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The evolution of climate change impact studies on hydrology and water resources in California

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Abstract Potential global climate change impacts on hydrology pose a threat to water resources systems throughout the world. The California water system is especially vulnerable to global warming due to its dependence on mountain snow accumulation and the snowmelt process. Since 1983, more than 60 studies have investigated climate change impacts on hydrology and water resources in California. These studies can be categorized in three major fields: (1) Studies of historical trends of streamflow and snowpack in order to determine if there is any evidence of climate change in the geophysical record; (2) Studies of potential future predicted effects of climate change on streamflow and; (3) Studies that use those predicted changes in natural runoff to determine their economic, ecologic, or institutional impacts. In this paper we review these studies with an emphasis on methodological procedures. We provide for each category of studies a summary of significant conclusions and potential areas for future work.

1 Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) report reaffirms that the climate is changing in ways that cannot be accounted for by natural variability and that "global warming" is occurring (IPCC 2001). This global warming is likely to have significant impacts on the hydrologic cycle, affecting water resources systems (Arnell 1999; IPCC 2001). These impacts will vary for different regions of the earth. Regions that have a

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large fraction of runoff driven by snowmelt would be especially susceptible to changes in temperature, because temperature determines the fraction of precipitation that falls as snow and is the most important factor determining the timing of snowmelt runoff. The California water system is highly dependent on snow storage and hence has great potential to suffer from the effects of global warming. This potential risk has spawned over 60 studies in the last 20 years in the field of climate change and its resulting impacts on water resources in California. The following paper presents a review of these studies with the objective of understanding how the field has evolved over time, what has been accomplished to date, and what remains to be done. This review builds on previous assessments of the impacts of climate change on Californian water resources (Gleick and Chalecki 1999; Wilkinson et al. 2002; Roos 2003; Kiparsky and Gleick 2003). Studies on the Colorado River were not included in this review because, although changes in its streamflow affect directly California, the Colorado River is a different hydrologic region than the rivers that are in the State of California.

This paper is organized to present the three main categories representing the field of climate change impacts on water resources. The first section covers studies that ask: what evidence of climate change do we see in historical streamflows to date? The second category covers studies that are focused on prediction of the potential future effect of climate change on streamflow. Finally, the third set of studies uses those predicted changes in natural runoff to predict their economic, ecologic, or institutional impacts. Presented in Fig. 1 is a timeline showing when this over 60 studies were published over the last two decades. The timeline shows an early interest in the field that peaked in the early 1990s followed by a slight decay in the mid-1990s and a rampantly increasing interest by the end of the century that appears to be ongoing.

2 The historical record: is there evidence of the effects of climate change on California hydrology?

It has been almost two decades since Roos (1987, 1991) first brought attention to changes that are occurring in California's streamflow patterns. Roos looked specifically at the Sacramento basin and determined that the seasonal fraction of runoff flowing through the snowmelt/spring season (from April to July) was decreasing throughout the twentieth century (see Fig. 2). This same behavior was confirmed by other studies using more complex statistical measures and extended to other basins in the State (Fox et al. 1990; Wahl 1991; Aguado et al. 1992; Pupacko 1993; Dettinger and Cayan 1995; Shelton and Fridirici 1997; Shelton 1998; Freeman 2002) (see Fig. 3 for a map showing which basins have been studied).

Using seasonal fractional runoff as a measure of changes in streamflow patterns could be misleading because it may either imply changes in the spring runoff or changes in the other seasons or both (Wahl 1991). Avoiding this uncertainty, Cayan et al. (2001), Stewart et al. (2004, 2005) and Regonda et al. (2005) each present a different approach to measure changes in streamflow patterns. Cayan et al. (2001) considered the 'spring pulse,' defined as the day when cumulative departure of daily streamflow from mean is the most negative. Their study, covering several basins in the Sierra Nevada Mountains, correlated the spring pulse with other measures of spring onset (e.g. flower blooming). Their results showed an organized earlier spring onset. Stewart et al. (2004, 2005) obtained a similar result using flow-weighted timing, or 'center of mass' of streamflow, as the metric to determine runoff

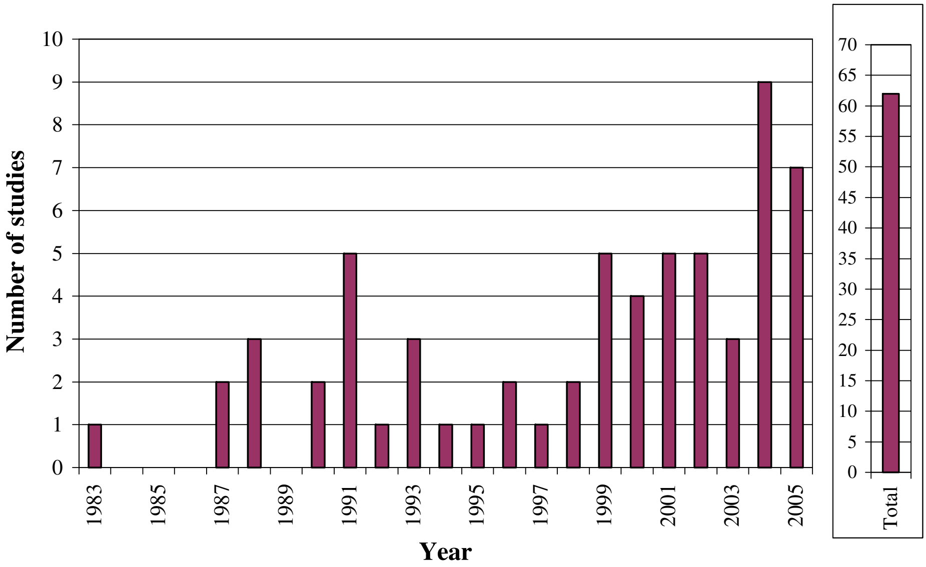

Fig. 1 Historical record of climate change and water resources/hydrology related studies in CA

timing (see Fig. 4). Regonda et al. (2005) used the "date (Julian day) on which 50% of the water-year flow is equaled or exceeded." All of these studies focused on different basins throughout the Western U.S., finding a shift towards earlier snowmelt. However, results for the Sierra Nevada basins were less statistically significant than in other regions, such as in the Pacific Northwest.

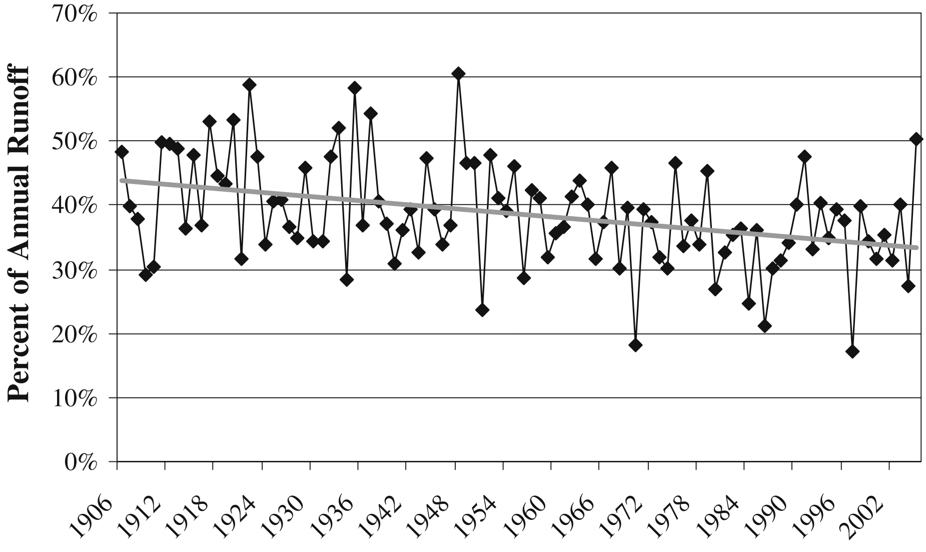

Fig. 2 Trend of April–July as percent of water year runoff for Sacramento four basin index (modified from Roos 1991)

