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ESTIMATED IMPACTS OF CLIMATE WARMING ON CALIFORNIA WATER AVAILABILITY UNDER TWELVE FUTURE-CLIMATE SCENARIOS

PIER PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Economic Analyses of Climate Change Impacts and Adaptation and GHG Mitigation contract, number 500-02-004, work authorization MR-006, by the University of California, Davis.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Spatially disaggregated estimates of over 131 streamflow, groundwater, and reservoir evaporation monthly time series in California have been created for 12 different climate warming scenarios for a 72-year period. Such disaggregated hydrologic estimates of multiple hydrologic cycle components are important for impact and adaptation studies of California's water system. A statewide trend of increased winter and spring runoff and decreased summer runoff is identified. Without operations modeling, approximate changes in water availability are estimated for each scenario. Even most scenarios with increased precipitation result in less available water because of the current storage systems' inability to catch increased winter streamflow in compensation for reduced summer runoff. The water availability changes are then compared with estimated changes in urban and agricultural water uses in California between now and 2100. The methods used in this study are relatively simple, but the results are qualitatively consistent with other studies focusing on the hydrologies of single basins or surface water along.

KEY TERMS: climate change; scenario; precipitation; temperature; runoff; California

1.0 Introduction

Much of California has cool, wet winters and warm, dry summers, and a resulting water supply that is poorly distributed in time and space. On average, 75% of annual precipitation of 584 millimeters (mm) (23 inches) occurs between November and March, whereas urban and agricultural demands are highest during the summer and lowest during the winter. Spatially, more than 70% of California's 88 billion cubic meters (bcm) average annual runoff occurs in the northern part of the state. However, about 75% of urban and agricultural water *use* is south of Sacramento (CDWR 1998).

In terms of runoff and temperature, great consistency and variability are evident in California's climate during the last few thousand years (Haston et al. 1997; Meko et al. 2001; Stine 1994). Perhaps the most-debated form of climate change for California is climate warming, usually attributed to increasing concentrations of carbon dioxide and other gases from industrialization (Snyder et al. 2002; Wigley et al. 2001). The Intergovernmental Panel on Climate Change Third Assessment Report (IPCC 2001) summarizes projections for future climate and the consequences on many sectors including water resources for which more serious floods and droughts are expected to occur. There have been many studies of the potential effects of climate warming on streamflows in California (Cayan et al. 1993; Gleick et al. 1999; Lettenmaier et al. 1990; Lettenmaier et al. 1991; Miller et al. 2003; Vanrheenen et al. 2004). The degree of change is usually estimated based on the results of general circulation models (GCMs). These studies all indicate that climate warming would change the seasonal distribution of runoff, with a greater proportion of runoff occurring during the wet winter months, and less snowmelt runoff during spring. Spatial variations of hydrologic changes in California were also identified (Synder et al. 2002). There is some reason to think that seasonal shifts in runoff patterns from spring to winter are already occurring in California (Roos, 1991; Aguado et al. 1992; Dettinger and Cayan 1995; Knowles and Cayan 2002).

However, almost all existing studies of California's hydrologic responses to climate change focus exclusively on streamflow changes, either macroscopically or for a few selected streams (Vanrheenen et al. 2004; Brekke et al. 2004; Dettinger et al. 2004; Miller et al. 2003; Carpenter et al. 2001; Cayan et al. 1993; Lettenmaier et al. 1990; Lettenmaier et al. 1991). Such studies are not of sufficient breadth or detail for understanding how management of California's vast integrated surface and groundwater system might adapt to climate change. Water management analysis across California's complex highly integrated and inter-tied (inter-connected) system requires a more integrated and complete hydrologic representation (Draper et al. 2003; Lund et al. 2003).

To this end, spatially disaggregated estimates of streamflow, groundwater inflow, and reservoir evaporation time series for 131 inflow and evaporation locations in California have been created for 12 different climate warming scenarios over a 72-year period (Zhu et al. 2003). Each hydrologic time series represents a permutation of the 72-year (October 1921 through September 1993) historically based monthly time series used in an economic-engineering optimization model of California's inter-tied water system, CALVIN (Draper et al. 2003; Lund et al. 2003). The underlying 72-year historical

monthly time series serves to represents hydrologic variability within each California climate scenario. While the approaches used here are simple, they allow for the more detailed spatial representation of several aspects of the hydrological cycle needed for more realistic studies of climate change impact and adaptation.

2.0 Twelve Climate Warming Scenarios

In this study, spatially distributed climate warming impacts on hydrology are derived from modeled climate warming streamflow estimates for six index basins in California ("watersheds" in Figure 1) and distributed statewide temperature shifts and precipitation change ratios that Miller et al. (2003) generated for 12 climate scenarios. The index basins spread across the state, from the northernmost area to the east-central region of the state, providing broad information for spatial estimates of the overall response of California's water supply and the potential range of hydrologic impacts. Besides the six index basins, Figure 1 also shows the CALVIN model's inflow, local runoff, and reservoir locations—as well as 28 groundwater basin centroids.

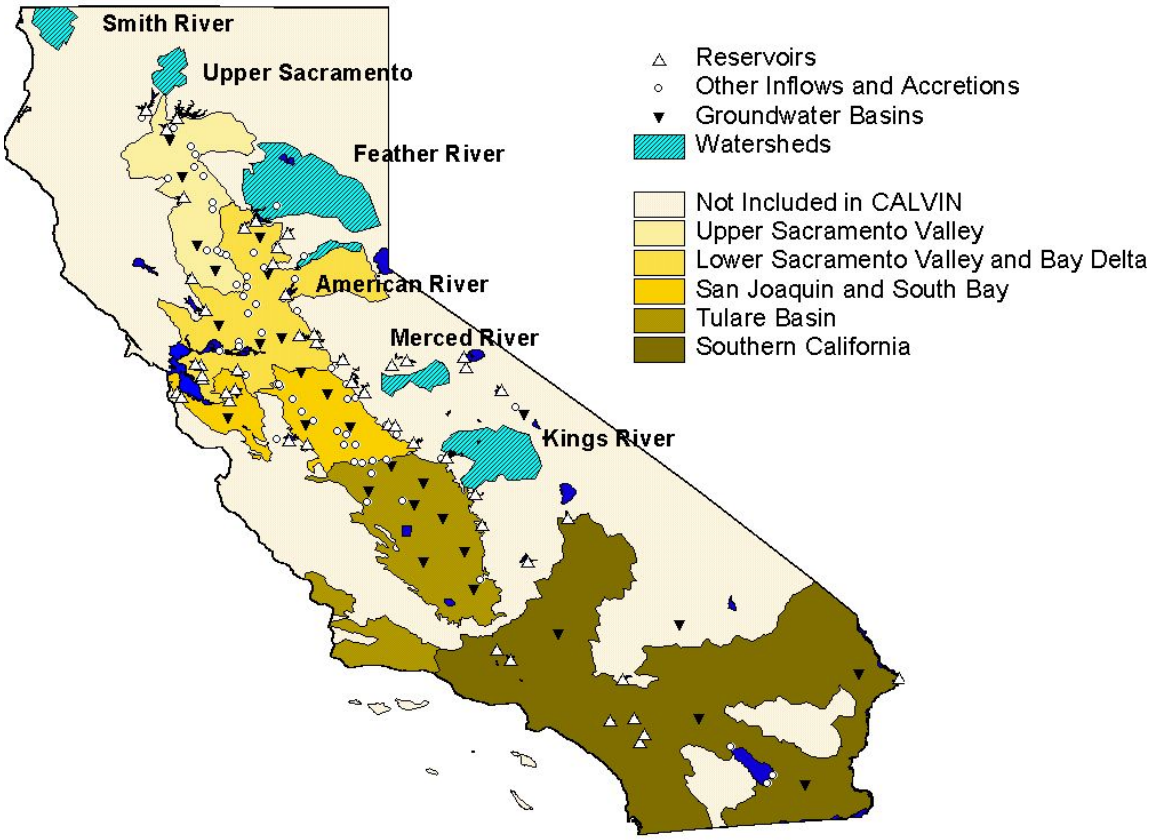

Figure 1. Index basins and hydrologic components of CALVIN

In Miller et al. (2003), two GCM projections for three projected future periods (2010 to 2039, 2050 to 2079, and 2080 to 2099) were used, based on 1% per year increase of carbon

dioxide (CO_2) relative to late twentieth century CO_2 conditions. These future periods are labeled by their mid-points: 2025, 2065, and 2090. The two GCM projections were statistically downscaled and interpolated to a 10 kilometer (km) (6 mile) resolution, representing the relatively warm/wet (the Hadley Centre's HadCM2 run 1) and warm/dry (NCAR PCM run B06.06) scenarios for California, compared to the GCM projections in the Third Assessment Report by IPCC (2001). Limiting this study to two GCM scenarios was based on the recommendations of the California Climate Change Panel and other constraints (Miller et al. 2003).

Because of the uncertainty inherent in projecting future climate, Miller et al. (2003) applied an additional set of specified incremental temperature (shifts) and precipitation (ratios) changes to fully bracket the possibility of changes, though such uniform parametric changes are admittedly idealized. Streamflow simulation of GCM scenarios and uniform change scenarios were accomplished using the National Weather Service River Forecast System (NWSRFS) Sacramento Soil Moisture Accounting (SAC-SMA) Model and Anderson Snow Model, partly because of its dependence on only precipitation and temperature.

The 12 climate warming scenarios are described below. The average temperature increases (in ºC) and precipitation changes reported for the six GCM-based scenarios are the spatially averaged changes.

1. 1.5ºC (2.7ºF) temperature increase and 0% precipitation increase (1.5 T; 0% P)
2. 1.5ºC (2.7ºF) temperature increase and 9% precipitation increase (1.5 T; 9% P)
3. 3.0ºC (5.4ºF) temperature increase and 0% precipitation increase (3.0 T; 0% P)
4. 3.0ºC (5.4ºF) temperature increase and 18% precipitation increase (3.0 T; 18% P)
5. 5.0ºC (5.4ºF) temperature increase and 0% precipitation increase (5.0 T; 0% P)
6. 5.0ºC (5.4ºF) temperature increase and 30% precipitation increase (5.0 T; 30% P)
7. HadCM2025 (1.4 T; 26% P)
8. HadCM2065 (2.4 T; 32% P)
9. HadCM2090 (3.3 T ; 62% P)
10. PCM2025 (0.4 T ; -2% P)
11. PCM2065 (1.5 T; -12% P)
12. PCM2090 (2.3 T; -26% P)

For all 12 scenarios, a larger proportion of the annual streamflow volume occurs in winter months because fewer freezing days result in less storage of water as snowpack compared to the historical climate. The hydrologic response varies for each scenario and the resulting hydrologic data sets provide bounds to the range of likely changes in streamflow, snowmelt, snow water equivalent, and the magnitude of annual high flow days.

3.0 Methods

Hydrologic components considered in this study include rim inflows, groundwater, local runoff, and reservoir evaporation. Flux time series for each component are constructed under climate warming scenarios with the following approaches.

3.1. Rim Inflows

Those major inflows into the Central Valley from the surrounding mountains are commonly called *rim inflows.* For each scenario, climate change impacts on 37 rim inflows were estimated with hydrologic response ratios (simulated monthly flows under a climate change scenario divided by corresponding simulated historical flows) developed by Miller et al. (2003) for the six index basins.

