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Response of California Summer Hydroelectricity Generation to Spring Temperature

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

Regions depending on winter snowpack for hydroelectricity generation may be adversely affected if spring temperatures increase. An inverse relationship between spring temperature and summer hydroelectricity generation is complicated by changing statistical properties of the variables involved. We use simple approaches to quantify, within broad limits, the effect of a change in spring temperature on hydroelectricity generation in subsequent months over a political entity as large and geographically diverse as the state of California, incorporating variables that are highly nonstationary in the mean and in covariances with each other. Looking at data from several simple perspectives provides insight and a physically realistic explanation of the observations. California's high-elevation hydropower reservoirs mitigate effects of dry winters; precipitation is limiting and spring temperature has no detectable effect. Following wet winters, however, warm springs can lead to earlier snowmelt and increased spillage so that water storage is limited by high-elevation reservoir capacity; during cold springs the snowpack melts more slowly, allowing it to act as a water reservoir for a longer period of time so that water can be supplied as needed. Following winters with over 70 cm of

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precipitation, water supply is abundant and hydropower seems limited by generation capacity. Our results demonstrate limitations of California's high-elevation hydropower system, especially if climate warms, and our findings should also aid in the development of more complex, physically based, hydrologic models to aid water managers.

Keywords: Hydroelectricity; hydropower; California; climate change; spring temperature; precipitation.

1. INTRODUCTION

Water supply is emerging as an important issue for a large and increasing number of people at all geographical scales. Some global-scale aspects are discussed by The United Nations [1,2,3]. In the United States, concerns exist in the southeast, [4,5,6], high plains [7,8,9] and the west including California [10,11,12].

Energy is an important and related issue [13]. According to statistics from 2000-2010 in various issues of Electric Power Monthly and Electric Power Annual, both publications of the Energy Information Administration (EIA) of the United States Department of Energy [14,15], 5 to 7 percent of the electricity generated in the United States is from hydropower and from 8 to 17 percent of the hydroelectricity in the United States has been generated in California, depending on the year selected. During that same period, hydroelectricity has accounted for 9-22 percent of California's electricity generation.

Barnett et al. [3] noted that regions depending on winter snowpack for water supply in subsequent months are sensitive to spring temperature. In California these effects have been observed and studied for over two decades [16,17,18,19]. California has a Mediterranean climate; almost 80 per cent of the annual precipitation falls during November – March while less than 10 percent falls during the five months of May-September. Water storage is therefore necessary to meet hydropower and agricultural demands during the summer.

Knowles et al. [20] and others suggest that warmer temperatures in early spring lead to more precipitation falling as rain, diminishing the snowpack "reservoir" which is California's largest surface water reservoir [21,22,23,24]. Additionally, warmer springs lead to earlier melting, so that the timing of maximum snowmelt occurs farther from the summer season when it is most needed for hydropower and/or irrigation [25,26,27,22,28,24,29]. Warmer springs would also increase evaporative losses, and liquid water stored for longer periods in constructed reservoirs would further increase such losses. Climate change is expected to bring warmer temperatures to California, but the effect on winter precipitation amounts is still unclear [3,27,30,31]. Therefore, our study will focus on evaluating the impacts of spring temperature on summer hydropower. However, as will become evident, this must be done in the context of winter precipitation.

Fig. 1 indicates 5-year temperature averages ending in the year indicated; for example, the point for 1970 is actually an average for 1966-1970. Some months mimic the annual trend better than others. California's annual average temperature has increased by a large fraction of 1ºC since the 1960s and 1970s. March temperatures have more or less followed the annual trend, although the magnitude of the March temperature increase has been greater than that of the annual averages. April temperatures declined until the mid 1960s, then rose about 3ºC from the late 1970s to around 1990, before declining by about 2ºC to present values. Recent April temperatures are actually slightly lower than they were at the middle of the 20th Century. Although April temperatures have been declining since around 1990, this decline cannot be counted on to continue in a warming world. Global climate model projections indicate warming in both summer and winter seasons in California, with some projections suggesting greater warming in summer than in winter [31]. Warming is generally associated with increased demand for electricity for air conditioning in summer [29], and with increased water stress on crops.

Madani and Lund [24] and Guégan et al. [32] used the Energy-Based Hydropower Optimization Model (EBHOM) [33] to study the response of California hydroelectricity generation to climate at 137 high-elevation sites. In their study, high-elevation hydropower plants are mainly the plants above 300 m, located below non-federal single-purpose high-head low-storage hydropower reservoirs regulated by the Federal Energy Regulatory Commission's licensing system [34]. Their results suggest a nontrivial decrease in hydroelectricity from May through September and a smaller increase in winter generation, even under a "warming-only" scenario, which retains the historical annual flow but shifts the timing differently in different elevation bands. Although their study was restricted to high-elevation power plants, those plants produce the vast majority (roughly 75%) of California's in-state hydroelectricity, so their results should be indicative of the sensitivity of hydroelectricity generation to warming in the state as a whole.

In most areas of the western United States, generation undergoes a general decline from June through the end of the "water year" on September 30, although the higher-elevation reservoirs in California, which generate much of their electricity during the summer months, slow the rate of decline there. These reservoirs are positioned to optimize the use of winter snowpack as a supplemental reservoir [24].