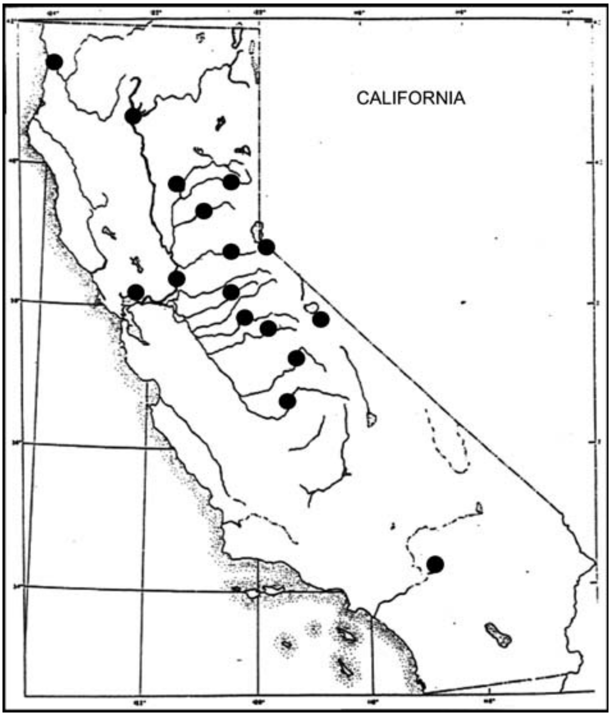

Fig. 3 Spatial coverage (*black dots*) of streamflow trend studies in California background map from: http://faculty.sierracollege.edu/ccox/images/maps/CA_rivers_map.jpg

Several factors have been postulated as causing the trend in the decline of fractional spring streamflow, including increases in winter precipitation and increases in spring temperatures. The latter factor was found to explain earlier spring runoff by Cayan et al. (2001), Stewart et al. (2004, 2005) and Regonda et al. (2005). The increase in spring temperature factor may also explain why the magnitude of the trends depends on the altitude of the basin. Basins located well above the 'freezing line' (above 2,000 m) show less pronounced changes in runoff patterns than mid-altitude basins (1,000–2,000 m) because they are less sensitive to changes in temperature, as shown by studies comparing trends for different basins (Roos 1987, 1991; Aguado et al. 1992; Pupacko 1993; Dettinger and Cayan 1995; Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2005). This may explain why lower-in-altitude basins located in the northern Sierra Nevada Mountains have experienced more pronounced trends than their higher-in-altitude counterpart basins in southern Sierra Nevada. Whether these changes in runoff patterns are a signature of a changing climate in California remains uncertain. Although some authors have suggested that these trends are due to climate change (e.g Pupacko 1993; Shelton and Fridirici 1997; Shelton 1998; Stewart et al. 2005), other have been more cautious, suggesting the possibility that the length of the historical record only shows one realization of a low frequency process such as the Pacific Decadal Oscillation (e.g. Aguado et al. 1992; Dettinger and Cayan 1995; Cayan et al. 2001).

Another geophysical factor that has been studied for historical trends is the snowpack level measured as the Snow Water Equivalent (SWE). Studies show a decreasing trend in the latter half of the twentieth century in SWE for most snowmelt basins throughout the Western U.S. that is consistent with temperature increases for the same period (Mote et al. 2005; Regonda et al. 2005).

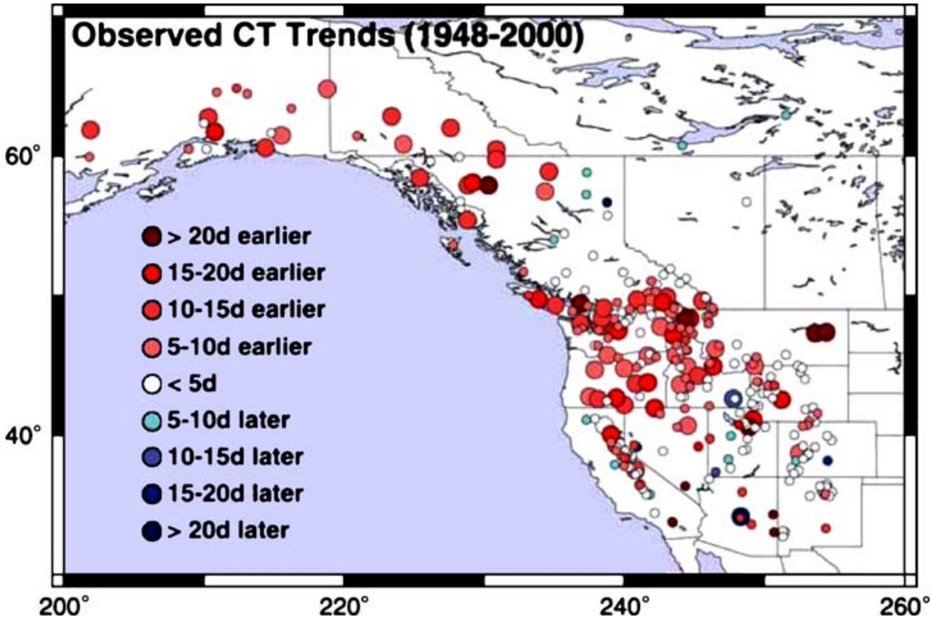

Fig 4 Observed changes in the timing of the center of mass of flow (from Stewart et al. 2004). Note: *Color of the symbols* corresponds to a given magnitude of the linear trend, which is given in terms of the corresponding overall shift (days) for the 1948–2000 historical period. *Larger circles* indicate statistically significant trends at the 90% level, *smaller circles* correspond to trend that do not meet the significance thresholds at the 90% confidence level

It is the author's opinion that an area of future research regarding the historic evidence of climate change in the geophysical record is the interaction between vegetation, surface runoff and the timing of streamflow in California. Some areas in the California Sierra Nevada have experienced changes in land cover due mainly to deforestation. These changes in land cover might have affected the albedo and the soil and vegetation functions of waterheds and thus streamflow runoff patterns. We could not find any study that considered trends in land cover vegetation to isolate this factor in streamflow trend analysis.

Summarized in Table 1 are the studies to date on historical trends of streamflow and snowpack level data in California. We classified the studies in the table according to the basins studied and measures used in the trend analysis.

3 Predicted future impacts on Californian natural streamflow due to climate change

3.1 Methodology

The methodologies used to assess climate change impacts on hydrology and water resources systems have been addressed by Gleick (1986, 1989) and Wood et al. (1997). There are two major steps involved in this process: (1) Determining changes in temperature, precipitation and other climatologic variables such as evapotranspiration and; (2) Using these changes to determine the resulting changes in streamflow. See Fig. 5 for a schematic of the methodology.