The nearest index basin is often not the best choice for mapping climate change impacts to a CALVIN rim inflow basin due to elevation differences (which are critical to snowpack formation and its role in California's hydrology) and differences in geographic complexity, including such factors as basin size, location, and storm characteristics patterns. A systematic approach was used to identify the appropriate index basins for each rim inflow basin through examining the correlation and temporal distribution between index basin flows and CALVIN rim inflows. First, monthly and annual correlation coefficients between historical runoff of the rim inflow from 1963 to 1993 and simulated historical runoff of each of the six index basins for the same period were calculated. The index basin that has the best annual correlation with the rim inflow was chosen as the best index basin for mapping, if most of its monthly correlation coefficients (e.g., eight months out of twelve) with the rim inflow also were the largest among those of the six index basins. Another method was applied to the remaining rim inflows to find appropriate index basins. It calculated summed square errors (SSE) of streamflow monthly percentages separately in the wet and dry seasons (October to March and April to September, respectively) between each rim inflow and each index basin. The best index basin (when wet and dry seasons mapped to the same index basin) or index basins (when wet and dry seasons use different index basins) were determined by choosing the index basin with the least SSE. This method partitions a water year into a wet season and a dry season to facilitate finding the best fit for snowmelt-dominant runoff and rainfall-dominant runoff regimes. Thus, the best matched index basins for wet and dry seasons are obtained for each of 37 rim inflows, resulting in a 37(rim inflow)×2(season) mapping matrix. This mapping matrix provides index information to apply hydrologic response ratios to each rim inflow. For example, the wet season monthly hydrologic response ratios of the Kings River index basin and the dry season monthly response ratios of the Merced River index basin under the "HadCM2025" scenario were applied to the "present climate" monthly time series of the Kaweah River streamflows from 1921 to 1993 to generate corresponding "HadCM2025" streamflows. This approach extends a similarly simple approach used by Brekke et al. (2004).

To compare simulated climate change impacts on index basin streamflows and constructed climate change rim inflows, the percent changes (from historical) of annual and seasonal mean flows due to climate change were calculated and compared for all index basins and rim inflows for each of the 12 climate change scenarios. To assure that

climate change impacts on index basins are well mapped to corresponding rim inflows under the same climate change scenario, the percent changes of each rim inflow should be similar to those of its index basins. Where constructed rim inflows did not meet this criterion, two measures were applied to improve fits: (1) Watershed conditions were further examined and their historical streamflow patterns were visually compared with those of the index basins; and (2) One-month lags in the hydrologic response ratios of some index basins were used to represent snowmelt timing changes on the east side of the Sierra. Of the 37 rim inflows, seven are mapped by examining temporal correlation (the first method), 18 are mapped by finding the least SSE, and 12 are identified by detailed examination and use of lags.

3.2. Groundwater and Local Runoff

To estimate climate change impacts on groundwater inflows and local runoff, precipitation changes were partitioned into local runoff and deep percolation portions for each groundwater sub-basin. These changes were then added to corresponding historical groundwater and local runoff time series. The unsaturated layer water balance and changes in stream-aquifer exchanges have not been considered.

A cubic regression equation was employed to represent the nonlinear historical relationship between monthly deep percolation and precipitation volumes for each groundwater sub-basin (Zhu et al. 2003). These empirical equations were established based on the Central Valley Ground and Surface Water Model (CVGSM) simulated data over the 1922–1990 period (USBR 1997). Deep percolation changes were then estimated for each groundwater sub-basin using its empirical equation based on precipitation changes for each climate change scenario. A cubic form was chosen because it fit the empirical data well for most groundwater basins, and had peak plateaus which can conceptually represent infiltration capacities. For the six parametric scenarios, the specified spatially and temporally uniform precipitation changes were applied for each month. For the six GCM scenarios, spatially and temporally varied monthly precipitation change ratios were available for each groundwater sub-basin.

Natural groundwater inflows or recharge, excluding recharge from operational deliveries to agricultural and urban demand areas, for each groundwater sub-basin in the Central Valley from CVGSM can be represented as

$$GW = DP + SA + BF + SS + LS + AR \tag{1}$$

where DP is deep percolation of precipitation, SA denotes gain from streams, BF represents gain from boundary flows (from outside the CVGSM modeled area), SS is gain in the sub-basin from subsurface flows across basin boundaries, LS denotes seepage from lake beds and bedrock in the sub-basin, and AR is seepage from canals and artificial recharge. Assuming other components of groundwater inflow are unchanged, changes in groundwater inflow are equivalent to changes in deep percolation from changes in rainfall over each groundwater sub-basin, that is

$$GW^P = GW + \Delta DP \tag{2}$$

where GW^P represents perturbed groundwater inflow for the groundwater sub-basin, and ΔDP is change in deep percolation.

To connect groundwater inflow with local runoff, each groundwater sub-basin is associated with a local accretion area that coincides with the groundwater sub-basin. Local runoff associated with a groundwater sub-basin can be represented as

$$LR = R + AG \tag{3}$$

where LR represents net local runoff, R denotes direct runoff, and AG is gain from the aquifer. Incremental local runoff over a groundwater sub-basin equals incremental precipitation minus incremental deep percolation, so that

$$LR^P = LR + \Delta P - \Delta DP \tag{4}$$

where LR^P is climate change perturbed local runoff and ΔP is increased precipitation volume. This equation assumes a negligible change in evaporation from changed precipitation, which is probably not a major error in most wet months.

3.3. Reservoir Evaporation

Changes in evaporation rate and total evaporation for each reservoir, assuming similar operations, were estimated for each climate scenario. A linear form was employed to regress historical monthly average net evaporation rate against historical monthly average air temperature and precipitation at each surface reservoir (Zhu et al. 2003). In the parametric climate scenarios (1 to 6), the temperature shifts and precipitation change ratios are uniform across months and locations. The GCM scenarios have average temperature and precipitation shifts that vary by month. The monthly incremental net evaporation rate at each reservoir was computed from monthly temperature and precipitation changes using the regression equation and then added to the historical monthly net evaporation rate time series for that reservoir. Next, the monthly net evaporation quantity, based on current storage operations, was obtained from the perturbed net evaporation rate using simulated historical reservoir monthly surface areas.

4.0 Results

4.1. Rim Inflows

There are 37 major inflows into the Central Valley. Historically, these rim inflows average 34.8 bcm/yr, accounting for 72% of all inflows into California's inter-tied water system. Table 1 shows total quantities and changes for rim inflows under the 12 climate change scenarios. Considerable range in rim inflow changes is presented. Total annual rim inflows could be 76.5% more than historical under the wettest scenario HadCM2090, and 25.5% less under the driest scenario PCM2090. Except for the three PCM scenarios, inflows increase in the wet season. In all but the HadCM2 scenarios, dry season inflows decrease. Even in HadCM2 scenarios, winter inflows increase much more significantly than in summer, resulting in an overall shift in annual runoff from the dry to the wet season in all scenarios except PCM2025.

Table 1. Overall Rim Inflow Quantities and Changes

Climate Scenario	Annual		October–March		April–September	
	Quantity (bcm)	Change (%)	Quantity (bcm)	Change (%)	Quantity (bcm)	Change (%)
Historical (1921–1993)	34.8	0	17.5	0	17.3	0
1. 1.5 T 0% P	35.3	1	20.3	16	15.0	-13
2. 1.5 T 9% P	40.0	15	23.1	32	16.9	-3
3. 3.0 T 0% P	35.2	1	22.4	28	12.7	-27
4. 3.0 T 18% P	44.7	28	28.8	64	15.8	-9
5. 5.0 T 0% P	34.5	-1	24.0	37	10.5	-40
6. 5.0 T 30% P	50.1	44	35.7	104	14.4	-17
7. HadCM2025 (1.4 T; 26% P)	47.5	36	27.2	55	20.4	18
8. HadCM2065 (2.4 T; 32% P)	51.0	46	31.9	82	19.1	10
9. HadCM2090 (3.3 T; 62% P)	61.5	77	41.1	134	20.5	18
10. PCM2025 (0.4 T; -2% P)	32.7	-6	16.3	-7	16.4	-6
11. PCM2065 (1.5 T; -12% P)	30.1	-14	16.9	-4	13.3	-24
12. PCM2090 (2.3 T; -26% P)	26.0	-26	15.0	-14	10.9	-37

Monthly mean total rim inflows for the 12 climate scenarios and historical inflows are plotted in Figure 2. It shows all the climate change scenarios would significantly shift the peak runoff from catchments where the annual hydrograph is currently dominated by spring snowmelt. Much more runoff would occur in winter and less in spring and summer. Therefore, reservoirs would have to maintain more empty space to maintain current levels of flood protection from increased winter storm runoff. This empty space would then be less likely to refill at the end of the flooding season, because of reductions in snowmelt after the storm season's end.

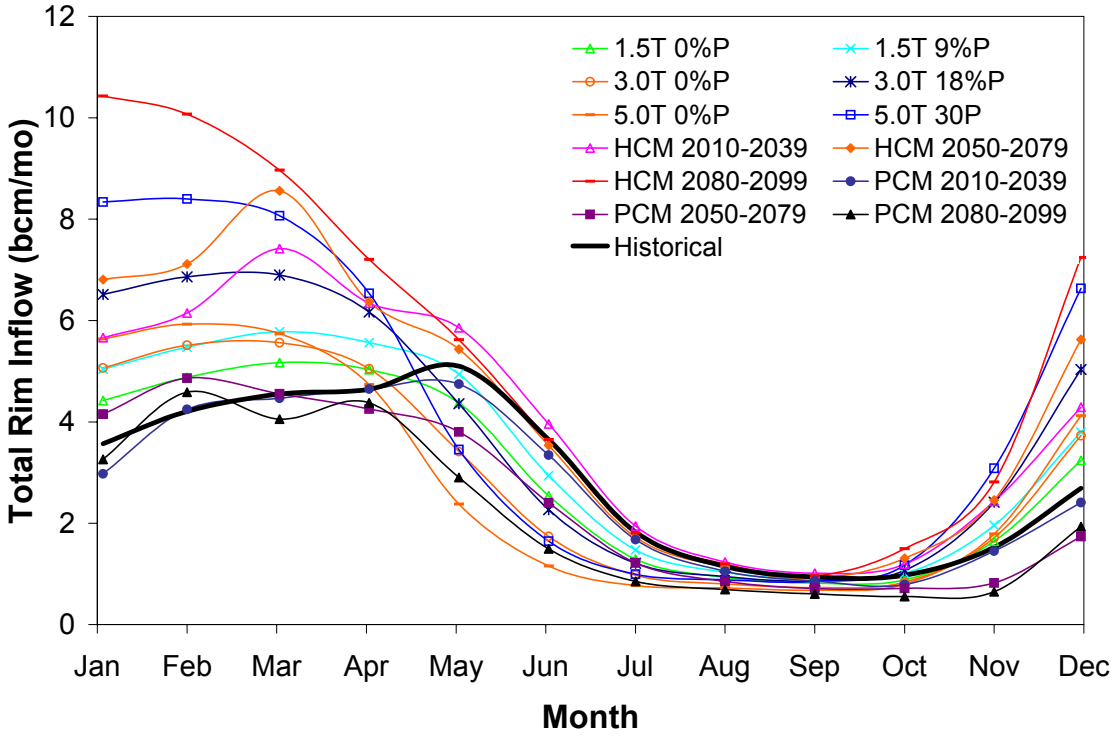

Figure 2. Mean monthly total rim inflow for 12 climate change scenarios and historical record

Regional analyses show rim inflows in the south increase relatively more than in the north with the extreme warm and wet climate HadCM2090. With the dry PCM2090 scenario, rim inflows decrease in all regions. Seasonally, wet season rim inflows increase for all the regions and scenarios, except the PCMs. Dry season rim inflows decrease for all regions and scenarios, except HadCM2090. For most cases, rim inflows in the north decrease relatively more than in the south during dry season. These regional conclusions should be tempered by understanding that mapping inflows to index basins tended to be poorer further south, where there were fewer index basins.