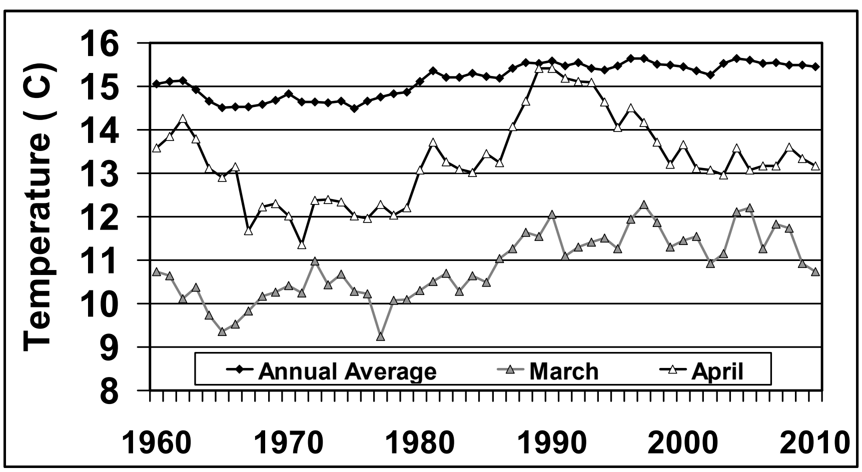

Fig. 1. March, April, and annual average temperature in California expressed as 5-year moving averages ending in the year indicated

With this background in mind, we addressed the question: "Can we specify the effect of spring temperature changes on summer (May-September) hydroelectricity generation, in terms of terawatt-hours (TW-h) per degree Celsius (ºC) of temperature change, for a political entity as large and geographically diverse as the state of California?" Our goal was not to demonstrate a relationship with a certain amount of confidence. The studies reviewed above have already established the relationships we are interested in analyzing. The motivation to focus on the inverse relationship between spring temperatures and summer hydroelectricity generation was that summer is the season when water supply is low and water demands are great in California. The purpose of using a well-defined political entity is to optimize benefit to planners with responsibilities specifically defined for the same entity.

Our approach is simple, easily replicable and strictly data-based. It makes no assumptions relating to hydrological-model parameters and it includes all hydroelectricity generated in California. The general idea was to look at available data in different ways so as to identify important nonstationarities and discover patterns in the way the variables involved relate to each other. Such information can be useful to modelers as well as to planners. The results are in terms of temperature effects only, although we identified nonstationarity in the temperature-hydropower covariance, via the effects of winter precipitation as a third variable.

This is not a conventional study to obtain improved predictability based on a complex statistical model. Such models tend to ignore assumptions of nonstationarity in the mean, and non-normality in the distribution of precipitation although some of the better models will partially circumvent these difficulties using logarithms or other transformations of the data. These models sometimes work well because of the strength of the relationships involved within the period of actuarial record, and they can be useful for their own purposes. Nonetheless, results may be different for actuarial experience before California's high-elevation reservoirs were constructed, if climatic statistics change appreciably, and/or if additional reservoirs are constructed.

This study is an attempt to use what data are available to elucidate physical processes that may be important in the future and, hence incorporated into process models to examine future possibilities. Some traditional statistics are used to lend objectivity to our thinking, so as to reduce speculations about statistical artifacts, to compare derived relationships with data not used in their derivation, and to provide some objective, indication of whether the amount of hydroelectricity "lost" to spring warming would matter in a state that imports more than 25% of its electricity [35]. It was tempting to add winter precipitation as a variable, but as explained above the direction of any future precipitation changes are not part of actuarial experience, and numerical climate models disagree as to whether precipitation will increase or decrease as discussed above. Therefore, precipitation is analyzed only to the extent that it influences our results; these influences are appreciable and are discussed in the text. Additionally, the monthly distribution of spring warming has changed within the period of record, and may change again if the climate continues to warm.

2. DATA

Monthly electricity data for California for 1999-2010 were obtained from Electric Power Monthly [14]. Although there are some inconsistencies within the EIA data (due to different methods for handling non-utility hydroelectricity) these inconsistencies were sufficiently small that they did not present a problem with the analysis. Additional data extending the California record back to 1982 were provided by the California Energy Commission. This allowed us to divide the data into two periods, one for deriving a statistical relationship (calibration period, 1999-2010) and the other for verifying it (verification period, 1982-1998). Within each of these periods, hydroelectricity values were calculated for two groups of months: May-July, and August-September. Monthly values of state temperature and precipitation data were obtained from the National Climatic Data Center [36]. Temperature data are monthly averages for the state, and are presumed to be indicative of monthly temperature anomalies at the most relevant elevations for this study. This assumption can work because temperature is very coherent in space, so that monthly temperature anomalies at the surface are generally indicative of those at higher elevations, at least on monthly or greater time scales. However, relationships between temperature at lower and higher elevations are different in different places, and cold-air drainage can provide contrary results on individual days [37]. Both of these difficulties are reduced by taking statewide monthly averages, although additional measurements from high-elevation sites would undoubtedly be helpful.

3. ANALYSIS AND RESULTS

3.1 Introduction

We initially used simple linear regression to examine a number of relationships. This has to be approached cautiously; for 100 regressions involving random numbers as predictor variables, one would expect a relationship to appear at the 99 percent confidence level once, at the 95 percent confidence level five times, etc. Another caution involves our relatively small sample sizes, for which some assumptions inherent in the statistical tests involved begin to break down. The Student t test was used to indicate relative confidence in the strength of a relationship between two variables, but we caution against too literal interpretation of the significance levels for the sample sizes we use. We simply used this test as an objective, relative, measure of the goodness of fit so as to avoid inadvertent "cherry picking" and subsequent errors in conclusions. All confidence levels in this paper are based on a one-tailed t test, as the hypothesis was that lower spring temperatures lead to higher values of hydroelectricity in succeeding months, and vice-versa, as indicated by the literature reviewed above. The fact that nature does not recognize calendar dates posed another problem with our use of monthly data.

Our goal was to examine the data to see if these already-established relationships might be useful in specifying the response of hydroelectricity generation to spring temperature change over the large and geographically diverse region that is the state of California. To do this in a preliminary sort of way, we had to simplify a group of complex relationships to obtain a measure of how much hydroelectricity would be lost per degree Celsius increase of spring temperature, expressed as the slope of a regression line, in terawatt hours per degree Celsius (TW-h/ºC), obtained from analysis of recent data.