Table 1 Summary of studies on the historic trend of streamflow and snowpack data in California

Study	Basin (length of record)	Trend found (at significant level unless explicitly expressed) and possible cause examined
Roos 1987	Sacramento River Index (1906–1986); Combined Kings and San Joaquin (1901–1986)	Reduction in fractional spring (snowmelt) runoff for both basins. More dramatic for Sacramento Index which is lower than Kings-San Joaquin. Not significance analysis performed. No cause explored.
Fox et al. 1990	Actual and unimpaired Delta outflow (1920–1986)	Increase in July through November flows and decrease in April and May flows. Increases in good agreement with increases in precipitation during the flood season.
Roos 1991	Sacramento River Index (1906–1990); Combined Kings and San Joaquin (1901–1990)	Reduction in fractional snowmelt runoff for both basins. More dramatic for Sacramento Index which is lower than Kings-San Joaquin. Not significance analysis performed. No cause explored.
Wahl 1991	Several basins in Western U.S. including California's Sierra Nevada and Cascades (median record length of 60 years finishing in 1989).	Reduction in fractional snowmelt runoff for 10 basins in CA. No cause explored
Aguado et al. 1992	Several basins in California, including Sierra Nevada and Cascades (1948–1986).	Reduction in fractional snowmelt runoff. Possible causes (identified by regression models): increase winter precipitation and spring temperature. Results more pronounced for high altitude basins.
Pupacko 1993	American and Carson rivers (1939–1990)	Increasing March and winter month's streamflow. Possible cause: increase minimum winter temperature. More pronounced trend for lower altitude basin (American)
Dettinger and Cayan 1995	Smith, American, San Joaquin, Carson and Merced rivers (1948–1991). 8-river index (1906–1990)	Reduction in fractional snowmelt runoff. Trend seems to have begun in the late 1940s and is most pronounced for mid-altitude river basins (1000–2000m). Possible cause: increase winter temperature.
Shelton and Fridirici 1997	Unimpaired inflow into the Delta (1921–1992)	Increasing March, September and October fractional runoff. Decrease in April and May fractional runoff. No cause explored.
Shelton 1998	Unimpaired Sacramento river (1921–1994)	Reduction in fractional snowmelt runoff. No cause explored.

Cayan et al 2001	Several basins in western U.S. including California's Sierra Nevada (1948–1995).	There is a trend toward earlier snowmelt timing since the mid-1970s. Snowmelt timing is measured as the "spring pulse," which corresponds to the day when cumulative departure from mean is most negative. This measure correlates well with other spring onset measures (e.g. flower blooming). Possible causes are warm episodes associated with larger-scale atmospheric conditions.
Freeman 2002	North Fork Feather and Yuba River (1952–1999)	Increase in March runoff and decrease in May runoff. Decrease in snowpack in Lake Spaulidng course. No cause explored.
Stewart et al. 2004	Several snowmelt dominated basins (279) in Western U.S. including California's Sierra Nevada (1948–2000).	A large majority of basins exhibit significant trends toward earlier snowmelt timing during the last few decades. Results not very significant in Californian basins. Snowmelt timing is measured as the "center of timing," that corresponds to the centroid of the hydrograph. The principal cause is an increasing spring temperature.
Mote et al. 2005	Several basins in western U.S. and Canada including California's Sierra Nevada and Cascades (1950–1997)	Decreasing springtime SWE in northern California. SWE decreases are related to increases in temperature. Increasing SWE in California's southern Sierra Nevada. SWE increases occurred in high-altitude basins or in basins with high increases in precipitation.
Regonda et al. 2005	Several mountain basins in western U.S. including California's Sierra Nevada (1950–1999)	Both earlier (at mid-altitude basins) and later (at high-altitude basins, normally over 2,500 m) timing for peak flows (both not statistically significant in Californian basins). Timing of snowmelt is measured as the date on which 50% of the water-year flow is equaled or exceeded. Decreasing levels of SWE, especially for low basins. Causes: temperature increases in low basins.
Stewart et al. 2005	Several snowmelt and non-snowmelt dominated basins in western U.S., Canada and Alaska including California's Sierra Nevada, Cascades and southern California (1948–2000).	A large majority of snowmelt basins have exhibited significant trends toward earlier snowmelt timing (measured both as "spring pulse" and "center of timing, CT") and decreasing snowmelt fractional runoff. Trends are less pronounced for high-altitude basins. The major cause of the timing trend has been winter and spring temperature increases. Indicators of low frequency natural fluctuations, such as PDO, are not sufficient to fully explain the observed timing changes. For cases of non-snowmelt-dominated basins there is a trend toward later snowmelt timing (as CT).

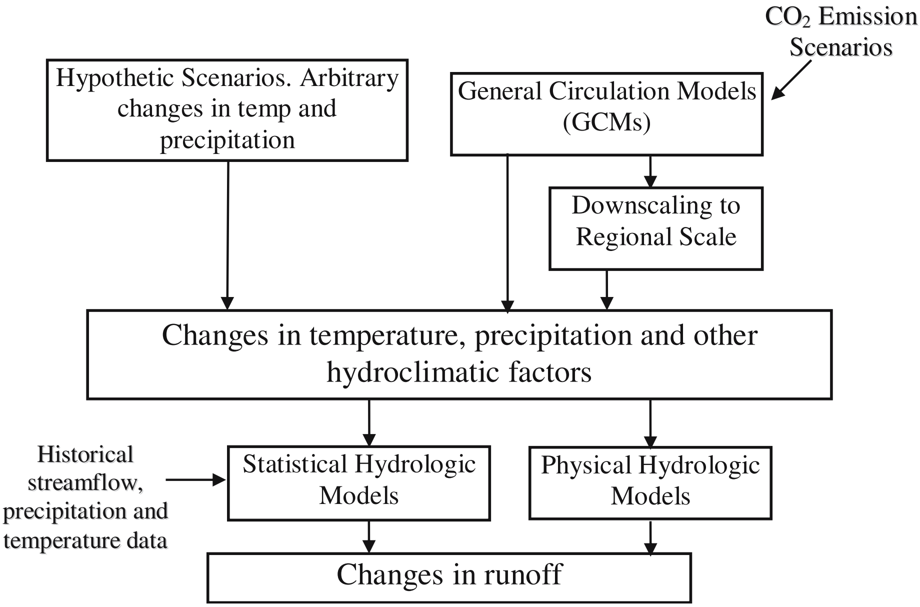

Fig. 5 Methodology to evaluate hydrologic implications of climate change

3.1.1 Determining changes in temperature and precipitation

There are two alternative approaches to determine the changes in temperature and precipitation associated with climate change. The more simple and direct approach is to develop hypothetical scenarios of changes in temperature and precipitation. The second approach obtains these changes in temperature and precipitation as output from a 'general circulation model' (GCM).

Proposed hypothetical climate scenarios in these studies include changes in temperature covering the plausible range for the twenty-first century (e.g. +2 to +5°C). Since projections of precipitation are less consistent and include both increases and decreases, hypothetical scenarios are selected within this range. The "hypothetical scenario" approach was used in the earliest studies (Revelle and Waggoner 1983; Gleick 1987; Jeton et al. 1996) and a recent study by Miller et al. (2003). However, it is important to mention that of all these studies, only Revelle and Waggoner (1983) relied solely on the 'hypothetical scenarios' approach. The other studies also included output from GCMs. The advantage of the hypothetical scenario approach is its simplicity in representing a wide range of alternative scenarios. These scenarios can be used to determine the sensitivity of a particular basin to changes in climate conditions and whether systems can adapt to the range of potential impacts. However, it is difficult to assign probabilities associated with these scenarios so that they can be used for making policy decisions in water resources management.

GCMs have evolved over the past 50 years since their original conception by Phillips (1956). Currently GCMs are representations of the coupled atmosphere-land-ocean-ice systems and their interactions. These models provide information on the response of the atmosphere to different scenarios of greenhouse gas concentrations (IPCC 2001). Most climate change studies of California used GCMs' output to represent climate change conditions (Gleick 1987; Lettenmaier et al. 1988; Lettenmaier and Gan 1990; Tsuang and Dracup 1991; Leung and Ghan 1999; McCabe and Wolock 1999; Miller et al. 1999; Wolock and McCabe 1999; Hay et al. 2000; Miller and Kim 2000; Wilby and Dettinger 2000; Carpenter and Georgakakos 2001; Kim 2001; Kim et al. 2002; Knowles and Cayan 2002; Snyder et al. 2002; Huber-Lee et al. 2003; Miller et al. 2003; Van Rheenen et al. 2003; Dettinger 2004; Dettinger et al. 2004; Hayhoe et al. 2004; Knowles and Cayan 2004; Leung et al. 2004; Stewart et al. 2004; Van Rheenen et al. 2004; Dettinger 2005; Georgakakos et al. 2005; Kim 2005; Maurer and Duffy 2005). Several factors distinguish these studies, the most important being the different GCMs used, different downscaling methodology and the methods used to characterize uncertainty.