Figure 2 demonstrates the monthly average of 72 year perturbed rim inflows for the 12 climate change scenarios presents a range of hydrological responses to climate change in California. Essentially, as statistical interpolations and extrapolations of the changes projected for the six index basins, the perturbed rim inflows present a set of possibilities under different climate change scenarios. However, for a few rivers, particularly in southern parts of California, their annual and seasonal mean flow changes deviate from changes of their corresponding index basins under the same climate change scenarios. A few problematic rim inflows revealed during verification of the mapping process account for a small portion (< 15%) of the total rim inflows. While small, these problems indicate that climate change hydrologic impact simulations of more southern index basins in the south, along the coast, and in the Central Valley floor, would be useful. In addition, the SAC-SMA results also appear to have some problems representing

increased evapotranspiration with increased temperature and do not include vegetation changes which could induce additional evapotranspiration effects of climate change.

4.2. Groundwater and Local Runoff

The CALVIN model has 28 groundwater inflows and 35 local runoff inflows (Figure 1). Due to limited data, the seven groundwater sub-basins located outside the Central Valley are not studied although these tend to have relatively small natural inflows. The 21 groundwater sub-basins and 21 corresponding nodes of local runoff in the Central Valley have been perturbed for climate warming. Total groundwater inflow and local runoff account for 8.4 and 5.5 bcm/yr, respectively, of all inflows into California's inter-tied water system, representing about 17% and 11%, respectively, of all inflows. Deep percolation of rainfall accounts for about 2.1 bcm/yr of the total 8.4 bcm/yr of average groundwater inflow in the Central Valley. Under the historical climate, this volume represents only about 12% of precipitation falling over groundwater sub-basins in the Central Valley. Figure 3 shows quantity and changes of average annual groundwater inflows over the modeled sub-basins, and average annual changes in local runoff.

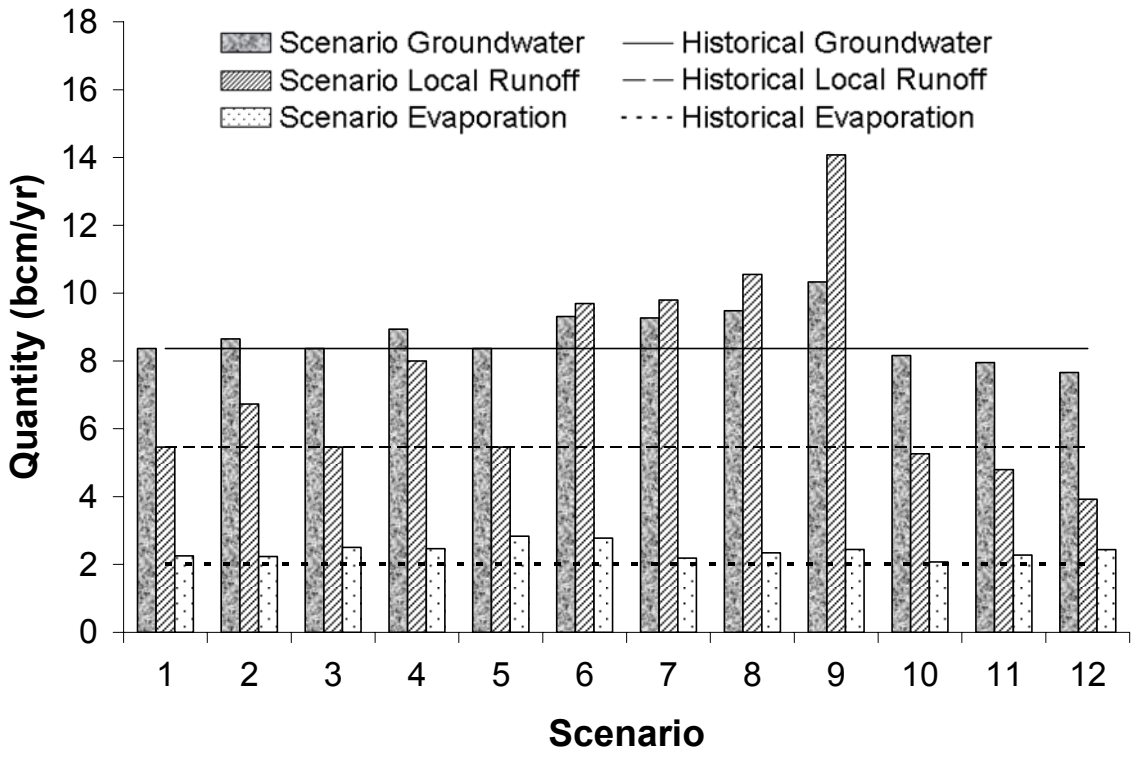

Figure 3. Average annual quantities of groundwater inflow, local runoff and surface reservoir evaporation

For all the three GCM periods, groundwater inflows and local runoff increase with HadCM2 scenarios and decrease with PCM scenarios. These trends continue over time. Most increased precipitation contributes to direct local runoff because infiltration capacity limits deep percolation. On average, local runoff in the wet season accounts for 80% of annual local runoff. Winter season groundwater inflow accounts for 53% of annual groundwater inflow. The proportions of winter season local runoff and groundwater inflow increase with more-precipitation scenarios (parametric changes and HadCM2) and decrease with less-precipitation scenarios (PCM).

4.3. Reservoir Evaporation

The CALVIN model has 47 surface reservoirs for which evaporation is calculated. Historically, over the 72-year hydrology used in CALVIN, 2.0 bcm/yr of water is lost from these reservoirs as net evaporation under current reservoir operations, which represents about 4% of all inflows.

The regression equations of most of the 47 reservoirs have high significance levels, with net evaporation rates being more sensitive to temperature than precipitation. Figure 3 also shows the surface reservoir evaporation results for the 12 scenarios, with relative increases between 3.6% and 41.3%.

4.4. Statewide Annual and Seasonal Inflows

Total water quantity available to California's inter-tied system is the sum of rim inflows, local runoff, and groundwater inflows, minus evaporation losses. Among these components, rim inflows account for most of the overall water quantity. Groundwater and local runoff also contribute significantly to overall water quantity.

In general, statewide results (Table 2 and Figure 4) show that climate warming would result in significant shifts in the peak season of water quantity. Snowmelt would come much earlier than historically. Relatively more annual runoff would occur in the wet season and less in the dry season. The three wet and warm HadCM2 scenarios indicate that future decades might experience much more water, and water quantity might increase over time. However, the system will likely not be able to capture all this water. The drier PCM scenarios indicate less water will be available and conditions will worsen with time. Compared with the historical average, drought years (1928–1934, 1976–1977, and 1987–1992) are expected to experience serious water decreases under the climate warming scenarios, though the HadCM2090 scenario shows only moderate reductions.

Table 2. Overall Water Quantities and Changes

Climate scenario	Annual		October–March		April–September	
	Quantity (bcm)	Change (%)	Quantity (bcm)	Change (%)	Quantity (bcm)	Change (%)
Historical (1921–1993)	46.7	0	25.9	0	20.8	0
1. 1.5 T 0% P	46.8	0	28.5	10	18.3	-12
2. 1.5 T 9% P	53.1	14	32.6	26	20.5	-2
3. 3.0 T 0% P	46.5	0	30.6	18	15.9	-23
4. 3.0 T 18% P	59.1	27	39.5	53	19.6	-6
5. 5.0 T 0% P	45.5	-3	32.0	24	13.5	-35
6. 5.0 T 30% P	66.3	42	48.0	86	18.3	-12
7. HadCM2025 (1.4 T; 26% P)	64.4	38	39.2	52	25.2	21
8. HadCM2065 (2.4 T; 32% P)	68.7	47	45.4	76	23.3	12
9. HadCM2090 (3.3 T; 62% P)	83.5	79	58.7	127	24.8	19
10. PCM2025 (0.4 T; -2% P)	44.1	-6	24.1	-7	20.0	-4
11. PCM2065 (1.5 T; -12% P)	40.6	-13	24.2	-7	16.4	-21
12. PCM2090 (2.3 T; -26% P)	35.1	-25	21.1	-19	14.0	-33

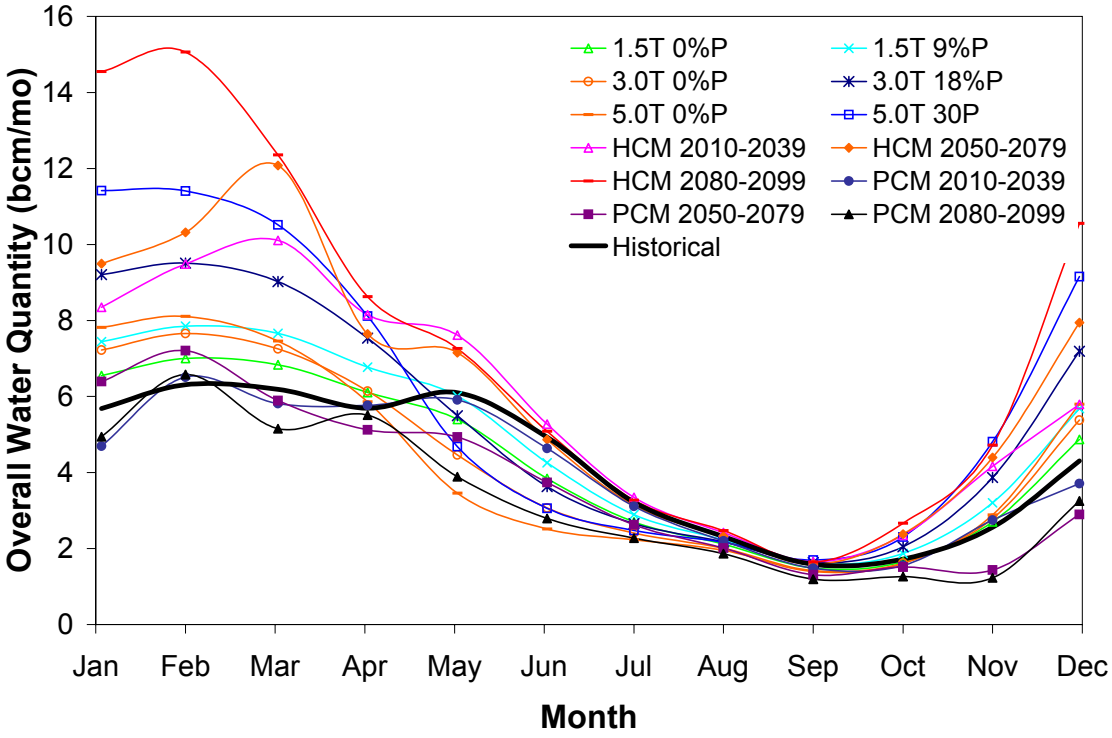

Figure 4. Mean monthly overall water quantity for 12 climate change scenarios and historical record

Figure 5 shows annual exceedance probabilities of statewide total water quantities, based on historical and selected perturbed 72-year hydrologies, among which the HadCM2090 and the PCM2090 form the upper and lower bounds of those curves.