3.2 Initial Analyses

We initially performed multiple regressions using SAS® software to predict hydroelectricity generation for various combinations of spring and summer months, using the previous winter's precipitation and spring temperature (again for various combinations of winter and spring months) as predictor variables. Relationships of spring temperature to hydroelectricity generation in succeeding months were always negative, as expected. The strong relationships between winter precipitation and spring temperature initially posed a problem. Examinations of the SAS output and the data were helpful in identifying some of these relationships, in interpreting our initial results, and in selecting a path forward as discussed below.

In the calibration period, simple and multiple regression equations were derived to relate winter precipitation and spring temperature to subsequent hydroelectricity values at time lags of one month or more. To no surprise, winter (November-March) precipitation was the most important variable in predicting subsequent values of hydroelectricity generation for each group of spring/summer months, as snowmelt from intermediate-high elevations provides much of the water for hydroelectricity in spring and summer in the contiguous western states [38,20,22]. March and April emerged as optimal months to represent spring temperature as a predictor of subsequent hydropower. From this point forward we used simple regression involving only one predictor variable to represent spring temperature. Because numerical climate models have yet to consistently specify the direction of any change in winter precipitation amounts in California, we can only make “if then” statements about effects of winter precipitation.

The regression analyses for the calibration period (1999-2010) indicated that the average temperature for March and April was a reasonably good predictor of May-July hydroelectricity (95% confidence) and could also provide information about hydroelectricity up to the end of the water year (September 30). However, the correlation with August-September hydroelectricity was only significant at the 90% confidence level.

3.3 Examination of Independent Data

Using the verification period (1982-1998) data as an independent test of our relationship derived from the 1999-2010 data, we arrived at the correlation coefficients presented in Table 1 and the following observations:

1. The magnitude of the (negative) correlation coefficient between March-April temperature and May-July hydroelectricity decreased from -0.54 in the calibration period to -0.28, or below the 90% confidence level, in the verification period;
2. The magnitude of the correlation coefficient between March-April temperature and August-September hydroelectricity generation stayed about the same (-0.44 in the calibration period, to -0.45 in the verification period). A larger sample size in the verification period pushed the confidence level past 95%;
3. Skill score results indicated that the decrease in predictability for May-July hydroelectricity was due to the influence of one year (1991); and
4. Eliminating year 1991 resulted in much stronger correlations (very near or above the 99% confidence level, even with 15 degrees of freedom) between April-May temperature and subsequent hydroelectricity (-0.54 for May-July and -0.74 for August-September).

Table 1. Correlation coefficients between March-April temperature and hydroelectricity generation for the following May-July and August-September in California. Asterisks indicate confidence levels of 90%*, 95%, and 99%*****

	May-Jul.	Aug.-Sep.
1999-2010	- 0.541**	- 0.439*
1982-1998	- 0.282	- 0.451**
1982-1998 without 1991	- 0.538**	- 0.735***

Year 1991 was indeed far from typical; February was warmer than the average March, and March was colder than the average February; a 3.3°C temperature decrease occurred from February to March. November-February precipitation was lowest in the period of analysis and second-lowest since records were begun in 1895. Three-and-five-year moving averages of winter precipitation were also at or among their lowest in the period of analysis, depending on how winter is defined. If the definition includes March, then winter precipitation in 1990-1991 was a respectable 34 cm. Only a “miracle March” avoided greater water shortages [39].

Correlations in the calibration period (1999-2010), though not particularly strong, were deemed too high to ignore. Verification tended to bear this out; although initial results for May-July were initially disappointing, results for the late-summer months were surprisingly good. When year 1991 was eliminated from the verification period, results were surprisingly good across all groups of months.

Table 2 summarizes our initial estimates of the reduction in summer generation per degree of spring (March-April) warming as slopes of regression lines. The first row gives the average slope for (1) the calibration, period (1999-2010), (2) the verification period (1982-1998) including year 1991, and (3) the verification period without year 1991 (three slopes that ranged from -0.59 to -1.20 for May-July hydroelectricity and from -0.30 to -0.77 for August-September). The second row gives the slopes obtained from analysis of the entire data set (1982-2010), and the third row is the same as the second except that year 1991 was removed from the data before analysis. These slopes suggest that the reduction in hydroelectricity for the five-month (May-Sep) period was around 1.3 TW-h/ºC, or around 7.5% of California average hydroelectricity generation for those months (Table 2). This percentage may be too high, as indicated in the further investigations below.

Table 2. Summary statistics for our first attempt at relating hydroelectricity to spring March-April) temperature. The first line gives the average slope for (1) the calibration, period (1999-2010), (2) the verification period (1982-1998) including year 1991, and (3) the verification period without year 1991 (3 slopes that ranged from -0.59 to -1.20 for May-July hydroelectricity and from 0.30 to 0.77 for August-September). The second line gives the slope obtained from analysis of the entire data set (1982-2010), and the third line is the same as the second except that year 1991 was removed from the data before analysis

	May-Jul.	Aug.-Sep.	May-Sep.
Average slope of regression lines for separate periods	- 0.94	- 0.50	- 1.45
Slope (TW-h/ºC) for all years (1982-2010) combined	- 0.74	- 0.32	-1.05
Same as above, but with year 1991 removed	- 1.00	- 0.42	-1.42
Average of above 3 rows.	-0.89	-0.41	-1.31
Average CA hydroelectricity generation for months indicated	11.46	6.00	17.46
Line 4 as a percentage of line 5.	7.77%	6.83%	7.50%

Surprisingly, results suggested the stronger relationship between spring temperature and summer hydroelectricity occurred during the verification period (1982-1998). This was a time when April temperatures were particularly high. We repeated our analysis using April temperatures only and discovered that a weak and statistically insignificant relationship during the calibration period (1999-2010) showed up at 95% (99%) confidence levels for May-July (August-September) hydroelectricity when year 1991 was included and always beyond 99% when it was not included. These mixed results from one period to the next indicate a change in the statistical properties (including covariances) of the variables being analyzed, and suggest that the period centered near 1990 represented a different regime in which warm Aprils reduced hydroelectricity in succeeding months, but particularly in the late summer when electricity demands are highest and hydroelectricity generation is lowest.