With respect to the choice of GCM output, it is interesting to note how the most prominent GCMs used in earlier studies, (the models of the Goddard Institute for Space Studies (GISS), and the Oregon State University (OSU)) were replaced by a different set of GCMs in later studies. The current GCMs prominently used are the UK's Hadley Center (HadCM2 and HadCM3), the NCAR (CCM3 and PCM) and the Canadian Centre for Climate Modeling and Analysis Canadian (CGCM1) models. According to experts in this field, the reason behind this evolution in the GCMs used for climate change studies is "computer resources" rather than a technical issue (D. Cayan, I. Fung and D Lettenmaier, personal communication).

One major limitation to using GCM output data is that the spatial and temporal resolution does not match the resolution needed for hydrologic models. For example, the spatial resolution of GCMs (about 200 km) is too coarse to resolve complex orography and sub-grid scale processes such as convective precipitation, which are of major relevance for mountainous terrains like the California Sierra Nevada Mountains (Wilby and Dettinger 2000). Several methods have been developed to "downscale" or transfer GCM output to surface variables at the river basin scale. The most common are: (a) delta/ratio (perturbation) methods; (b) stochastic/statistical downscaling and (c) dynamic downscaling or nested models (Wood et al. 1997). It's interesting to note how the evolution of this field of study in California has followed the evolution of the downscaling methodologies. Earlier studies did not consider downscaling GCM output but instead used raw GCM output. The delta/ratio method, that basically modifies the historic climate data time series (usually temperature and precipitation) by applying a delta (ratio) obtained by comparing the GCM output for both climate altered and controlled scenarios, then became the preferred method. Recently, studies have tended to use more complex downscaling methods (either statistical or dynamic). Improved downscaling methodologies have provided means of expanding the temporal aspect of the analysis. Earlier studies relied solely on monthly perturbations of historical time series, while later studies have explored the derivation of a 'new' (not based on historical data) time series of climate variables (either daily or monthly), including the analysis of changes in the frequency of extreme events (e.g. flood or droughts) and in interannual variability (e.g. Miller et al. 2003; Dettinger et al. 2004; Hayhoe et al. 2004; Stewart et al. 2004; Van Rheenen et al. 2004; Kim 2005; Maurer and Duffy 2005).

GCMs consistently project an increase of temperature for California of between 2.5 and 9°C by 2100 (Dettinger 2004, 2005). However, the GCMs exhibit greater variability in their precipitation projections (see Fig. 6) (Dettinger 2004, 2005). This inconsistency adds a high degree of uncertainty to making water resources management decisions. Recent studies have tried to tackle this problem using different approaches. Some have considered using a various (and differing) GCMs' outputs, under multiple greenhouse gas

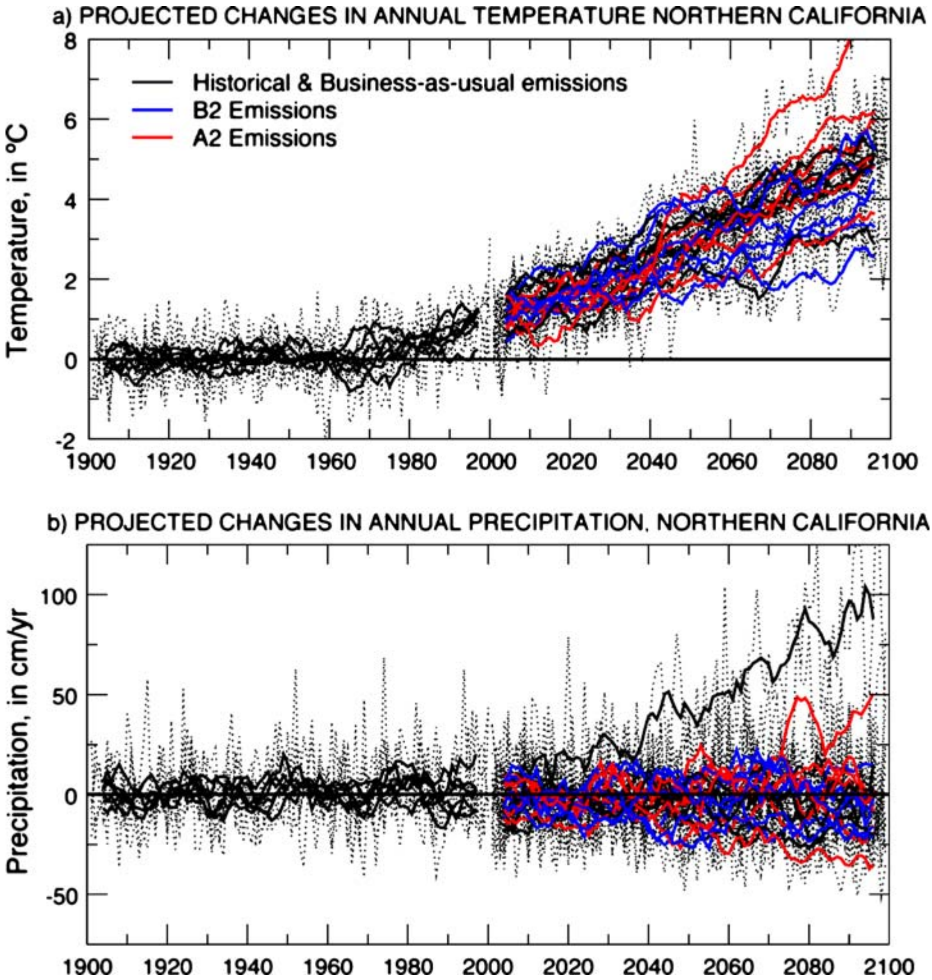

Fig. 6 Ensemble of historical and future temperature and precipitation projections from six coupled ocean-atmosphere general-circulation models (from Dettinger 2004, 2005)

emission scenarios (e.g. Miller et al. 2003; Hayhoe et al. 2004; Leung et al. 2004). With that approach they intend to bracket plausible changes, but they still do not explicitly account for the uncertainty in projections.

Dettinger (2004, 2005) focused explicitly on the uncertainty related to GCM projections in California. He developed "projection distribution functions" (pdfs) based on a resampling technique of 18 available projection scenarios (six models times three emission scenarios each). Another approach is that by Maurer and Duffy (2005), whose study of 10 GCMs allowed them to assess statistically significant projections across all GCMs. The explicit consideration of uncertainty, that is embedded in climate change projections, can be taken into account by assigning probabilities to the different scenarios. The authors believe that this is an important approach, as it will lead to better-informed decisions by the water resource community in California.

3.1.2 Prediction of changes in natural runoff

Perturbed series of climatic data (mainly temperature and precipitation) are used to drive hydrologic models to predict changes in streamflow runoff (see Fig. 5). There are two alternative approaches: using either statistically or physically based hydrologic models.