Regional analyses indicate southern regions are more sensitive to climate changes under HadCM2 scenarios, with increased water quantity even in the dry season. Under PCM scenarios, water quantity decreases for all seasons in all regions. No significant spatial trend was identified for PCM scenarios.

4.5. Statewide Water Supply Availability

Approximate water supply changes with climate warming are estimated without modeling facility operations (Table 3). It is assumed: (1) All changes in dry season inflows directly affect water deliveries (because water is most easily managed during the dry season); (2) Increases in wet season surface inflows are lost because of low water demand and low surface storage flexibility resulting from flood control; and (3) changes in wet season groundwater inflows directly affect water supply availability because they directly affect groundwater storage. Since there is likely to be more wet season storage flexibility than is assumed here, the resulting estimates are likely to be more dire than more realistic results from operations modeling.

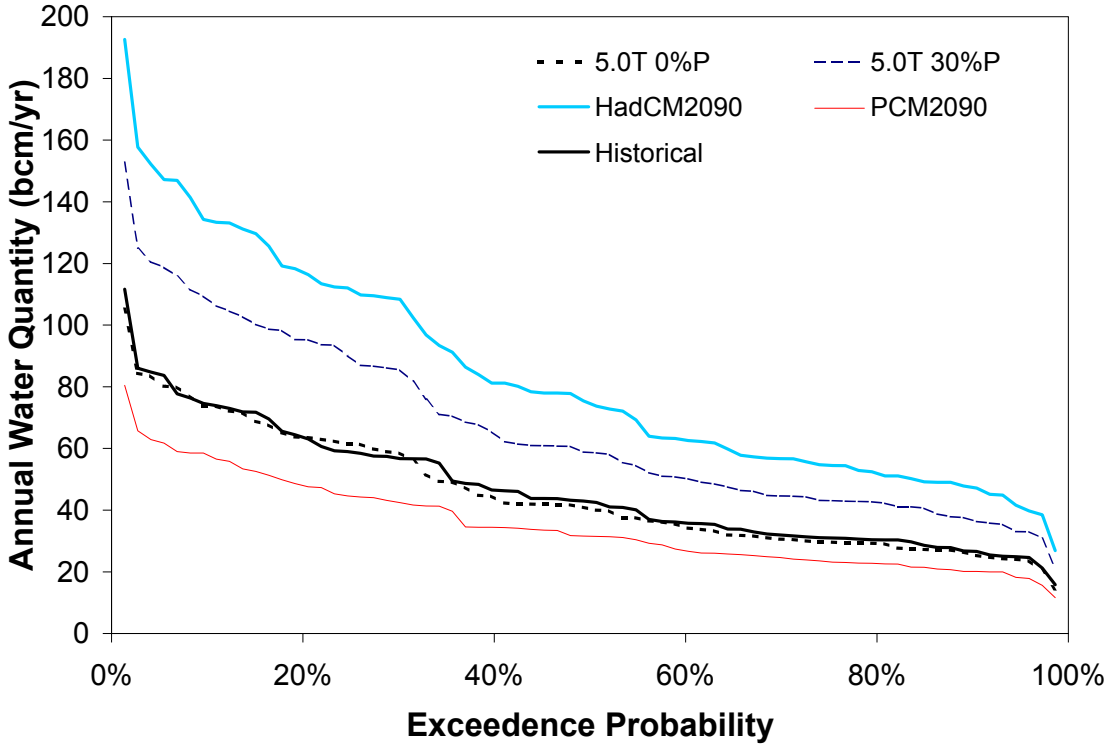

Figure 5. Overall Water Quantity exceedance probability

As Table 3 indicates, on average, water availability decreases for nine of the twelve scenarios, the exceptions being the three HadCM2 scenarios, in which water availability increases, even in the dry season. For the three uniform precipitation and temperature increase scenarios (scenarios 2, 4, 6 in Table 3) water availability decreases though overall water quantities increase (Table 2). It was estimated elsewhere that urban and agriculture demand changes from year 2020 to 2100 are 10.1 bcm/yr and -3.3 bcm/yr, respectively (Lund et al. 2003). The net demand increase of 6.8 bcm/yr is challenging to the system, even exceeding water availability increases of the three HadCM2 scenarios. In some scenarios climate change losses are similar in magnitude to this projected net demand increase. These are important for identifying potential long-term water supply problems.

Considering that most wet season groundwater inflows are stored for dry season consumption, the sum of dry season water availability plus wet season groundwater inflows decreases much less significantly than either rim inflows or overall water availability in the dry season under the parametric and PCM scenarios (when the dry season experiences serious water decreases). This indicates groundwater inflow helps to dampen overall fluctuations in water availability. Efficient groundwater management, such as conjunctive use and groundwater banking could be crucial to meet increasing water demand under climate change conditions.

Table 3. Estimated Raw Water Supply Availabilities and Changes

Climate Scenario	Volume (bcm/yr)	Change (bcm)	Change (%)
Historical	46.7	0.0	0
1. 1.5 T 0% P	44.1	-2.6	-6
2. 1.5 T 9% P	46.5	-0.2	0
3. 3.0 T 0% P	41.6	-5.1	-11
4. 3.0 T 18% P	45.8	-0.9	-2
5. 5.0 T 0% P	39	-7.7	-16
6. 5.0 T 30% P	44.7	-2.0	-4
7. HadCM2025 (1.4 T; 26% P)	51.7	5.0	11
8. HadCM2065 (2.4 T; 32% P)	50	3.3	7
9. HadCM2090 (3.3 T; 62% P)	52.3	5.6	12
10. PCM2025 (0.4 T; -2% P)	44.1	-2.6	-6
11. PCM2065 (1.5 T; -12% P)	40.6	-6.1	-13
12. PCM2090 (2.3 T; -26% P)	35.2	-11.5	-25

5.0 Limitations

By including multiple hydrologic components (particularly many rim inflows, local inflows, groundwater inflows, and reservoir evaporation) over the entire system, this work has a more complete representation of hydrology for California's water system than previous climate change studies. However, this required great simplicity in the methods used to represent climate change effects for each individual component. In particular, groundwater inflow and local inflows are estimated solely based on deep percolation changes, with other influencing factors treated as unchangeable. Furthermore, deep percolation for each groundwater sub-basin is calculated with empirical historical relationships, with unsaturated layer water balance neglected. Climate change rim inflows are estimated using monthly percent changes of index basin streamflows under climate warming scenarios. Index basin coverage for the many rim inflows is less than ideal, while the approach relies on rainfall-runoff models for the individual index basins.

Hydrologic response to climate change might not be linear, and might vary between wet and dry years (hydrologic "year-types"). This was explored, with year-type varying response ratios estimated for all CALVIN rim inflows. On average, these changes do not

cause great changes in the results presented here. However, for drought years, this observed non-linearity in hydrologic response worsens the effects of dry forms of climate warming and lessens droughts for wet forms of climate warming compared with the constant monthly ratio results presented here. This is shown in Table 4 for the HCM2050 and PCM2050 scenarios.

Table 4. Rim Inflow Average Drought Year Statistics

Scenario	Method	Annual		Oct–Mar		Apr–Sep	
		Quantity (bcm/yr)	Change (%)	Quantity (bcm/yr)	Change (%)	Quantity (bcm/yr)	Change (%)
HCM2050	Year-Type Ratio	33.0	78.1	17.1	95.1	15.9	62.7
	Constant Ratio	26.9	44.9	16.1	82.8	10.8	10.8
PCM2050	Year-Type Ratio	17.8	-3.8	8.4	-4.1	9.4	-3.5
	Constant Ratio	15.8	-14.9	8.3	-5.7	7.5	-23.1
Historical	-	18.6	0.0	8.8	0.0	9.8	0.0

While quite simple, the methods used here do seem able to represent the essential signals of climate warming for California's water system, in patterns and magnitudes similar to those found applying more sophisticated methods for a few basins or hydrologic components. Nevertheless, there are several areas where more detailed hydrologic investigations would be particularly desirable. For instance, climate change impact simulation of more southern index basins, along the coast and in the Central Valley floor, and better representation of evapotranspiration in the precipitation-runoff model would be useful.

The application of more sophisticated methods to such an extensive and complex hydrologic system would be difficult, expensive, and embody uncertainties in many hydrologic details, as well as the significant uncertainties in the climatic boundary conditions driving any hydrologic representation of the system (which our methods share). It was felt that a simpler approach would allow the development of a wider range of generally reasonable climate warming scenarios with an extensive scale, a greater number of important hydrologic components, with a spatial representation commensurate with water resource system management and performance assessment models. This work is not the final step in representing California's hydrology with climate change.

A non-technical advantage of employing permutation of the 72-year historically derived time series as our basic approach is that the resulting climate change fluxes are more explicitly comparable with hydrologic fluxes commonly employed for understanding and modeling water management and policy in California (Brekke et al. 2004).

6.0 Conclusions

Inflows to California's entire inter-tied water system are estimated over a range of annual hydrologic conditions, represented by a systematic modification of the 1922–1993 historical period. Such comprehensive representations of inflows to a water management system are needed for impact, management, and adaptation studies of climate change.

This study generalizes and confirms findings of significant climate warming effects of increased winter flows and decreased spring snowmelt runoff found in earlier climate warming studies of California. Groundwater flows are especially important for such studies, given their significant proportion of total water availability and use, ability to shift water availability seasonally, and ability to store water for drought periods. The potential magnitude of water supply effects of climate warming can be very significant, both positive and negative. These changes can be significant even relative to estimates of increased water demands due to population growth, and in some scenarios the estimated water supply losses in this study equal in magnitude to projected increase in water demands.

For more credible climate change impact and adaptation studies, more comprehensive and system-wide examination of hydrologic processes is needed. Additional GCM-driven hydrologies might better characterize the range and likelihood of climate changes. A larger number and diversity of index basins and better evapotranspiration representation in the rim inflow runoff model also would be useful. Finally, the results of this study are limited by the simplicity of approaches employed although it is not yet clear that more sophisticated methods would yield very different results. Further work will be valuable here.

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APPENDIX A

CLIMATE CHANGE HYDROLOGIES FOR CALIFORNIA WATER RESOURCES SYSTEM MODELING: USING ANNUALLY-VARYING RESPONSE RATIOS FOR RIM INFLOW PERTURBATION

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January 24, 2005

INTRODUCTION

Much of California has cool, wet winters and warm, dry summers, and a resulting water supply that is poorly distributed in time and space. On average, 75% of annual average precipitation of 23 inch occurs between November and March, while urban and agricultural demands are highest during the summer and lowest during the winter. Spatially, about 75% of California's 71 maf (million acre-feet) average annual runoff occurs north of Sacramento[1]. However, about 75% of urban and agricultural water use is south of Sacramento (CDWR, 1998). This already unevenly distributed hydrology could be further distorted by potential climate change, which would significantly affect the management and operation of California's inter-tied water system, at both local and statewide scales.

Impact and adaptation studies of California's vast water system need disaggregated hydrologic estimates of multiple hydrologic cycle components. However, many existing studies have focused only on one or a few watersheds, and almost exclusively on surface water. To examine the comprehensive water resources impacts of climate change on California, systematic climate warming hydrologies have been developed for use in the

[1] This includes most of the North Lahontan amount (Maury Roos, personal communication).

economic-engineering optimization model, CALVIN (Zhu et al., 2003). In that study, spatially disaggregated estimates of over 131 streamflow, groundwater, and reservoir evaporation monthly time series in California have been created for 12 different climate warming scenarios for a 72-year period. Among the hydrologies for the 12 climate change scenarios, the HadCM2100 and PCM2100 were used to evaluate water management in year 2100, a distant future (Lund et al., 2003). Those distributed hydrologic components are shown in Figure 1.