The situation is shown graphically in Fig. 2, which shows 5-year moving averages for November-March precipitation, April temperature, and hydroelectricity generation for May-July and August-September. The averaging period ends in the year indicated. A period of particularly low hydroelectricity generation ending in the mid 1990s coincided with a period of particularly low winter precipitation and April temperatures 1-2ºC above anything else in the period of climatological record. While both April temperature and winter precipitation were involved in causing the low amounts of hydroelectricity generation, the coincidence of those climatological factors led to a higher correlation between temperature and hydroelectricity than would likely be the case over a longer time period. Our collective results seemed to indicate a meaningful, although complex and temporally inconsistent, relationship between spring temperatures and hydroelectricity generation during the following months.

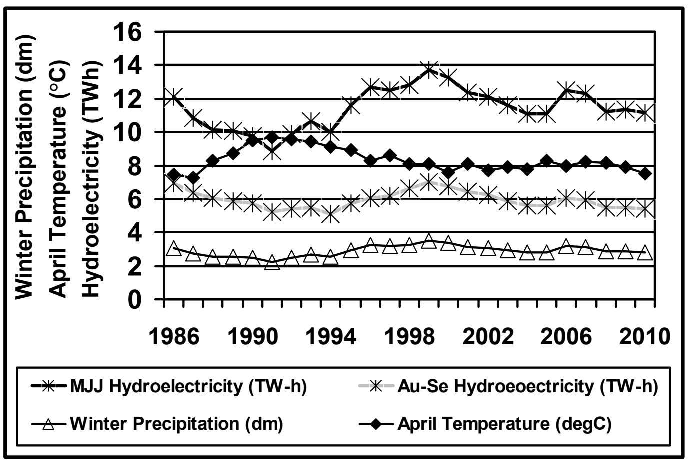

Fig. 2. Five-year moving averages of winter (November-March) precipitation, April Temperature, and hydroelectricity generation for May-June-July (MJJ) and for August September (Au-Se) in California

We also considered the possibility of systematic differences in the two data sets used (Electric Power Monthly and the California Energy Commission data). While there were some differences in the period of overlap (1999-2003), we could not attribute our findings to these differences. Mean hydroelectricity generation decreased somewhat in the later period, but so did winter precipitation. The change in winter precipitation from 1998-99 (transition from one data set to the other) was of the same sign as corresponding changes in May-July and August-September hydroelectricity generation. No discontinuities were apparent in the combined data set. At this point we decided to combine our data sets to form a single set extending from 1982-2010.

3.4 Incorporation of Winter Precipitation Influences

We made two attempts to normalize for winter precipitation. First we examined the data by selecting 6 cold springs (4 with wet winters and 2 with dry winters) and 6 warm springs (3 with wet winters and 3 with dry winters), such that the average winter precipitation in the 4 wet winters followed by cold springs was within 0.2 cm of the average precipitation for the 3 wet winters followed by warm springs. Additionally, the average winter precipitation for the 2 dry winters followed by cold springs was within 0.4 cm of the 3 dry winters followed by warm springs. Thus, we had (very small) sets of wet springs having clear temperature differences but no appreciable precipitation differences, and dry springs having clear temperature differences with no appreciable precipitation differences. A clear response of hydroelectricity to a spring temperature increase emerged following the wet winters; but the dry winters gave little, if any, discernable response. Overall, the decrease in May-September hydroelectricity generation was 0.56 TW-h/°C, or -3.2% of the current average (May-September) generation, per 1°C of spring temperature increase, roughly divided as -4% of May-July hydroelectricity and -2% of August-September hydroelectricity. Again, these estimates of percentages of "lost hydroelectricity" and the estimates that follow serve only to indicate that a nontrivial amount of summer hydroelectricity may be lost to a state that is a net importer of electricity. Because the direction of winter precipitation trend in the future is not well predicted by numerical models of climate, we can only provide limited guidance for anticipation of future hydrologic conditions. Here, we investigate some important influences of winter precipitation, so that hypotheses about future events can be more firmly grounded.

Based on findings and observations to this point, we eliminated years following winters with precipitation over 70 cm when the reservoir system is overwhelmed and any additional water from that precipitation is spilled. We also eliminated year 1991. Then, based on the difference in clarity of result between wet and dry winters discussed above, we divided the remaining 25 years into 3 groups: wet winters (9 years), dry winters (8 years) and moderate winters (8 years). We then used regression analysis with March-April temperature as a predictor of hydroelectricity generation in succeeding months. Again, the wet winters provided impressive results, as a correlation coefficient of 0.79 is good (98% confidence, if only for 9 data points and associated limitations of the t distribution applied to such a small sample). Moderate winters provided arguable results, and no predictive skill was obtained for hydroelectricity after dry winters. This seems to be because a dry winter leads to a spring in which total water supply becomes limiting and spring temperature has little effect. The limited winter precipitation that was stored in the snowpack is handled by California's high-elevation reservoirs and little water remains to be spilled.

The slope of the regression line to predict May-July generation for wet years only was -0.7 TW-h/ºC, or 5.5% of the average May-July generation following only the 9 wet years. When we weighted the (wet winter) results to cover all 29 years, this was only 2% of May-July hydroelectricity generation in California, or about 1.3% of the average generation for May-September. If one is willing to accept 4:1 odds that a relationship is valid (80% confidence with a small sample size), then August-September hydroelectricity generation could be predicted following wet and moderate winters, which would have the net effect of losing another 0.09 TW-h/ºC of March-April temperature. This adds up to 2% of May-July hydroelectricity; 1.5% of August-September hydroelectricity, and overall, 1.8% of hydroelectricity generated in California for the 5-month period May-September.