Statistical hydrologic models determine potential future runoff values according to the characteristics of the historical record. A statistical model used for climate change impact assessment might determine (through regression or observational analysis) the relation between streamflow runoff and climate variables such as temperature and precipitation. The first study of the impacts of climate change on Californian water resources used a statistical model that considered annual values of streamflow, temperature and precipitation (Revelle and Waggoner 1983). Most recent studies use monthly time scales to determine changes in the total annual volume as well as changes in the seasonal pattern (Cayan and Riddle 1993; Duel 1994; Risbey and Entekhabi 1996; Peterson et al. 2000; Stewart et al. 2004). One major limitation of these statistical approaches is that they do not incorporate the physical mechanisms and processes that determine basin response to climate forcing. Also, the statistical approach is limited to those levels of forcing that have historically occurred.

Physically-based hydrologic models have been the preferred tool to assess the impacts of climate change in the California hydrology. Some researchers developed their own models for their analysis (e.g. Gleick 1987; Tsuang and Dracup 1991; McCabe and Wolock 1999; Wolock and McCabe 1999). However, most studies used previously developed physically based models, including: the USGS Precipitation-Runoff Modeling System (PRMS); the U.S. National Weather Service River Forecast System Sacramento Soil Moisture Accounting and Anderson Snow Models (SAC-SMA); the Variable Infiltration Capacity (VIC) model; and the Water Evaluation and Planning System (WEAP) model. The spatial parameterization of these models ranges from distributed to lumped, and the spatial resolution ranges from regional (entire U.S. West Coast) down to subbasin.

Although some models include-state-of-the-art levels of complexity, there are important factors that have not yet been taken into account. The most important of these missing factors, in the author's opinion, is the dynamic interaction between vegetated land cover and climatic variables. Also, factors that affect watershed responses have been treated as static parameters in the models, rather than changing with time or with future climate.

3.2 Predicted climate change impacts on Californian natural streamflows: most significant results

Although the studies assessing the impacts of climate change on California hydrology have differed in their methodological approach, their results tend to agree in certain critical areas. Results consistently show that increasing temperatures associated with climate change will impact Californian hydrology by changing the seasonal streamflow pattern to an earlier (and shorter) spring snowmelt and an increase in winter runoff as a fraction of total annual runoff (see Fig. 7). These impacts on hydrology vary by basin, with the key parameter being the basin elevation relative to the 'freezing line' during snow accumulation and melt periods and the prediction of temperature increases. Most studies have shown, coinciding with the 'trend studies' presented in the first section, that basins located at medium altitudes (northern Sierra Nevada Mountains) will be affected more by climate change (see Lettenmaier et al. 1988; Lettenmaier and Gan 1990; Cayan and Riddle 1993; Duel 1994; Jeton et al. 1996; Wilby and Dettinger 2000; Kim 2001; Kim et al. 2002;

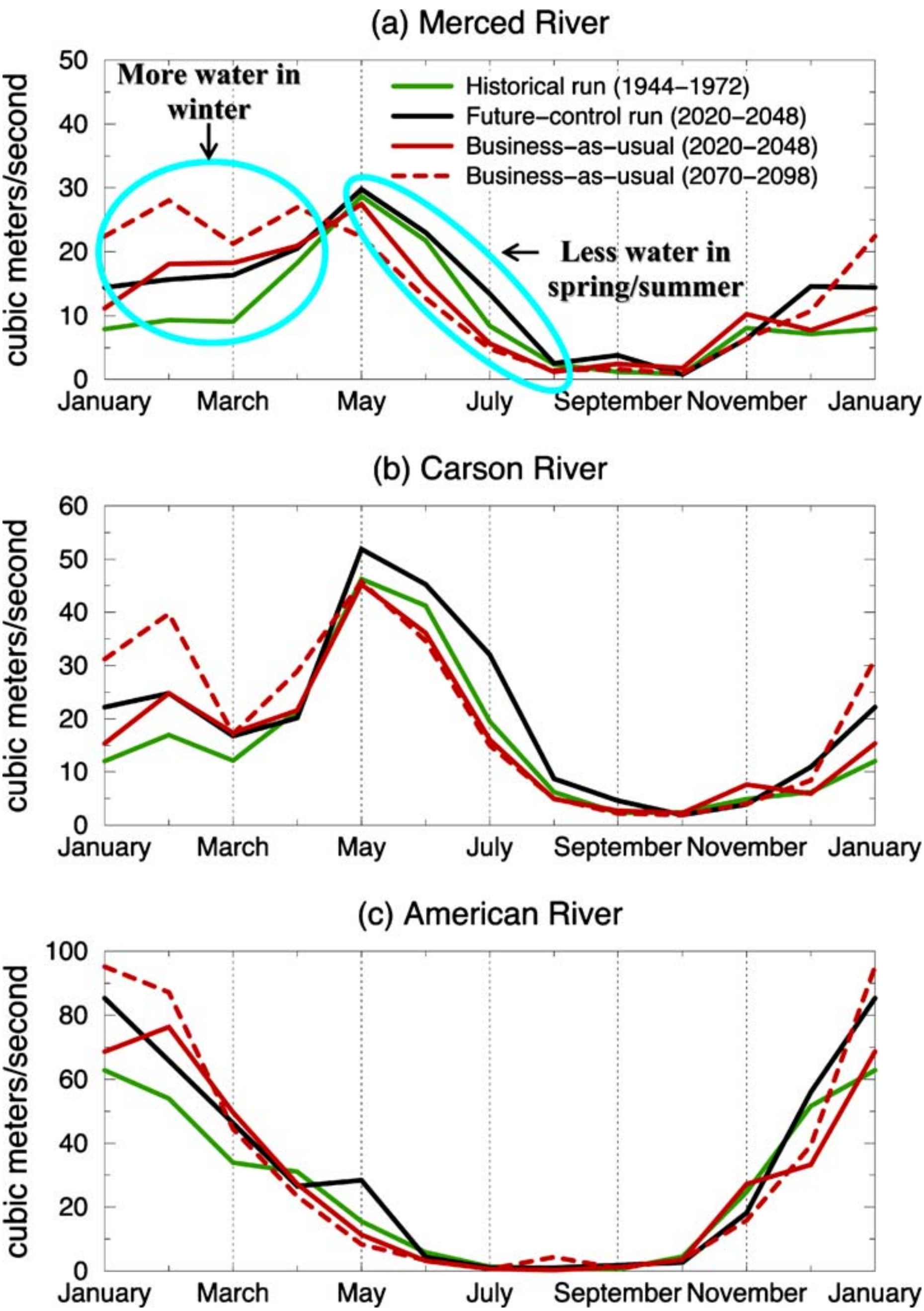

Fig. 7 Mean-monthly streamflow rates in the Merced (**a**), Carson (**b**), and American (**c**) Rivers, in responses to PCM-simulated climates during selected 29-year periods. Historical run is a PCM simulation with historical radiative forcings imposed, the business-as-usual run is a simulation with future business-as-usual increases in greenhouse gases, and the future-control run is a simulation with future greenhouse-gas concentrations held constant at 1995 levels (modified from Dettinger et al. 2004)

Knowles and Cayan 2002; Miller et al. 2003; Knowles and Cayan 2004; Leung et al. 2004; Kim 2005). However, later studies are showing just the opposite, i.e. higher impacts in higher elevation basins in southern Sierra Nevada Mountains (Dettinger et al. 2004; Hayhoe et al. 2004; Van Rheenen et al. 2004). Two factors help explaining this inconsistency: First, with regards to the "trend studies" it's important to note that the measured historic trend in temperature has shown increases of only 1–2°C for the last century. These are low compared to the temperature increases predicted by the GCMs which are 4–8°C. Secondly, most GCM's projections used in previous studies showed either high increases in winter precipitation (HadCM2) or just mild increases in temperature (around 2°C for PCM) but none has shown before combinations of high increases in temperature with decreases in precipitation. So a plausible explanation of this 'supposed' inconsistency is the following: historic temperature increases have not been high enough to perturb the 'temperature insensibility' of high elevation basins like those found in the southern Sierra Nevada Mountains. Also, results from previous studies have not been in the right direction to cause this perturbation, because they either masked temperature impacts with high increments in precipitation (e.g. HadCM2) or because they just didn't cross the temperature threshold to perturb the regime of high elevation basins (e.g. PCM). Later studies are showing that the combination of sufficiently high temperature and decreases in precipitation are enough to cause significant impacts in the hydrologic conditions in the southern Sierra Nevada Mountains with impacts larger than their northern Sierra Nevada counterpart basins.