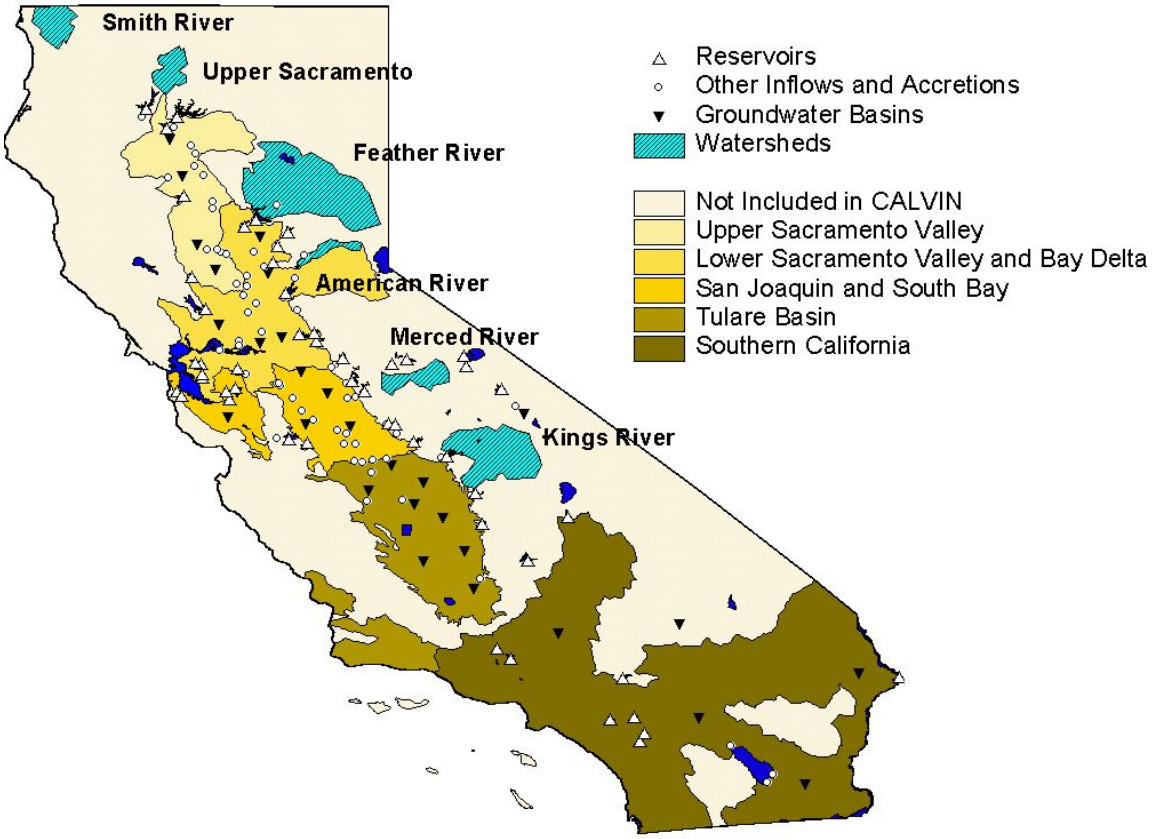

Figure 1. Index basins and hydrologic components of CALVIN (after Zhu et al. 2003). The "Watersheds" marked with blue color represent the six index basins simulated by Miller et al. (2003).

In Miller et al. (2003), two GCM projections for three projected future periods (2010 to 2039, 2050 to 2079, and 2080 to 2099) were used, based on 1 percent per year increase of CO_2 relative to late 20th Century CO_2 conditions. The two GCM projections were statistically downscaled and interpolated to a 10 km resolution, representing the relatively warm/wet (the Hadley Centre's HadCM2 run 1) and warm/dry (NCAR PCM run B06.06) scenarios for California, compared to the GCM projections in the Third Assessment Report by IPCC (2001).

The study summarized in this appendix develops refined climate warming hydrologies of the HadCM2 and PCM climate warming scenarios for the year 2050-2079 level. For simplicity, we call them HCM2050 and PCM2050 in the following sections. Those hydrologies are developed based on the streamflow simulations of the six index basins (Figure 1) by Miller et al. (2003). Detailed geographic characteristics of the six index basins are shown in Table 1.

This study systematically revised rim inflow perturbations by incorporating inter-annual variability of hydrologic responses to climate change. Instead of using constant monthly ratios as in last climate change hydrology study (Zhu et al., 2003), this study employs annually-varying monthly hydrologic response ratios[2], which are dependent on the exceedence probabilities of the annual flows from which these ratios are derived. Climate change estimates for surface reservoir evaporations are not modified in this study due to limited temperature and precipitation data available for further refining the estimates. Groundwater inflows and local runoff estimates are not refined either due to limited

[2] A monthly hydrologic response ratio is defined as the ratio of a simulated monthly climate warming rim inflow to its corresponding monthly historical flow, at the same location, in the same month of the same year.

groundwater inflow data availability in Southern California for which the climate warming effects on groundwater inflows were not done in last study.

Table 1. Comparison of index basins and corresponding CALVIN rim inflow locations (after Zhu et al., 2003)

Basin/Inflow Location		Smith	Sacramento	Feather	NF American	Merced	Kings
LBNL Index Basin (Miller, et al. 2001)	Location	Jed Smith State Park	Delta	Oroville Dam	North Fork Dam	Pohono Bridge	Pine Flat Dam
	Gage Latitude	41º 47’ 30” N	40º 45’ 23” N	39º 32’ 00” N	38º 56’ 10” N	37º 49’ 55” N	36º 49’ 55” N
	Gage Longitude	124º 04’30” W	122º 24’ 58” W	121º 31’ 00” W	121º 01’ 22” W	119º 19’ 25” W	119º 09’ 25” W
	Area	1706 km^2	1181 km^2	9989 km^2	950 km^2	891 km^2	4292 km^2
CALVIN Rim Inflow Location	Location	N/A	Shasta Lake	Oroville Lake	Folsom Lake	Lake McClure	Pine Flat Reservoir
	Gage Latitude	N/A	40° 43’ 06’’ N	38º 35’ 18” N	38°42’00’’ N	37º 35’ 02” N	36º 49’ 51” N
	Gage Longitude	N/A	122° 25’ 12” W	121º 27’48” W	121° 10’ 01’’W	120º 16’ 01” W	119º 20’ 06” W

METHODS

In the earlier climate change hydrology study (Zhu et al., 2004), climate warming rim inflows were developed using constant monthly hydrologic response ratios[3] derived from GCM hydrologic simulations at the six index basins (Figure 1). That approach could provide estimates of climate warming impacts on streamflow, but inter-annual variability of perturbation ratios was not accounted. The current research on rim inflow hydrology is an improvement on the previous study. It still uses the basin-to-location "mapping matrix" (Zhu et al., 2003). The new mapping involves not only seasonal issues but also the influence of hydrologic year types (for a CALVIN rim inflow location, the response ratios vary with year types as well as seasons).

Development of Annually-Varying Hydrologic Response Ratios of Index Basins

The simulated daily flows at the six index basins for historical climate scenario, HadCM2 2050-2079 climate scenario and PCM 2050-2079 climate scenario (hereafter called HCM2050 and PCM2050 for short) are first aggregated to monthly flows at the six index basins for each of the three scenarios[4]. Then, hydrologic response ratios for each month in each year at each index basin are derived with the following equation

$$\alpha_{ijk}^{s} = \frac{Q_{ijk}^{s}}{Q_{ijk}^{h}}$$

[3] Here the constant monthly perturbation ratios mean for each month at an index basin an average ratio is applied to all the simulation years.
[4] Simulated daily flows from October 1, 1963 through September 30, 1993 for the three scenarios were provided by Norman Miller at Lawrence Berkeley National Laboratory.

In the equation, α_{ijk}^{s} denotes the perturbation ratio at index basin *i* (*i*=1,…,6), in month *j* (*j*=1,…,12) of year *k* (*k*=1,…,30), for the GCM scenario *s* (*s*=HCM2050 or PCM2050). The flows are represented by *Q* and the simulated historical scenario is represented by *h*. For any index basin *i* (*i*=1,…,6), there are 30 monthly perturbation ratios for month *k* (*k*=1,…,12). Those perturbation ratios compose a column vector $\boldsymbol{\alpha}_{ik}$.

To examine the inter-annual variability of monthly hydrologic response ratios, this study correlates the monthly hydrologic response ratios to annual flow exceedence frequency of the simulated historical flows. For each GCM scenario and each index basin, thirty years of annual flows are derived from the simulated monthly flows from year 1963 to year 1993. Exceedence probabilities for the 30-year annual flows (in sequence) for each GCM scenario and each index basin are derived and marked with a column vector $\mathbf{P_i}$ (*i*=1,…,6).

Stepwise regression analyses are conducted for each month at each index basin and for each GCM scenario to derive the relationship between monthly perturbation ratios and annual flow exceedence probabilities, for the specific month, index basin and climate change scenario. For simplicity, the polynomial form regression equations are used and the highest power of independent factors is limited to three. Thus, the regression equations have the form

$$\hat{\alpha}_{ijk}^{s} = a_j^s + b_j^s P_{ik} + c_j^s P_{ik}^{\ 2} + d_j^s P_{ik}^{\ 3}$$

where $\hat{\alpha}_{ijk}^{s}$ (*i*=1 to 6; *j*=1 to 12; *k*=1 to 30; and *s*=HCM2050 or PCM2050) denotes the predicted perturbation ratio; P_{ik} represents the annual flow exceedence probability for

year k at index basin i; a_j^s represents the intercept and b_j^s, c_j^s, and d_j^s denote the regression coefficients for month j with scenario s.

Rim Inflow Perturbation with Annually-Varying Hydrologic Response Ratios

Major inflows into the Central Valley from the surrounding mountains are commonly called rim inflows. For each scenario, climate change impacts on 37 rim inflows are estimated with annually-varying monthly hydrologic response ratios derived from the regression equations established for each index basin. There are two steps: find the appropriate index basins for each CALVIN rim inflow; and apply the hydrologic response ratio regression equations of index basins to CALVIN rim inflows.

Matching Index Basins to CALVIN Rim Inflows

The matching between index basins and CALVIN rim inflows are taken from the previous climate change hydrology study (Zhu et al., 2003). This section summarizes the procedures used to find index basins that "best" match a CALVIN rim inflow.

To identify the appropriate index basins for each rim inflow, first, monthly and annual correlation coefficients between historical runoff of the rim inflow from 1963 to 1993 and simulated historical runoff of the six index basins for the same period are calculated. The index basin with the best annual correlation with the rim inflow is chosen as the best index basin for mapping, if most of its monthly correlation coefficients (e.g., eight months out of twelve) with the rim inflow also are the largest among those of the six index basins. Another method is applied to the remaining rim inflows to find appropriate index basins. It calculates summed square errors (SSE) of streamflow monthly

percentages in wet and dry seasons (October to March and April to September, respectively) between each rim inflow and each index basin. The best index basin (when wet and dry seasons share the same index basin) or index basins (when wet and dry seasons use different index basins) are determined by choosing those with the least SSE. This method partitions a water year into a wet season and a dry season to facilitate finding the best fit for snowmelt-dominant runoff and rainfall-dominant runoff regimes. Thus, for each of 37 rim inflows the best index basins for wet and dry seasons are obtained, resulting in a 37(rim inflow)×2(season) matching matrix (Table4). This matching matrix provides index information to apply the hydrologic perturbation equations to each rim inflow.