We next investigated years for which winter precipitation was above the November-March average of 44.3 cm for the period of record. Fig. 3 shows the result of a simple regression analysis to predict California hydroelectricity generation for May-September as a function of spring temperature for those 14 years. A correlation coefficient of over 0.72 ($R2=0.521$) was obtained, compared to 0.69 ($R2=0.473$) when only May-Jul was predicted, suggesting that winters with moderate-high precipitation did indeed influence August-September generation, as we (weakly) inferred in the previous paragraph. May-September generation following wetter-than-normal winters would be reduced by 0.86 TW-h/ºC, or about 4.4% of California's current average May-September generation following wet winters. For generation following all winters, that reduction would only be about 2.4%, as spring temperature following dry winters has little effect on generation.

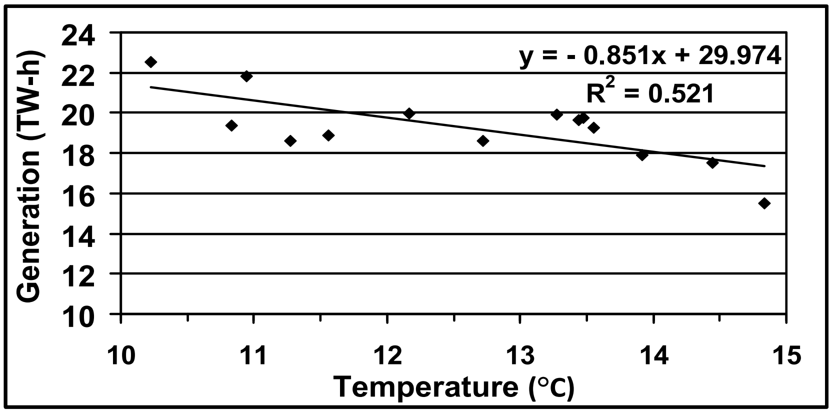

Fig. 3. May-September hydroelectricity generation in California as a function of spring (March April) temperature for years when winter (November-March) precipitation was above its average (44.3 cm) for the period of analysis (1982-2010)

Finally, we plotted generation against winter precipitation for the ten warmest and ten coldest springs in the period of analysis, after eliminating the three wettest winters and year 1991(Fig. 4a). A difference in the regression slopes begins to emerge at about 35 cm of winter precipitation. Above 35 cm, the slopes indicate that more hydropower can be expected following cold springs than following warm springs for any specified amount of winter precipitation. Replacing year 2008 with year 1991 (to form a different set of 10 coldest springs) did not appreciably change this result (Fig. 4b), as was expected considering the low spring-summer hydroelectricity generation for that year was caused mainly by reduced winter precipitation and not by spring temperature (the second-coldest during 1982-2010). For a winter with 50 cm of precipitation the difference is around 2 TW-h of May-September generation, or about 11.5% of the average May-September generation, in favor of cold springs. The advantage of cold springs increases as precipitation approaches 70 cm. Adding the three winters with greater than 70 cm of winter precipitation (all of which were followed by cold springs) to the pool from which 10 the coldest springs were chosen, but rejecting year 1991, produced a "tail wagging the dog" effect which reduced the slope of the regression line for cold springs by adding leverage for winters with over 70 cm of precipitation (Figs. 4c and 4d). The amount of May-September generation was still around 1-2 TW-h higher following a cold spring than a warm one. Inclusion of year 1991 in the 10 coldest springs (Fig. 4d) reduced the magnitude of the difference between warm and cold springs, but did not change the sign; at least 1.25 TW-h more generation was always indicated following a cold spring for any specified amount of winter precipitation. When generation following the three wettest winters were included (Figs. 4c and 4d) a quadratic curve (dashed line) fit the points representing cold springs better than a straight line, adding around 18% to the variance accounted for in both cases. We interpret this as confirmation that winter precipitation greater than 70 cm will overwhelm the system and lead to greater spillage, rather than producing additional generation from California's high-elevation reservoirs.

4. SUMMARY AND DISCUSSION

Due to the complexity of the relationships we were able to unravel, it seemed appropriate to look at the data from different perspectives using only simple graphical approaches to discover the important underlying relationships involved. Our findings are compatible with known mechanisms and provide some insight into some previously unexplored ones. In general, our results suggest that hydroelectricity generation following dry winters is dependent on how much water can be collected by high-elevation reservoirs, which may depend on just how dry a winter is (i.e., on winter precipitation only). The objective is to keep the high-elevation reservoirs as full as possible, storing as much water as possible for later use when the price of electricity and the need for irrigation water downstream are both highest. During dry-moderate years we can make only questionable statements, but results for moderate-wet years suggest that timing of winter snowmelt becomes an issue. In a cold spring melting is relatively slow, so water enters the system gradually and electricity can be generated in early spring, as well as in summer without significant water spillage. However, in a warm spring following a moderate-wet winter melting occurs rapidly and more precipitation at mid elevations falls as rain, overwhelming the system somewhat and leading to spillage of water that might otherwise be used later for electricity generation. Following an extremely wet winter (i.e., a winter with more than 70 cm of precipitation, which occurred 3 times from 1982 through 2010) there seems to be sufficient winter snowfall to provide hydroelectricity well into the summer, regardless of spring temperature. This is because the total water storage capacity (snowpack plus constructed reservoirs) is sufficient during extremely wet winters, even with considerable spillage. In general, for a given amount of precipitation, it seems that the warmer the spring, the more the constructed reservoir capacity becomes limiting. While we did not have a period of record including as many replications of as many possible situations as we would have liked, we will put our conclusions forward as tentative hypotheses, to be tested by more sophisticated hydrologic modeling as well as by future observations.