Changes in total runoff volume depend on the precipitation prediction (scenario), which depends on the GCM chosen, as previously discussed. Assessments using GCMs that project wetter conditions (e.g. UK's HadCM2) tend to produce higher overall streamflow runoff as compared to "drier" GCMs (e.g. NCAR's PCM). An example of such diverging results is shown by Miller et al. (2003) (see Fig. 8). Other examples of such studies are: Gleick (1987), Lettenmaier et al. (1988), Lettenmaier and Gan (1990), Jeton et al. (1996), Dettinger (2004), Hayhoe et al. (2004) and Maurer and Duffy (2005). Improvements in the characterization of uncertainty related to climate impact assessment would improve the ability to use these diverging results in a manner useful for water resources management.

Table 2 summarizes the studies to date on the impacts of climate change on hydrology in California. We have sorted the studies presented in the table according to the different methodological approaches they have used.

4 Future predicted impacts on Californian water resources systems due to climate change

Most of the streamflow in California (especially that draining the Sierra Nevada) is regulated by large reservoirs. Significant changes in the timing of streamflow that feeds these reservoirs will alter their ability to serve their design functions under current operating rules: flood control, water supply for agricultural, urban and industrial uses, hydropower generation, environmental services, navigation and recreation. For example, an earlier and shorter snowmelt spring runoff could make it more difficult to refill reservoir flood space (determined by considering historical hydrologic conditions) during the late spring and early summer, thus reducing the amount of water supply that can be delivered (Roos 2003). The ultimate impact on California water resources and their associated functions will depend on the ability of the man-made infrastructure to cope with these changes. The

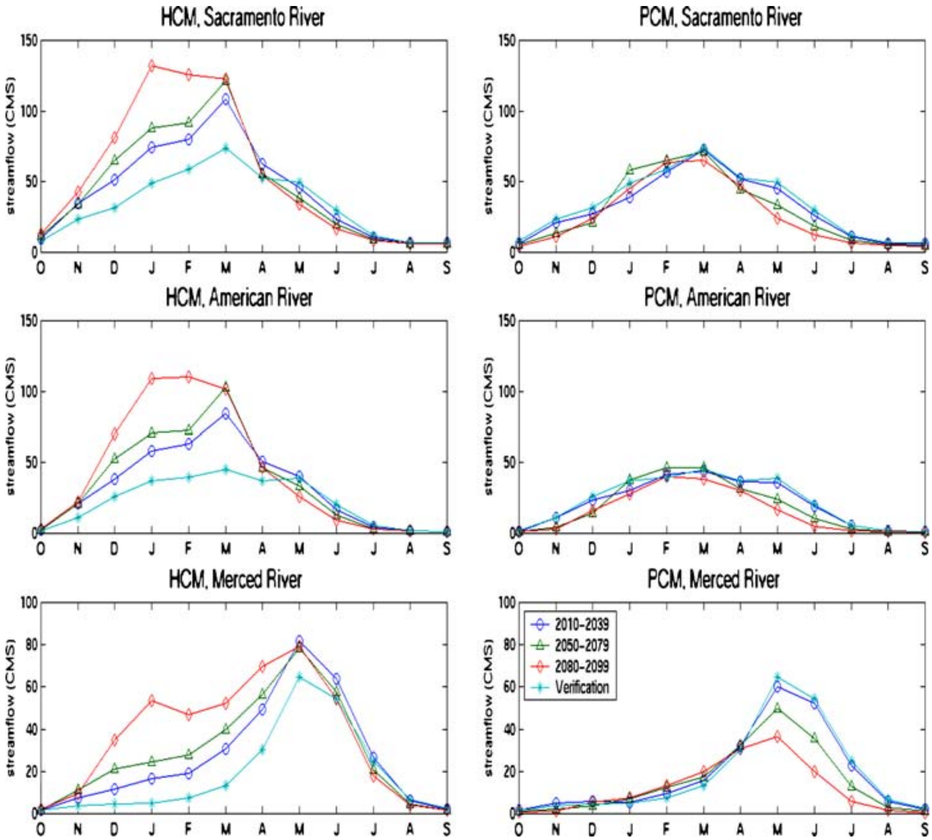

Fig. 8 Streamflow monthly climatologies based on the HadCM2 and the PCM (from Miller et al. 2003)

analysis of the performance of the California water system under hypothetical hydrologic scenarios such as climate change requires the aid of water resources systems models (also called reservoir system analysis models).

The performance of the California water system under climate change scenarios was first studied by Lettenmaier and Sheer (1991), and by Sandberg and Manza (1991). Both of these groups examined the implications of climate change scenarios on the performance of the State Water Project (SWP) and the Central Valley Project (CVP) using simulation models. Most of the later studies on the impact of climate change on Californian water resources have also relied on simulation models (Williams 1988; Dracup et al. 1993; Yao and Georgakakos 2001; Knowles and Cayan 2002; Van Rheenen et al. 2003; Huber-Lee et al. 2003; Brekke et al. 2004; Knowles and Cayan 2004; Quinn et al. 2004; Van Rheenen et al. 2004). An exception to this approach is the optimization model (CALVIN) developed by Lund et al. (2003). The models used in all of these studies also differ in terms of the accuracy of their representation of the system being model (e.g., inclusion of groundwater sources or accuracy of environmental regulation description). The results of these studies in terms of water deliveries and reservoir storage also reflect the climatic projections used to derive streamflow runoffs (see previous section). In this regard, predicted drier conditions reduce the ability of the system to perform at historical levels, if no changes are made in

Table 2 Summary of studies on the prediction of the impact of climate change impacts on hydrology in California

Study	Determining changes in climatic variables			Determining changes in climatic variables	
	Methodology	GCM(s) chosen	Downscaling method	Methodology	Model used (if applicable)
Revelle and Waggoner 1983	Hypothetic scenarios	NA	NA	*Regression*	NA
Gleick 1987	Hyp. Scen. + GCMs	3 GCMs: GFDL, GISS, NCAR CCM	No downscaling method applied	Hydrologic	Water budget model
Lettenmaier et al. 1988	GCMs	3 GCMs: GFDL, GISS, OSU	No downscaling method applied	Hydrologic	U.S. National Weather Service SAC-SMA and Anderson Snow Model
Lettenmaier and Gan 1990	GCMs	3 GCMs: GFDL, GISS, OSU	No downscaling method applied	Hydrologic	SAC-SMA
Tsuang and Dracup 1991	NA	NA	NA	Hydrologic	Energy based snowmelt model.
Cayan and Riddle 1993	NA	NA	NA	*Regression*	NA
Duell 1994	NA	NA	NA	*Regression*	NA
Jeton et al. 1996	Hyp. Scen. + GCMs	3 GCMs: GFDL, GISS, OSU	No downscaling method applied	Hydrologic	Precipitation-Runoff Modeling System (PRMS)
Risbey and Entekhabi 1996	NA	NA	NA	*Regression (Observational)*	NA
Leung and Ghan 1999	GCMs	CCM3	Dynamic	Hydrologic	Not clear which
Miller et al. 1999	GCMs	HadCM2	Dynamic	Hydrologic	TOPMODEL and Sacramento Model
McCabe and Wolock 1999	GCMs	CGCM1 and HadCM2	Interpolation using VEMAP	Hydrologic	Conceptual Snow model, no changes in runoff
Wolock and McCabe 1999	GCMs	CGCM1 and HadCM2	Interpolation using VEMAP	Hydrologic	Annual water balance model
Miller and Kim 2000	GCMs	HadCM2	Dynamic	Hydrologic	TOPMODEL and Sacramento Model
Hay et al. 2000	GCMs	HadCM2	Delta/ratio and Statistical	Hydrologic	PRMS