To compare climate change impacts on index basin streamflows and constructed climate change rim inflows, the percent changes (from historical) of annual and seasonal mean flows due to climate change are calculated for all index basins and rim inflows for each of the 12 climate change scenarios. To assure that climate change impacts on index basins are mapped to corresponding rim inflows, it is required that, under the same climate change scenario, the percent changes of each rim inflow should be similar to the changes of its index basins. Where constructed rim inflows did not meet this criterion, two measures are applied to improve fits: (1) Watershed conditions were further examined and their historical streamflow patterns were visually compared with those of the index basins; and (2) One-month lags in the hydrologic response ratios of some index basins were used to represent snowmelt timing changes on the east side of the Sierras. Among the 37 rim inflows, index basins of seven of them are identified by examining

temporal correlation (the first method), 18 by finding the least SSE, and 12 by analyzing the details and using one-month time lags.

Apply Hydrologic Response Ratios to Historical CALVIN Rim Inflows

As discussed above, for climate change scenario and each index basin, twelve monthly hydrologic response ratio equations are developed based on monthly GCM streamflow and simulated historical streamflow from year 1963 to year 1993 of the index basin. To apply those hydrologic response ratio equations to CALVIN rim inflows, annual flow exceedence probabilities of each CALVIN rim inflow location are derived for year 1963 to year 1993.

Most CALVIN model rim inflows and their corresponding index basin simulated inflows have similar inter-annual wet and dry cycles. With the Sacramento River as an example, Figure 2 illustrates monthly CALVIN rim inflows into Shasta Lake from 1921 to 1993 and monthly flows at Delta of upstream from year 1963 to 1993.

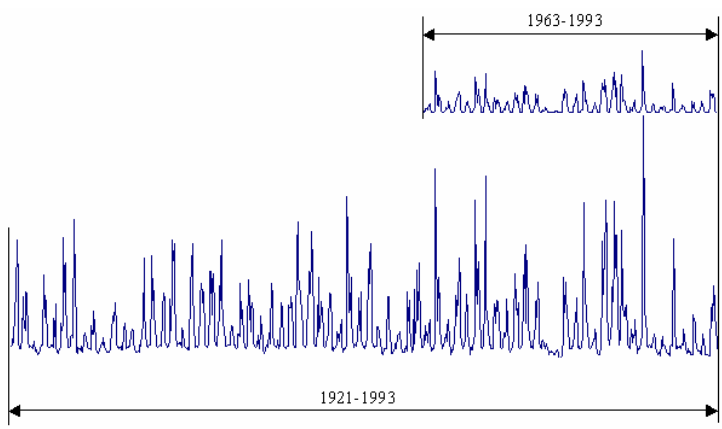

Figure 2. **Mapping annual variability of rim inflow monthly perturbation ratios. The bottom line is the total inflow to Shasta Lake and the top line represents the monthly flow of upper Sacramento at Delta.**

For each monthly flow from year 1963 to year 1993 of each of the 37 CALVIN rim inflows, hydrologic response ratio equations developed for its corresponding index basins (wet and dry seasons may have two different index basins) and the corresponding annual flow frequency of historical CALVIN rim inflow are used to derive the hydrologic response ratios for this particular month in the year, for each GCM climate change scenario. For CALVIN rim inflows in each year of the remaining period, namely year 1921 to 1962, frequency of a year in the 1963-1993 period that has the closest annual flow amount to the study year is used to calculate response ratios.

With hydrologic response ratios derived for all 12 months in each year from 1921 to 1993 for all the 37 CALVIN rim inflows, climate change rim inflows are developed by applying those response ratios to historical CALVIN rim inflows. For example, the wet season monthly hydrologic response ratio regression equations of the Kings River and dry season monthly regression equations of the Merced River under the "HadCM 2050-2079" scenario are applied to the "present climate" monthly time series of the Kaweah River streamflows from 1921 to 1993 to generate corresponding "HadCM 2050-2079" streamflows[5]. This approach extends a similarly simple approach used by Brekke et al. (2004).

[5] The Kings River and the Merced River are index basins for the Kaweah River for wet and dry seasons, respectively.

RESULTS AND DISCUSSTIONS

This section presents the detailed results of hydrologic response ratio equations and rim inflow perturbations for the climate warming scenarios, HCM2050 and PCM2050.

Perturbation Ratio Equations

The intercepts and regression coefficients for all the 12 months of each index basin for HCM2050 and PCM2050 climate warming scenarios are shown in Table 2. Those parameters are estimated using a stepwise regression tool in the statistics tool box of MATLAB 6.5, with a significance level of 0.05. For some months at some index basins (e.g., Sacramento River in January for HCM2050), no satisfactory fit was found. In this case, their constant monthly ratios were used for rim inflow perturbation, exactly the same as in last climate change hydrology study (Zhu et al., 2003). For HCM2050 scenario, about 43% of all the monthly ratio equations use constant ratios; for PCM2050, the percentage is 29%. The matching between index basins and CALVIN rim inflows is shown in Table 4. This "mapping matrix" is a revision of the matrix in the previous study (Zhu et al, 2003).

For diagnostic purposes, the fitting plots of Sacramento River (index basin) are provided in Appendix A-1. No consistent ratio change trends are identified. However, for the HCM2050 scenario, all the months have increasing trends except December and those months where constant ratios are used; for PCM2050, January, February and April have decreasing trends, November has an increasing trend, June, August and September have nonlinear trends, and the rest months use constant ratios.

Table 2. Parameters of perturbation ratio equations for HCM2050 scenario

Index Basin	Independent Variable Power	January	February	March	April	May	June	July	August	September	October	November	December
Smith	0	1.269	1.176	1.350	0.965	1.036	1.010	0.984	0.951	0.984	1.672	1.243	1.320
	1	0	0	0	0	0	0	0	0	0	0	0	0.321
	2	0	0	0	0	0.146	0.122	0.123	0	0	0	0	0
	3	0	0.164	0	0.204	0	0	0	0	0	0	0	0
Sacramento	0	1.794	1.550	1.524	1.059	0.592	0.436	0.615	0.772	0.781	1.388	1.475	2.358
	1	0	0	0	0	0.383	0.642	0.557	0.405	0.400	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0.530	0	0	0	0	0	0	0	0	-1.055
Feather	0	2.227	1.916	1.776	1.117	0.670	0.408	0.728	0.833	0.868	1.365	1.700	2.735
	1	0	0	0	0	0	0	0	0	0	0.0	0	0
	2	0	0	0.837	0	-3.593	0	0	0.582	0	0.0	0	-1.112
	3	0	0	0	0	5.607	2.414	1.291	0	0.811	0.0	0	0
American	0	1.893	1.345	1.776	1.248	0.639	0.390	0.465	0.748	0.894	1.628	1.874	1.930
	1	0	0.000	1.178	0	0	0	0	0	0	0	0	0
	2	0	7.891	0	0	0	0	0	0	0	0	0	3.625
	3	0	-7.725	0	0	1.324	1.604	1.629	1.432	1.228	0	0	-4.648
Merced	0	6.133	3.601	2.960	1.863	1.212	0.903	0.636	0.572	0.590	1.252	3.045	5.000
	1	0	0	0	0	0	0	0	0	0	0	0	0.0
	2	-4.098	0	0	0	0	0	0.918	1.168	1.080	0	0	0
	3	0	0	0	0	0	0.617	0	0	0	0	0	-4.333
Kings	0	2.055	1.561	1.526	1.954	1.001	-0.069	0.528	0.694	0.603	1.066	1.668	1.434
	1	0	0	0	0	0	4.149	0	0	0	0	0	0
	2	0	0	6.477	0	0	0	0	0	0	0	0	0
	3	0	3.246	0	2.820	3.435	0	4.605	4.121	3.177	0	0	3.032

Table 3. Parameters of perturbation ratio equations for HCM2050 scenario

Index Basin	Independent Variable Power	January	February	March	April	May	June	July	August	September	October	November	December
Smith	0	1.155	0.989	0.869	0.864	0.924	1.034	0.969	0.891	0.730	0.612	0.476	0.694
	1	0	0	0	0	0	0	0	0	0	0	0	-0.135
	2	-0.317	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0.094	0
Sacramento	0	1.233	1.186	0.964	0.898	0.680	0.437	0.717	0.748	0.711	0.681	0.523	0.668
	1	-0.358	-0.348	0	0	0	0.772	0	0	0	0	0.228	0
	2	0	0	0	0	0	0	0	1.176	1.698	0	0	0
	3	0	0	0	-0.311	0	-0.626	0	-1.473	-2.095	0	0	0
Feather	0	1.267	1.372	1.076	0.883	0.584	0.516	0.644	0.763	0.774	0.818	0.499	0.641
	1	0	0	0	-0.301	0	0	0	0	0	0	0.241	0
	2	0	-0.473	0	0	0	0.478	2.176	1.382	1.005	0	0	0
	3	0	0	-0.282	0	0	0	-2.648	-1.983	-1.415	0	0	0
American	0	0.992	1.190	1.030	0.960	0.626	0.411	0.355	0.756	0.872	0.811	0.347	0.547
	1	0	0	0	-0.255	0	0	0.513	0	0	0	0	0
	2	0	0	0	0	0	0.321	0	0	0	0	0.476	0
	3	-0.303	-0.288	0	0	0	0	0	0	-0.174	0	0	0
Merced	0	1.836	2.212	1.294	1.441	0.903	0.910	0.716	0.443	0.538	0.852	0.511	0.699
	1	-1.221	-2.273	0	-0.724	-0.375	0	0	0	0	0	0	0
	2	0	0	0	0	0	-5.947	-5.710	0	-0.631	0	0	0
	3	0	1.444	0	0	0	7.016	7.390	0	0	0	0	-0.294
Kings	0	0.687	0.718	0.838	1.132	0.598	0.362	0.340	0.393	0.434	0.805	0.746	0.624
	1	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	2.124	0	0	0	0	0	0
	3	4.898	3.723	2.619	0	2.139	0	4.000	2.854	2.502	0	0	0

Table 4. Wet and dry season index basins for each CALVIN rim inflow (revision of Zhu et al, 2003).