Stewart [26] has commented on the loss of water available for hydropower if increased temperatures lead to an increased percentage of precipitation falling as rain, which can lead to increased spillage. More precipitation would have to fall during the coldest months and stored as snowpack to alleviate this effect. All other factors being constant, the loss of 1 cm of November-March precipitation costs California about 0.27 ± 0.05 TW-h for May-July and another 0.15 ± 0.03 TW-h for Aug-Sep (range is one standard deviation either way). This is around 2.5 percent of the 1982-2010 average hydroelectricity generation in California for each group of months. Because March temperatures were relatively constant in the period of analysis while April temperatures varied greatly, we could not conclude as much as we would have liked to about the effects of increased March temperature on rain/snow ratio at the relevant elevations. However, the effect of a higher percentage of March precipitation falling as rain would likely add to spillage and decrease hydroelectricity production for a given amount of winter precipitation.

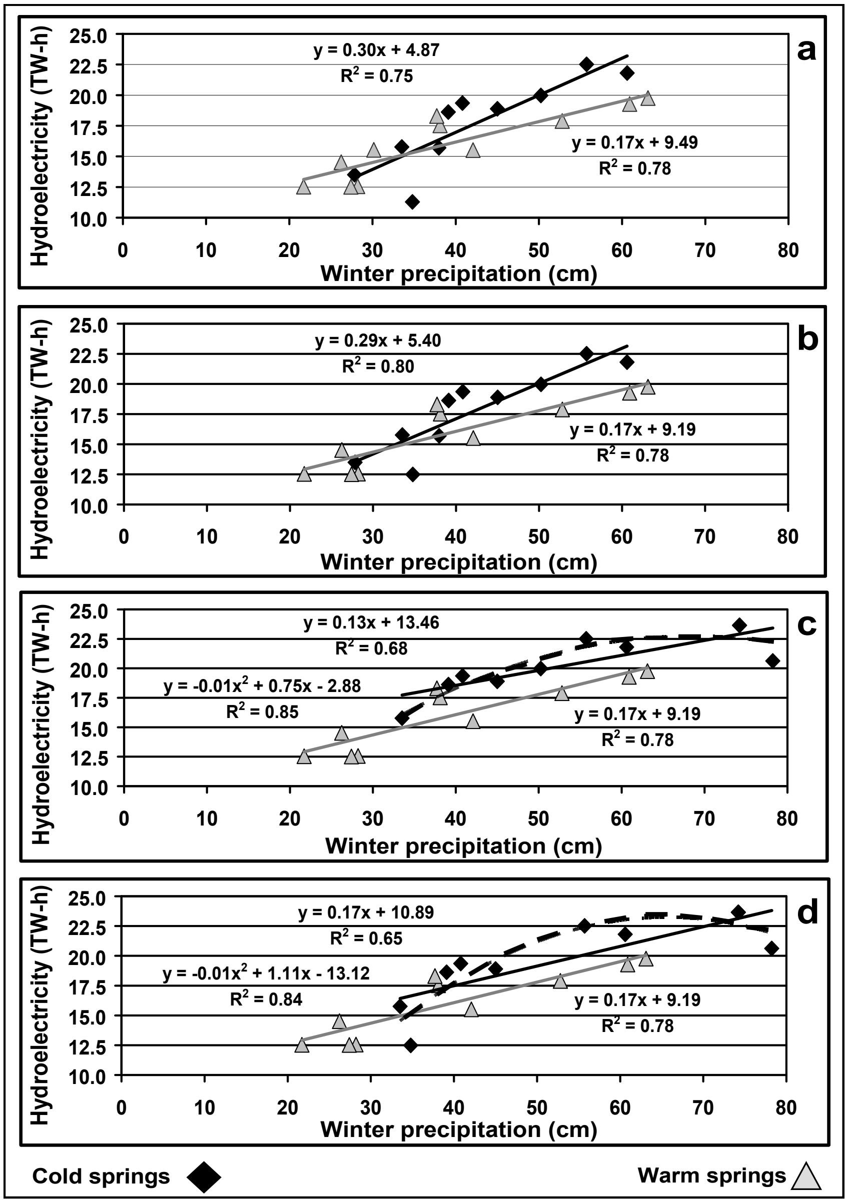

Fig. 4. California summer (May-September) hydroelectricity generation versus previous-winter (November-March) precipitation following the 10 coldest and 10 warmest springs (March-April) chosen from a pool of years including: (a) all years from 1982 to 2010 except 1991 and the three years for which winter precipitation was 70 cm or more, (b) same as (a) except that 1991 is also in the pool, (c) all years except 1991 were in the pool, and (d) all years in the analysis period were in the pool

We noted an inverse relationship between winter precipitation and spring temperature, possibly due to less extensive snow cover leading to lower albedo and less energy lost to melting/evaporation, although general circulation factors might override such relationships in many cases. Any relationship between winter precipitation and temperature the following spring complicates attempts to relate one or the other variable directly to hydroelectricity generation during subsequent months. The correlation coefficient between November–March precipitation and March-April temperature for 1982-2010 was -0.38. The relationship between winter precipitation and spring temperature may merit further investigation from a climatological viewpoint.

This paper focused solely on hydroelectricity; other uses of water were ignored. Agricultural uses are also important; California has consistently led all other states in cash receipts from crops [40]. Total water use (agricultural plus urban) declined from 1980 to 2005 [41] as more efficient management of water and some changes in the types of crops produced have reduced water demands. However, water resources are strained and any reduction in water supply would be detrimental. Spring warming could lead to increased spillage from reservoirs at a time when irrigation water is not needed as much as it is during the summer. Fortunately, this spillage would likely be less in dry years, as high-elevation reservoirs can at least partially replace the snowpack as a water-storage mechanism.

5 CONCLUSIONS

The answer to our original study question: "Can we specify the effect of spring temperature changes on summer (May-September) hydroelectricity generation, in terms of terawatt-hours (TW-h) per degree Celsius (°C) of temperature change, for a political entity as large and geographically diverse as the state of California?" is "Yes" within broad limits. The negative relationship between spring temperature and hydroelectricity during the following months was robust, if variable in strength. Reductions in summer hydroelectricity generation would probably be in the mid-high end of our range of estimates (of 1-7% decrease per °C). If temperature increases occur in both March and April, an increase in March temperature would also be associated with a greater percentage of winter precipitation falling as rain and an increase in April temperature would contribute additionally to rapid early melting. We note that March temperature was increasing *and* April temperatures were particularly high during our earlier (1982-1998) data period, which seemed to indicate the strongest relationships between spring temperature and subsequent hydroelectricity generation in California. In contrast, during our later data period (1999-2010) March and April temperatures were relatively constant and April temperatures had decreased. More refined process-based hydrologic models taking into account the complex relationships involved would almost surely be able to provide more robust answers. Ability to specify future winter precipitation changes would add greatly to the accuracy and precision of the information that could be provided to policymakers.