Table 2 (continued)

Study	Determining changes in climatic variables			Determining changes in climatic variables	
	Methodology	GCM(s) chosen	Downscaling method	Methodology	Model used (if applicable)
Peterson et al. 2000	NA	NA	NA	*Regression*	NA
Wilby and Dettinger 2000	GCMs	HadCM2	Statistical	Hydrologic	PRMS
Carpenter and Georgakakos 2001	GCMs	CGCM1	Statistical	Hydrologic	SAC-SMA
Kim 2001	GCMs	HadCM2	Dynamic	Hydrologic	Not clear which
Kim et al. 2002	GCMs	HadCM2	Dynamic	Hydrologic	Not clear which
Snyder et al. 2002	GCMs	CCM3	Dynamic	Hydrologic	Not clear which
Knowles and Cayan 2002	GCMs	PCM	Statistical	Hydrologic	SAC-SMA (modified)
Van Rheenen et al. 2003	GCMs	PCM	Statistical	Hydrologic	Variable Infiltration Capacity (VIC)
Huber-Lee et al. 2003	GCMs	2 GCMs: HadA2 and HadB2	Statistical	Hydrologic	WEAP
Miller et al. 2003	Hyp. Scen. + GCMs	2 GCMs: PCM and HadCM2	Statistical	Hydrologic	SAC-SMA
Dettinger 2004	GCMs	6 GCMs*3 Emission Scenarios = 18 projections	No downscaling method applied	Hydrologic	Sensitivity Analysis from Jeton et al (1996)
Dettinger et al. 2004	GCMs	PCM	Statistical	Hydrologic	PRMS
Van Rheenen et al. 2004	GCMs	PCM	Statistical	Hydrologic	VIC
Stewart et al. 2004	GCMs	PCM	Statistical	*Regression*	NA
Knowles and Cayan 2004	GCMs	PCM	Statistical	Hydrologic	SAC-SMA (modified)
Leung et al. 2004	GCMs	PCM	Dynamic	Hydrologic	Not clear which
Hayhoe et al. 2004	GCMs	2 GCMs: PCM and HadCM3	Statistical	Hydrologic	VIC
Maurer and Duffy 2005	GCMs	10 GCMs	Statistical	Hydrologic	VIC
Kim 2005	GCMs	HadCM2	Dynamic	Hydrologic	Not clear which
Dettinger 2005	GCMs	6 GCMs*3 Emission Scenarios = 18 projections	No downscaling method applied	Hydrologic	Sensitivity Analysis from Jeton et al (1996)
Georgakakos et al. 2005	GCMs	CGCM1	Statistical	Hydrologic	SAC-SMA

reservoir operating rules or other water management policies. On the other hand, predicted wetter conditions would tend to overcome changes in the seasonality of streamflows, producing an overall improvement of system performance. An example of these diverging results in is presented in Fig. 9.

Frederick and Schwarz (1999) have not followed the approach discussed in the previous paragraph but have estimated impacts to water resources without the aid of a water resources system model. The approach followed by Frederick and Schwarz (1999) which was part of the Water Sector report of the National Assessment Team for the U.S. Global Change Research Program (Gleick 2000) considered changes in annual streamflow upstream of reservoirs, and compared those with annual water demands to obtain water scarcity indices with associated economic costs. A major drawback of this procedure is that it does not account for changes in streamflow timing, which is a significant potential impact on California.

Most authors have focused on water storage and deliveries from reservoirs to assess the impacts of climate change on California water resource systems. However, it is worthwhile noting some studies that have also included other means of measuring impacts. For

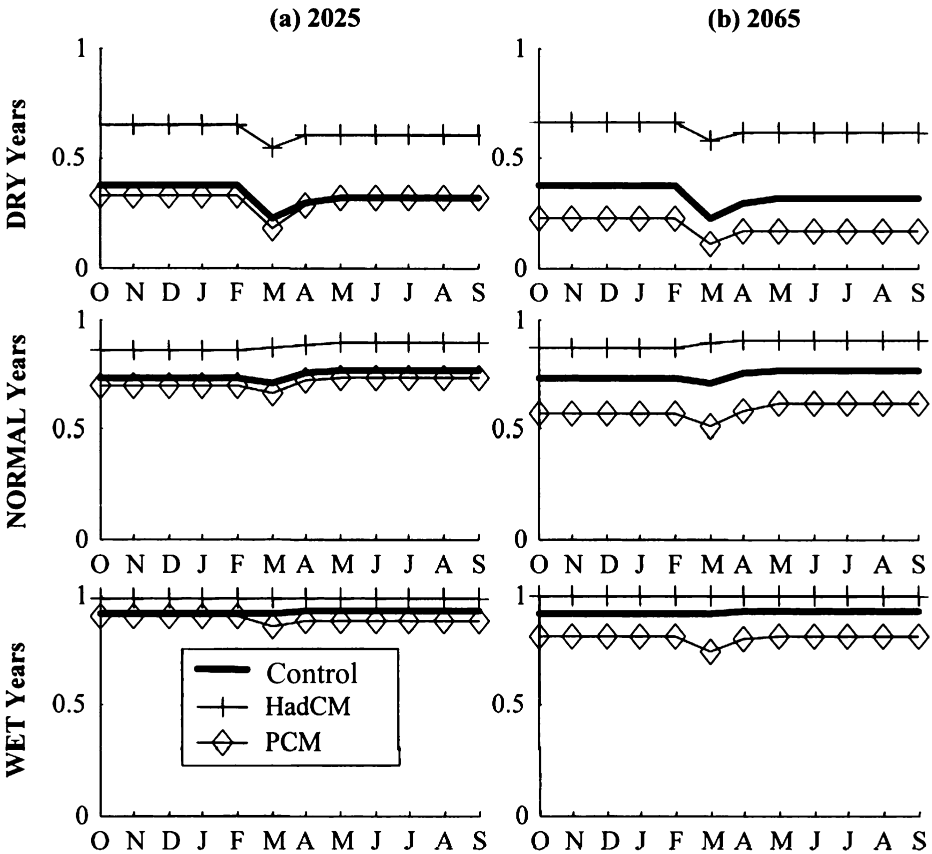

Fig. 9 Simulated monthly mean delivery levels (i.e. ratio of delivery to demand) for all CVP agricultural users South of the delta for DRY, NORMAL and WET years, under control and two GCMs scenarios: **a** 2025 and **b** 2065 (from Brekke et al. 2004)

example, Knowles and Cayan (2002, 2004) studied the impacts on San Francisco Bay salinity levels. Dracup et al. (1993) performed a series of studies on several water resources functions such as hydropower generation (for CVP/SWP system), agricultural economic costs and chinook salmon population.

The authors believe that there has been a dearth of studies related to climate change impacts on water resources systems in California in the following areas: (1) The impact on hydropower production in general and specifically in high altitude hydropower generation facilities; (2) The impact associated with changes in reliability (and therefore economic costs) among different water users (with different water rights and water sources) in the California system and; (3) How the different reservoir objectives tradeoffs (e.g. hydropower vs. water supply or flood control vs. water supply) could be altered under changes in seasonal patterns predicted by climate change assessments.