CALVIN rim inflow	Wet season index basin	Dry season index basin	CALVIN rim inflow	Wet season index basin	Dry season index basin
1. Trinity River	Sacramento	Sacramento	20. Greenhorn Creek and Bear River	American	American
2. Clear Creek	Smith	Smith	21. Kelly Ridge	Smith	Smith
3. Sacramento River[6]	Sacramento	Sacramento	22. Stanislaus River	Feather	Kings
4. Stony Creek	Smith	Smith	23. San Joaquin River	Kings	Kings
5. Cottonwood Creek	Smith	Smith	24. Merced River	Merced	Merced
6. Lewiston Lake Inflow	Feather	American	25. Fresno River	Smith	Smith
7. Middle and South Forks Yuba River	American	American	26. Chowchilla River	Smith	Smith
8. Feather River	Feather	Feather	27. Local Inflow to New Don Pedro	Sacramento	American
9. North and Middle Forks American River	American	American	28. Tuolumne River	Merced	Merced
10. South Fork American River	Feather	Feather	29. Cherry Creek and Eleanor Creek	Kings	Merced
11. Cache Creek	Smith	Smith	30. Santa Clara Valley Local	Smith	Smith
12. Putah Creek	Smith	Smith	31. Kern River	Kings	Kings
13. North Fork Yuba River	NF American	NF American	32. Kaweah River	Kings	Merced
14. Calaveras River	Smith	Smith	33. Tule River	Feather	Feather
15. Mokelumne River	Feather	Kings	34. Kings River	Kings	Kings
16. Cosumnes River	American	Feather	35. Lower Owens Valley - Haiwee	Kings	Kings
17. Deer Creek	Smith	Smith	36. Mono Basin	Merced	Kings
18. Dry Creek	Smith	Smith	37. Upper Owens	Kings	Sacramento
19. French Dry Creek	Smith	Smith			

[6] The Pit River flow included in the Sacramento River flow to Shasta may not be changed much for a warming scenario but rather is more subject to changes in precipitation. So, it is not appropriate to estimate Pit River flows from the upper Sacramento. However, disaggregated Shasta Lake inflows (e.g., Sacramento, McCloud and Pit) are not available at this time.

Rim Inflows

There are 37 major inflows into the Central Valley from the surrounding mountains, commonly called rim inflows. Historically, these rim inflows average 28.2 maf/yr (34.9 bcm/yr), accounting for 72% of all inflows into California's inter-tied water system.

The climate warming rim inflows are generated for HCM2050 and PCM2050 scenarios. The changes of total flows at each CALVIN rim inflow location are illustrated in Appendix A-2. Table 5 shows the statistics for each scenario and compares with that of the historical CALVIN rim inflows. In general, the annually-varying response ratio method leads to higher mountain inflow quantity than does the constant monthly ratio method, but the differences are not very significant. For HCM2050 scenario, the changes of annual total rim inflow is 50.8%, slightly higher than 46.4%, the result generated with constant ratio method in the previous climate change hydrology study. For PCM2050, the changes of annual rim inflow is -13.3%, less than -13.6%, the reduction of PCM2050 scenario with constant ratio method. Seasonal rim inflow changes have the same trend, except the wet season (October to March) in PCM2050, in which the annually-varying response ratio method results in a slightly higher flow reduction (-3.9%) than that of the constant ratio method (-3.8%).

Table 5. Climate Warming Average Rim Inflow Statistics (quantity in taf/yr)

Scenario	Method	Annual		Oct-Mar		Apr-Sep	
		Quantity	Change	Quantity	Change	Quantity	Change
HCM2050[7]	Annually-Varying Ratio[8]	42594	50.8%	26685	87.9%	15909	13.3%
	Constant Ratio[9]	41348	46.4%	25842	82.0%	15506	10.4%
PCM2050[10]	Annually-Varying Ratio	24478	-13.3%	13647	-3.9%	10831	-22.9%
	Constant Ratio	24398	-13.6%	13654	-3.8%	10744	-23.5%
Historical	-	28244	0.0%	14199	0.0%	14045	0.0%

Figure 3 illustrates the monthly distribution of total rim inflows calculated with annually-varying response ratio method and constant ratio method respectively, for HCM2050 and PCM2050 scenarios. For comparison, the historical monthly total rim inflow also appears in Figure 3. For HCM2050, the annually-varying response ratio method results in higher total monthly flows than the constant ratio method in all months except May. For PCM2050, the annually-varying response ratio method results in higher total monthly flows than the constant ratio method in all months except January, February, May and December.

Drought years are often important for evaluating the reliability of a water resources system. With a warmer and drier climate, the operating cost of California water system could be significantly increased, along with the reduction of water supply reliability (Lund et al, 2004). Table 6 summarizes the rim inflow changes during drought years (1928-1934, 1976-1977 and 1987-1992) under HCM2050 and PCM2050 climate change scenarios.

[7] For California, the HCM2050 scenario projected an average temperature increase of 2.4 ºC and precipitation increase of 32%, compared to historical level (Zhu et al., 2003).
[8] The annually-varying ratio refers to the method used in this study.
[9] The constant ratio refers to the method used in the previous climate warming hydrology study (Zhu et al., 2003).
[10] For California, the HCM2050 scenario projected an average temperature increase of 1.5 ºC and precipitation reduction of 12%, compared to historical level (Zhu et al, 2003).

The statistics in Table 6 (drought years) are significantly different from that in Table 5 (all the years) not only in flow quantities but in percentage changes. The annually-varying response ratio method results in much more rim inflow quantity than the constant ratio method for both HCM2050 and PCM2050. Most of these differences are in the dry season (April to September). These could lead to significant differences in climate change adaptations.

Table 6. Climate Warming Rim Inflow Average Drought Year Statistics (quantity in taf/yr)

Scenario	Method	Annual		Oct-Mar		Apr-Sep	
		Quantity	Change	Quantity	Change	Quantity	Change
HCM2050	Annually-Varying Ratio	27141	80.7%	14428	102.8%	12714	60.8%
	Constant Ratio	21769	44.9%	13005	82.8%	8764	10.8%
PCM2050	Annually-Varying Ratio	14446	-3.8%	7083	-0.4%	7364	-6.9%
	Constant Ratio	12788	-14.9%	6707	-5.7%	6081	-23.1%
Historical	-	15020	0.0%	7113	0.0%	7907	0.0%

Figure 4 shows the monthly distribution of the total rim inflows in drought periods. For HCM2050, the monthly distribution curve of annually-varying response ratio method is above that of the constant method in all months except January, October and November where the two curves overlap. For PCM scenario, the curve of annually-varying response ratio method is above that of constant ratio method in all months except February, April and December. For both climate change scenarios, the curves of annually-varying response ratio method better follow the shape of historical curve than do the curves of the constant ratio method. The reason of that is not clear yet but these monthly distributions are important for local water resources management where storage capacity is insufficient.

In drought years, the annually-varying response ratio method results in more water in dry seasons than does the constant ratio method. However, these trends do not hold for all the rivers. Figures 5, 6, 7, and 8 show the monthly flows of the Sacramento River (CALVIN rim inflow) in drought periods for HCM2050 and PCM2050. For HCM2050 (Figure 5 and Figure 6), the annually-varying response ratio method curves are consistently higher than that of constant ratio method in dry seasons. This is consistent with the results in Table 6 and Figure 4. While, for PCM2050 (Figure 7 and Figure 8), we found annually-varying response ratio flows are lower than constant ratio flows in dry season for some years. These are because the ratio curves of dry season (e.g., August and September) have low values in high frequency area (see PCM2050 plots in Figure 11 in Appendix A-1).

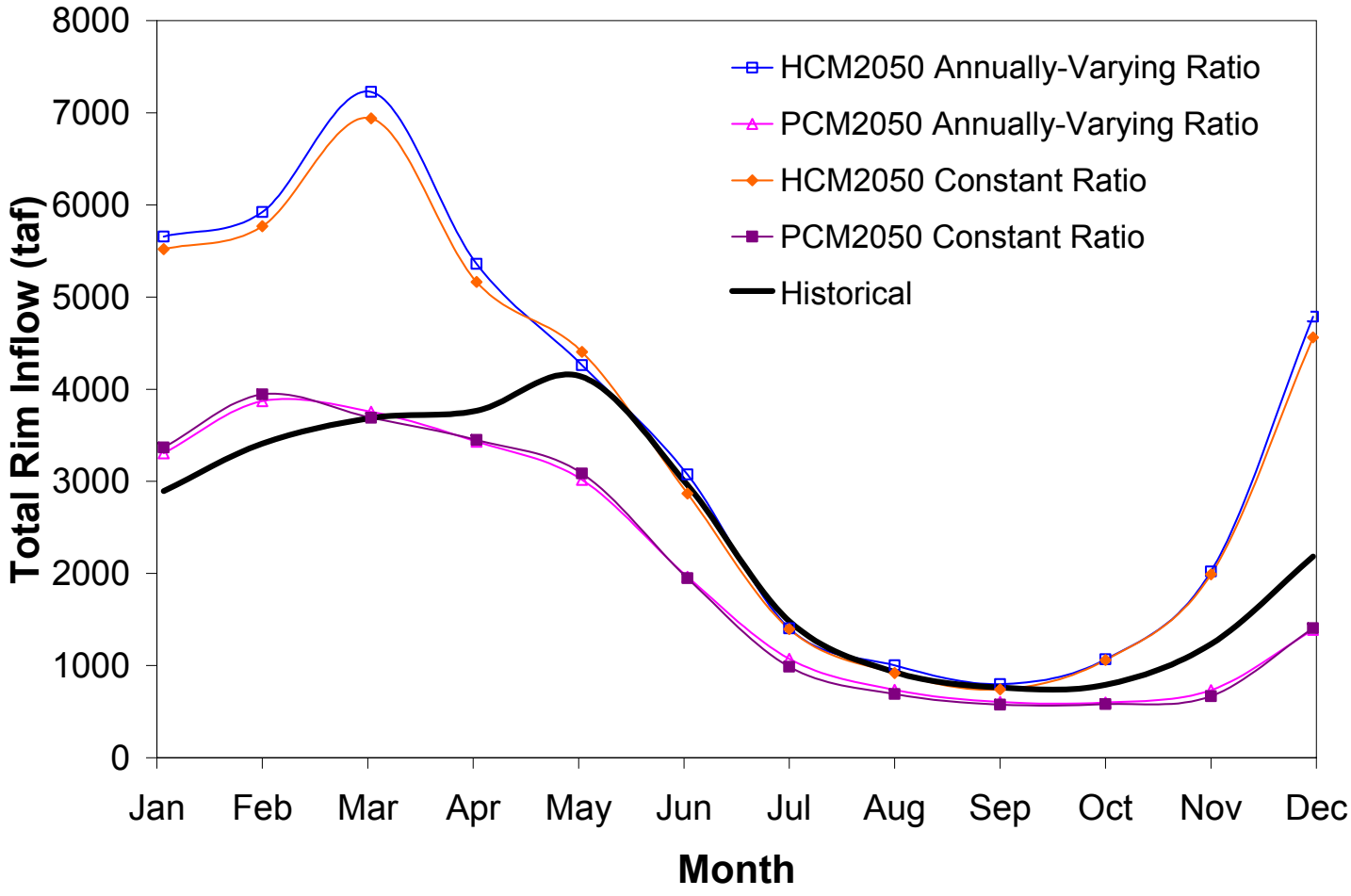

Figure 3. Total Rim Inflow Monthly Distribution. In the legend, "Annually-Varying Ratio" refers to the result developed with annual flow frequency dependent perturbation ratios in this study; and "Constant Ratio" refers to the result developed with constant monthly ratios in the previous study.