Should winter precipitation increase, an increased temperature would detract from any additional hydropower realized due to limited storage capacity. Should winter precipitation decrease, spring temperatures would have proportionally less effect as spillage (wasted water) would be reduced by California's existing reservoir system.

California's water supply depends primarily on winter precipitation. When stored as snow, this precipitation acts as the largest surface water reservoir in California, storing water for use during late spring and summer months when it is most needed. Spring temperatures can influence the amount of this stored water available for use during subsequent months.

California's high-elevation reservoirs have been built for hydropower production, relying on snowpack as the major water-storage mechanism. These reservoirs also supplement water storage for drought mitigation purposes, and provide limited flood protection during wet years. Following dry winters, hydroelectricity generation is limited primarily by precipitation stored in the snowpack during the previous winter; spring temperatures have little or no effect on spillage, although they can affect evaporation from early meltwater stored for long periods in constructed reservoirs. Following moderate-wet winters, warm springs lead to increased spillage when high-elevation reservoirs cannot capture all of the meltwater. This decreases the water supply available for hydroelectricity generation in subsequent months. During cold springs the snowpack melts more slowly, allowing it to act as a water reservoir for a longer period of time so that water can be supplied as needed. In the case of increased winter precipitation and warmer springs, the benefits of the precipitation increases would be reduced by increased spillage and earlier disappearance of snow cover. Following winters with over 70 cm of precipitation, spring temperatures are no longer limiting. Reservoir capacity constrains the amount of water that can be stored and the amount of subsequent hydroelectricity generation.

A decrease in California's hydroelectricity generation in spring and summer might be largely offset by an increase in winter generation in wet years, as indicated by the results of Madani and Lund [24] and Guégan et al. [32]. Given the higher value of electricity in summer, revenue losses are expected even if summer generation decreases were accompanied by winter generation increases of the same magnitude. These seasonal imbalances would be even greater if summer and winter climate both warm, as air conditioning demands would increase the value of summer electricity while reduced heating demands would decrease the winter value [29]. In California, 22% of the homes are heated with electricity [42].

Finally, as with any preliminary and simplified investigation of complex phenomena, our analysis was quite limited. Nonetheless, our findings are indicative of phenomena that merit continued investigation. Our study establishes rough quantitative limits on the impact of warmer springs, and suggests avenues for further research in California, and perhaps in other states, using process-based hydrological modeling. We believe that warmer springs would add to the already nontrivial challenges for California's water planners. This is of particular importance for a general climate warming, as hydropower supply and demand would become more unbalanced, increasing seasonal price fluctuations.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. United Nations. Water: A Shared Responsibility. The United Nations World Water Development Report 2. United Nations Educational, Scientific and Cultural Organization (UNESCO), New York. 2006. Available at: http://www.unesco.org/water/wwap/wwdr/index.shtml
2. United Nations. Water Rights and Wrongs: A young people's summary of the Human Development Report 2006 - Beyond scarcity: Power, poverty, and the global water crisis. United Nations Development Programme, New York. 2007. Available at: http://www.unwater.org/downloads/water_rights_and_wrongs_en.pdf
3. Barnett TP, Adams JC, Lettenmaier DP. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 2005;438:303-309.
4. Cason K. Before wells run dry: How will we manage Georgia’s growing demand for water? Outreach, Winter 2007, 14-18. (Published by: University of Georgia, Office of the Vice President for Public Service and Outreach, Athens Georgia.)
5. Sun G, McNulty SG, Moore-Myers JA, Cohen EJ. Impacts of multiple stresses on water demand and supply across the southeastern United States. J Am. Water Resour. As. 2008:44:1441-1457.
6. Seager R, Tzanova A, Nakamura J. Drought in the southeastern United States: Causes, variability over the last millenium, and potential for future hydroclimate change. J Climate. 2009;22:5021-5045.
7. Sophocleous, M. Groundwater recharge and sustainability in the high plains aquifer in Kansas USA. J Hydrogeol. 2005;13:351-365.
8. Texas Water Development Board. Water for Texas 2007, Volume I, Highlights of the 2007 State Water Plan, Document No. GP- 8-1, Texas Water Development Board, Austin, Texas, 2007, 39 pp. including Appendix.
9. McGuire VL. Water-level changes in the High Plains aquifer, predevelopment to 2007, 2005–06, and 2006–07: U.S. Geological Survey Scientific Investigations Report 2009–5019, 9 p. United States Geological Survey, Reston VA. 2009. Available at: http://pubs.usgs.gov/sir/2009/5019/
10. Jenkins MW, Lund JR, Howitt RE, Draper AJ, Msangi SM, Tanaka SK, Ritzema RS, Marques GF. Optimization of California’s Water Supply System: Results and Insights. J Water Res. Pl. & Mgmt. July/August: 2004;271-280.
11. Hanak E. Water for Growth: California’s New Frontier, Public Policy Institute of California, San Francisco. 2005, available: http://www.ppic.org/main/home.asp
12. Sabo JL, Sinhaa T, Bowling LC, Schoups GH, Wallenderd WW, Campana ME, Cherkauer KA, Fuller PL, Graf WL, Hopmans JW, Kominoski JS, Taylor C, Trimble SW, Webb RH, Wohl EE. Reclaiming freshwater Sustainability in the Cadillac Desert. Proc. Natl. Acad. Sci. USA. 2010;107:21263–21270.
13. Wolfe JR, Goldstein RA, Maulbetsch JS, McGowin CR. An electric power industry perspective on water use efficiency. J Contemporary Water Res. and Educ. 2009;143:30-34.
14. EIA (Energy Information Administration, U.S. Department of Energy). Electric Power Monthly. Available at: 2011a, http://www.eia.doe.gov/cneaf/electricity/epm/epm_ex_bkis.html.