A further important step in the analysis of predicted impacts to water resource systems associated with climate change has been to devise changes in water resources management practices to cope with predicted changes in streamflows. This approach was pursued by Van Rheenen et al. (2004), who developed a series of mitigation strategies such as changing the

Table 3 Summary of studies on the impact of climate change on water resources (and associated functions) in California

Study	Model used	Model spirit	Impacts considered
Riebsame 1988	NA	NA	Policy Analysis. Flood and Drought reservoir operations
Williams 1988	PROSIM*	Simulation	San Francisco Bay Salinity
Lettenmaier and Sheer 1991	WRMI	Simulation	Water supply deliveries
Sandberg and Manza 1991	PROSIM	Simulation	Water supply deliveries
Dracup et al. 1993	PROSIM	Simulation	Water supply deliveries + agricultural sector + hydropower generation + Salmon population
Risbey 1998	NA	NA	Policy Analysis. Scenario comparison
Frederick and Schwarz 1999	NA	NA	Economic costs of annual changes in water supplies. No water resources model used.
Haddad and Merrit 2001	NA	NA	Policy Analysis
Yao and Georgakakos 2001	Decision Module	Simulation	Reservoir performance under different management and forecasting procedures
Van Rheenen et al. 2003	CVMod	Simulation	Reservoir water storage
Knowles and Cayan 2002	Historic releases	Simulation	Salinity levels in the Bay Delta
Huber-Lee et al. 2003	WEAP	Simulation	Economic Impacts related to scarcity costs + Hydropower + Envrionmental Constraints
Lund et al. 2003	CALVIN	Optimization	Economic Impacts related to scarcity costs + Hydropower + Envrionmental Constraints
Brekke et al. 2004	CalSim-II	Hybrid	Water supply deliveries and reservoir storage + delta salinity
Quinn et al. 2004	CalSim-II	Hybrid	Water supply deliveries and reservoir storage + delta salinity
Knowles and Cayan 2004	Historic releases	Simulation	Salinity levels in the Bay Delta
Van Rheenen et al. 2004	CVMod	Simulation	Reservoir releases and storage + environmental, hydropower, flood control targets

flood control rule curves of reservoir releases to lessen the impacts of climate change. They concluded that even with the most comprehensive approaches,

> achieving and maintaining status quo (control scenario climate) system performance in the future would be nearly impossible, given the altered climate (change) scenario hydrologies.

However, Yao and Georgakakos (2001) in research also prepared for the Water Sector report of the National Assessment Team for the U.S. Global Change Research Program (Gleick 2000) reached different conclusions. Yao and Georgakakos (2001) developed an integrated forecast-decision system to assess the sensitivity of reservoir performance to various forecast-management schemes under historical and future climate scenarios. Their assessments are based on various combinations of inflow forecasting models, decision rules, and climate scenarios. Their study demonstrated that

> (1) reliable inflow forecasts and adaptive decision systems can substantially benefit reservoir performance and (2) dynamic operational procedures can be effective climate change coping strategies.

The authors believe that although these two studies reflect important advances, however there are still some areas of work that should be addressed. These include studying potential adaptation opportunities using, for example, a conjunctive use management approach or optimization techniques (e.g. Stochastic Dynamic Programming) to determine whether current reservoir release policies should be modified.

Finally a group of studies (Riebsame 1988; Risbey 1998; Haddad and Merrit 2001) approached the impacts of climate change on California water resources not from a quantitative perspective but from a qualitative policy-oriented approach. Riebsame (1988) used an historic perspective to analyze the approaches taken by water managers in California to adjust to climate variability and how those could be used in a climate change scenario. Risbey (1998) performed a qualitative sensitivity analysis of the different adaptation policies that can be undertaken in the Sacramento basin considering the uncertainties embedded in climate and streamflow projections.

In Table 3 we present a summary of studies on the topic of predicting climate change impacts on water resources in California.

5 Conclusions

We have presented a review of studies in the field of climate change impacts on California hydrology and water resources systems. These studies date from 1983 and can be categorized in three major fields: (1) Studies of historical trends of streamflow and snowpack in order to determine if there is any evidence of climate change in the geophysical record; (2) Studies of potential future predicted effects of climate change on streamflow and; (3) Studies that use those predicted changes in natural runoff to determine their economic, ecologic, or institutional impacts.

In California we found more than 60 of these studies, with a majority focused on predicting the hydrologic impacts of climate change. In Fig. 10 we show a distribution of all these studies according to the classifications followed in this paper. The number and breadth of studies permits a review of the different methodological issues.

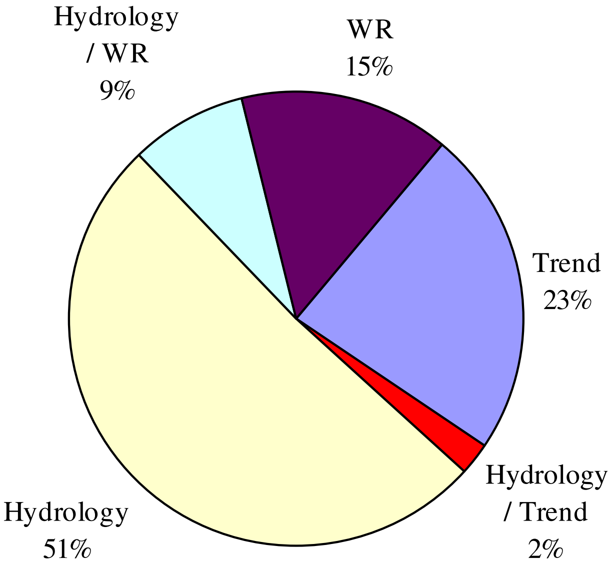

Fig. 10 1983–2005 studies on climate change impacts on hydrology and water resources in California, separated by type of study. Nomenclature: *Trend*: studies on the historic record; *Hydrology*: on the potential future impacts of climate change on hydrology and; *WR*: on the impacts to water resources systems. Some studies belong to two categories (i.e. Hydrology/WR and Hydrology/Trend)

Major conclusions that can be derived from these studies are the following:

- In the last few decades there has been a trend towards an earlier timing of streamflow, i.e. earlier spring pulse onset and earlier center of mass of the hydrograph, in the California Sierra Nevada Mountains. These trends correlate well with an increasing trend in temperature levels. Whether these trends are due to climate change or climate variability is a subject of continuing debate.
- Several different approaches have been used to predict future streamflows related to climate change. These approaches use either global climate models (GCMs) or hypothetical scenarios to forecast changes in climatic variables. These changes of climatic variables have been used to assess changes in natural runoff using different types of hydrologic models (e.g. statistical or physically based). Results derived from these studies consistently show a change in timing in streamflow runoff due to a consistent increase in temperature. However, changes in the total volume of runoff are still not clear, mainly due to uncertainties in future precipitation projections. The methodology used to assess changes in hydrology has improved both in terms of downscaling outputs from GCMs and in the characterization of uncertainty. Further improvements, such as the refinement of the spatial and temporal resolution of the models, will enhance the ability of policy makers to use this information in decisions-making.
- The forecasted hydrologic conditions associated with climate change will affect the performance of the water infrastructure in California. Some research has addressed these issues using water resource system models (either optimization or simulation) to redistribute the hydrologic changes throughout the California water system. We believe that there is a potential for significant research on the impacts of climate change on California water resource systems.

6 Caveat

A reduced version of this paper was previously presented at the Environmental & Water Resources Institute Congress, American Society of Civil Engineers, Anchorage, AK, May 15–19. This reduced version of the paper was also published in the proceedings of the conference (Dracup and Vicuna 2005).

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