changes in hydropower generation as a result of warming. Although we found an overall decrease in annual hydropower generation, in the wet months (December to March-April), there was an increase in hydropower generation as a result of corresponding increased flows. In contrast, during dry months (May to October), there were substantial decreases in hydropower generation that led to an overall annual decrease in generation. Although reductions in annual hydropower generation under all warming scenarios were greater for the MFP project, the YB-DS project was more sensitive to warming in the summer, with greater decreases in summer generation than the MFP (Figure 6). These results show that climate warming impacts will be more acute in the summer, which is also the time of peak demand for power. Even a low-warming scenario (2°C) is sufficient to reduce peak summer hydropower generation by close to 35% and 25% respectively for the YB-DS and MFP projects.

**Table 3 | Annual average hydropower under historical and climate warming scenarios**

<table>
<thead>
<tr>
<th></th>
<th>YB-DS (GWh)</th>
<th>MFP (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical</td>
<td>1267.8</td>
<td>759.9</td>
</tr>
<tr>
<td>+2°C (%)</td>
<td>-4.39</td>
<td>-5.60</td>
</tr>
<tr>
<td>+4°C (%)</td>
<td>-14.42</td>
<td>-16.15</td>
</tr>
<tr>
<td>+6°C (%)</td>
<td>-19.68</td>
<td>-22.47</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

We developed an integrated river basin management model for the CUBY watersheds using WEAP. The resulting CUBY model simulated hydrology of the CUBY watersheds, and water systems operations of the Yuba-Bear, Drum-Spaulding and Middle Fork projects, under historical and climate warming scenarios. This research details the significant impact on snowmelt, evapotranspiration, stream flows and hydropower in the selected project areas. All four watersheds responded to increased climate warming with corresponding increases in wet season flows, decreases in dry season flows and a net annual decrease. Yuba and Bear Rivers were strongly influenced by reservoir storage and inter-basin transfers, compared to the Cosumnes and American Rivers. A low degree of warming is sufficient to lose approximately 45% of historical snow in the Yuba and American watersheds, which amounts to between one-fifth and one-quarter of historical inflows into their downstream reservoirs. Historical patterns of systems operation will likely result in reduced hydropower generation – between 5% and 20% losses in hydropower generation were simulated, depending on the degree of warming.

The CUBY model encompasses one of the most intricate sets of interconnected hydropower and water storage facilities in the United States. As such, several assumptions were made with respect to operational rules and boundary conditions, and thus there are limitations to its use and interpretation. Foremost, conveyance spills were not
explicitly included and specific operational logic would need to be provided by utilities for them to be included. Secondly, the weekly time step of the model precludes analysis of phenomena at finer resolution, such as ramping rates. Since hydropower scheduling by utilities takes place at an hourly or finer time step, this model was not intended for hydropower dispatching purposes. Lastly, the monotonic temperature index method of defining climate warming scenarios assumes uniform warming in space and time. Recent research suggests asymmetrical seasonal differences in warming, such as increased summer warming compared to other seasons, and differential warming by elevation (Daly et al. 2010). Further, we have used the historical precipitation record uniformly across the modelling domain, though spatial and temporal differences in precipitation across Sierra Nevada basins compared to historical conditions are now anticipated (Maurer 2007). These differences, especially in precipitation, would impact our conclusions – for example, increasing precipitation would buffer the negative impacts of warming on hydropower. We note, however, that the historical precipitation captured a high degree of variability in precipitation – a 5-year drought, the wettest year on record and a flood year of record. Also, given the limited project area (~15% of the Sierra Nevada), the anticipated spatial variance in surface air temperature and precipitation found in regional scale climate model forecasts is likely to be of insufficient magnitude to preclude our application of uniform 2°C increases in surface air temperature for the entire modelling domain. This sensitivity analysis approach to understanding CABY hydropower generation response to climate warming-mediated alteration of the hydrologic flow regime provides insights that heretofore were poorly characterized if even recognized. This is not to indicate certainty in outcomes from employing this approach; rather it is to emphasize operational behaviour based on current regulatory and contractual agreements, under projected climatic and hydrologic conditions that are consistent with projected end-of-century atmospheric warming.

The utility of the CABY model, and IRBM in general, is that it provides stakeholders a valuable asset capable of scenario configuration to explore potential weaknesses in hydropower generation and water deliveries with changing hydrology. Enough scientific evidence exists to assume hydrologic stationarity no longer holds in water resource planning (Milly et al. 2008). We have modelled here contemporary climate with extremes, exacerbated by warming scenarios that are reasonable and foreseeable in the coming decades. As such, our results, which are consistent with the findings of others with respect to the nature of changing hydrology (e.g. more rain and less snow, earlier centre of mass), indicate that all else being equal (i.e. no change in operational behaviour) there will be a net loss in hydropower generation with regional climate warming. When used within a stakeholder forum, such as hydropower relicensing through FERC, this IRBM approach should provide sufficient evidence that licensee operations in the CABY region will need to plan for a changing climate to maintain hydropower generation at current levels while meeting other water delivery obligations and in-stream flow requirements. While the results presented here are intended solely to evaluate the sensitivity of highly integrated hydropower operations to changing hydrologic conditions, similar approaches to IRBM could be used to identify and evaluate future compensatory actions by licensees to sustain hydropower generation.

While the merging of natural and altered hydrological conditions is important to our study region in California, it also has implications for other rivers with a Mediterranean-montane climate and largely predictable snowmelt signal (see Yarnell et al. 2010). Thus, significant water operations in Australia, Chile and South Africa and portions of the Mediterranean Basin could benefit from understanding the potential reductions in ecosystem services with climate warming mediated hydrologic alteration.

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