15. EIA (Energy Information Administration, U.S. Department of Energy). Electric Power Annual. Available at: 2011b, http://www.eia.gov/electricity/annual/
16. Roos M. Possible changes in California snowmelt patterns. Proceedings of the Fourth Pacific Climate Workshop, Consortium for Integrated Climate Research in Western Mountains, Pacific Grove. 1987;CA. 22-31.
17. Roos M. A trend of decreasing snowmelt runoff in northern California. Proceedings of the 59th Western Snow Conference, Western Snow Conference, Juneau, Alaska. 1991;29–36.
18. Medellin-Azuara J, Harou JJ, Olivares MA, Madani K, Lund JR, Howitt RE, Tanaka SK, Jenkins MW, Zhu T. Adaptability and Adaptations of California's Water Supply System to Dry Climate Warming. Climatic Change. 2008;87(Suppl 1):S75-S90.
19. Connell-Buck CR, Medellin-Azuara J, Lund JR, Madani K. Adapting California’s Water System to Warm vs. Dry Climates. Climatic Change. 2011;109 (Suppl 1):S133-S149.
20. Knowles N, Dettinger MD, Cayan DR. Trends in snowfall versus rainfall in the western United States. J Climate. 2006;19:4545-4559.
21. Caldwell, P, Chin, H-NS, Bader, DC, Govindasamy, B. Evaluation of a WRF dynamical downscaling simulation over California. Climatic Change. 2009;95:499-521.
22. Maurer, EP, Stewart, IT, Bonfills, C, Duffy, PB, Cayan, DR. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. J Geophys Res. 2007;112.
23. Mote PW, Hamlet AF, Clark MP, Lattenmaier DP. Declining mountain snowpack in western North America. B. Am. Meteorol. Soc. 2005;86:39-49.
24. Madani K, Lund JR. Estimated impacts of climate warming on California’s high-elevation hydropower. Climatic Change. 2010;102:521-538.
25. Stewart I, Cayan DR, Dettinger MD. Changes toward earlier streamflow timing across western North America. J Climate. 2005;18:1136-1155.
26. Stewart IT. Changes in snowpack and snowmelt runoff for key mountain Regions. Hydrol. Process. 2009;23;78–94.
27. Maurer EP. Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. Climatic Change. 2007;82:309-325.
28. Madani K, Lund JR. Aggregated modeling alternatives for modeling California’s high-elevation hydropower with climate change in the absence of storage capacity data. J Hydrological Science and Technology. 2007;23:137-146.
29. Guégan M, Uvo CB, Madani K. Developing a module for estimating climate warming effects on hydropower pricing in California. Energy Policy. 2012;42:261-271.
30. Cayan DR, Luers AL, Franco G, Hanemann, GM, Croes, B, Vine, E. Overview of the California Climate Change Scenarios Project. Climatic Change. 2008a;87(Supplement 1):S1-S6.
31. Cayan DR, Maurer EP, Dettinger MD, Tyree M, Hayhoe K. Climate change scenarios for the California region. Climatic Change. 2008b;87(supplement 1):S21-S42.
32. Guégan M, Madani K, Uvo CB. Climate Change Effects on the High-Elevation Hydropower System with Consideration of Warming Impacts on Electricity Demand and Pricing”, California Energy Commission. 2012;CEC-500-2012-020.
33. Madani K, Lund JR. Modeling California’s high-elevation hydropower systems in energy units. J Water Resour. Res. 2009;45.
34. Madani K. Hydropower licensing and climate change: insights from game theory. Adv Water Resour. 2011;34:174-183.
35. EIA (Energy Information Administration, U.S. Department of Energy). State Electricity Profiles at: 2012, Available: http://www.eia.gov/electricity/state/california/.

36. NCDC (National Climatic Data Center). U.S. National/State/Divisional Data Top of Form. 2011, (1895 - present, national/state/divisional averages by month). Available at: http://www1.ncdc.noaa.gov/pub/data/cirs/
37. Lundquist JD, Cayan DR. Surface temperature patterns in complex terrain: Daily variations and long-term change in the central Sierra Nevada, California. J Geophys Res. 2007;112.
38. Bales RC, Molotch NP, Painter TH, Dettinger MD, Rice R, Dozier J. Mountain hydrology of the western United States. J Water. Resour. Res. 2006;42. doi:10.1029/2005WR004387
39. Gollehon N. California Drought Persists. Agricultural Outlook. Economic Research Service, United States Department of Agriculture (July issue). 1991;24-26.
40. USDA (United States Department of Agriculture, Economic Research Service). Farm income data files, U.S. State Farm Income and Wealth Statistics. Historical monthly cash receipts, for total commodities and crops/livestock, (includes U.S. total and annual totals), 1980-2011. (Aggregate monthly cash receipts for all commodities, all Livestock and all crops, by state and U.S. United States Department of Agriculture< Washington, D.C. Available at: http://www.ers.usda.gov/Data/FarmIncome/finfidmu.htm#cashrec Accessed on April 26, 2012.
41. Hanak E, Lund JR, Dinar A, Gray B, Howitt RJ, Mount J, Moyle P, Thompson B. Managing California's Water - From Conflict to Reconciliation. Public Policy Institute of California. San Francisco. 2011, available: http://www.ppic.org/main/home.asp .
42. United States Department of Energy. Energy consumption in California homes. United States Department of Energy, Washington, D.C. Last updated, August 15, 2008. Available at: http://apps1.eere.energy.gov/states/residential.cfm/state=CA. Accessed 28 June 2012.

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