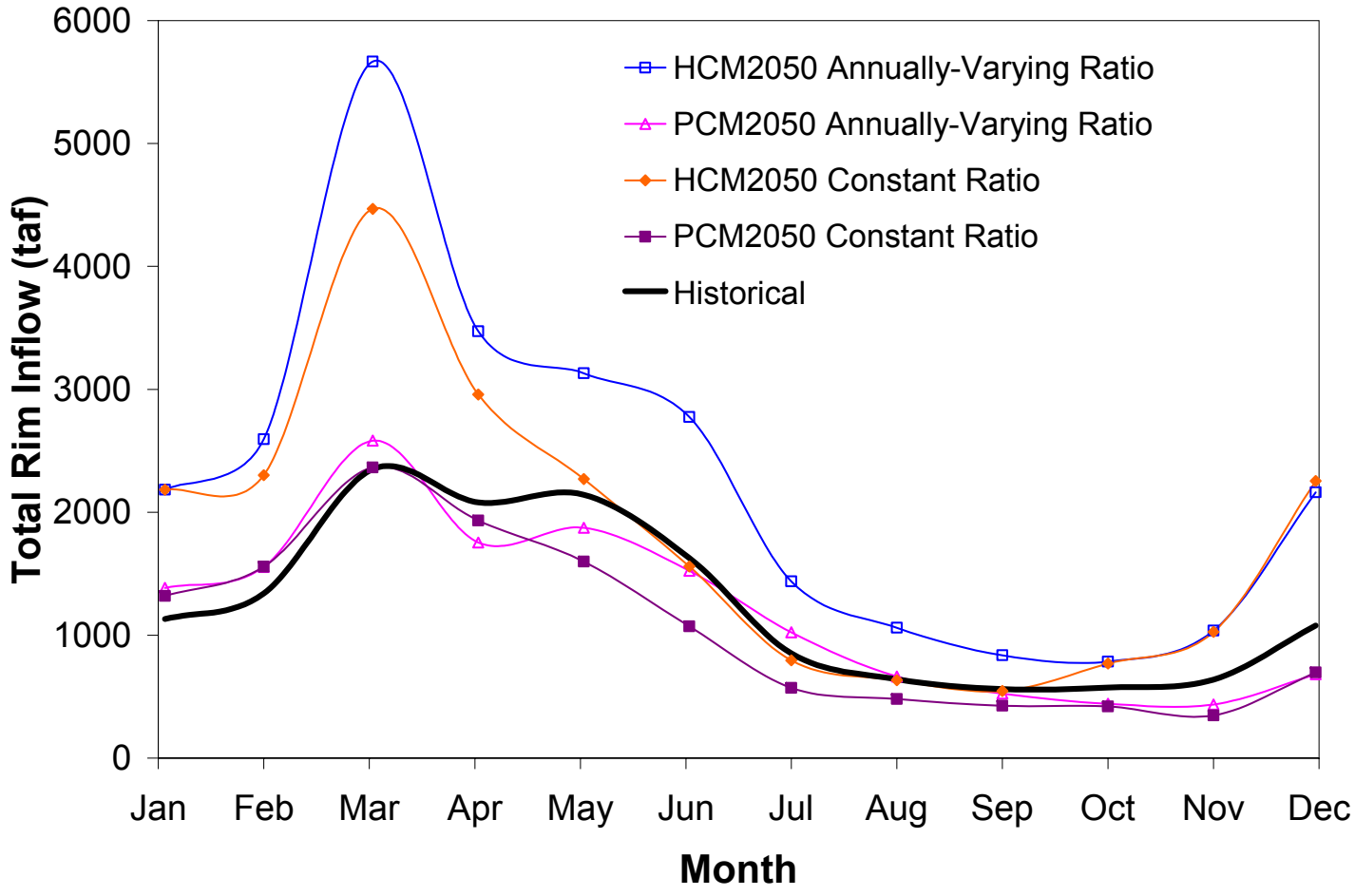

Figure 4. Drought Year Average Total Rim Inflow Monthly Distribution (1928-1934, 1976-1977, 1987-1992). In the legend, "Annually-Varying Ratio" refers to the result developed with annual flow frequency dependent perturbation ratios in this study; and "Constant Ratio" refers to the result developed with constant monthly ratios in the previous study.

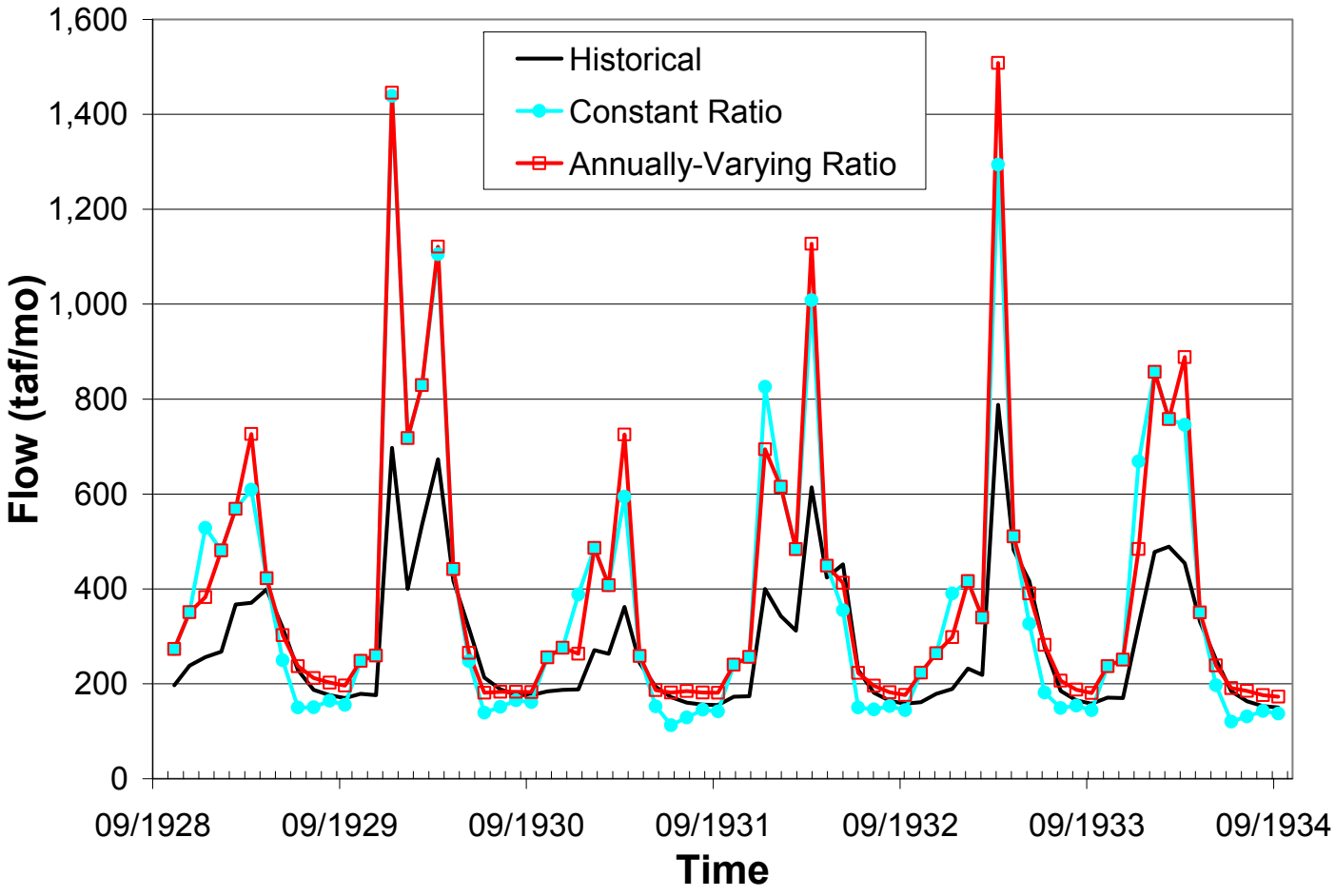

Figure 5. Sacramento River monthly flows under HCM2050 scenario during the drought period from 1928 through 1933 water years.

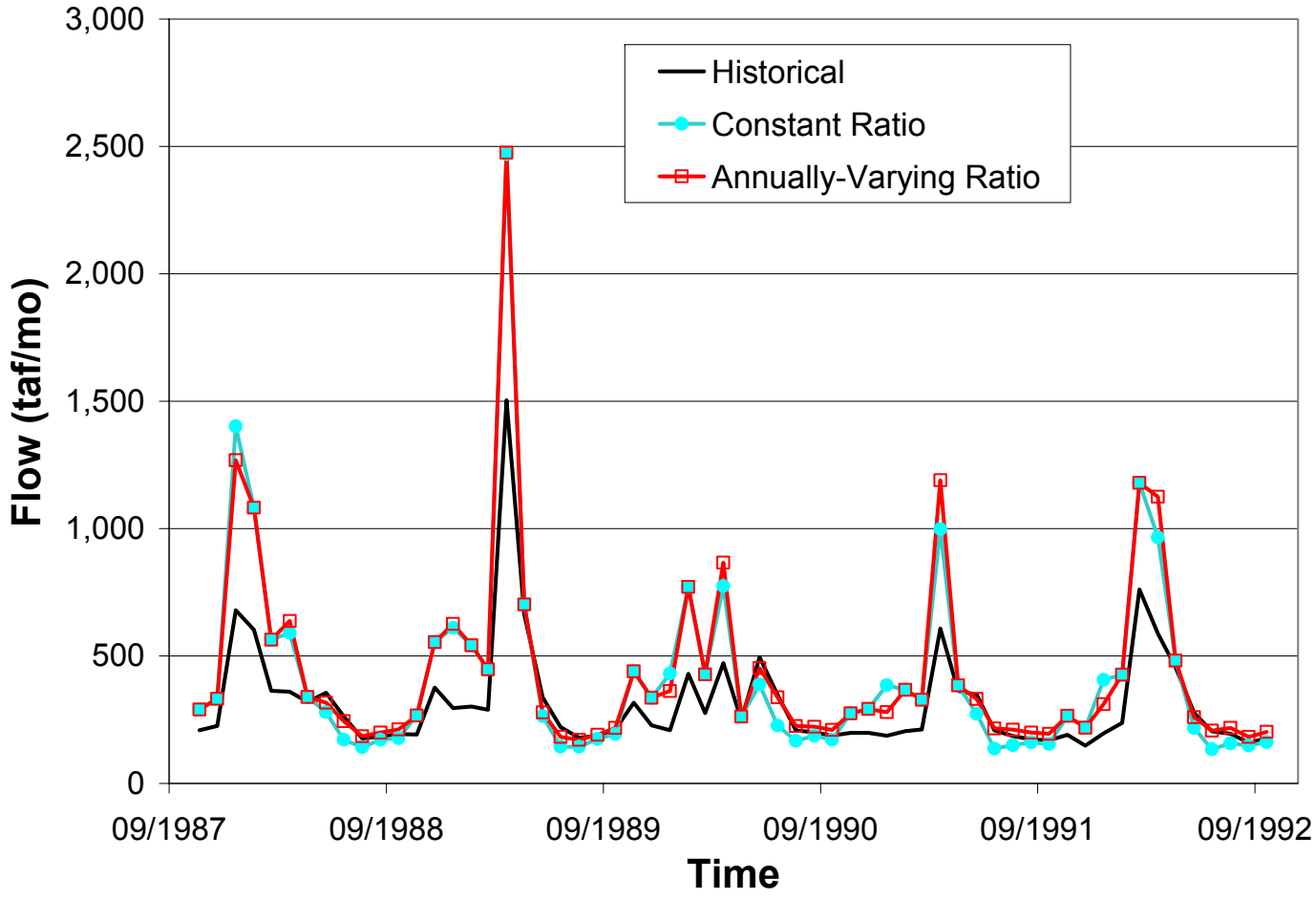

Figure 6. Sacramento River monthly flows under HCM2050 scenario during the drought period from 1987 through 1991 water years.

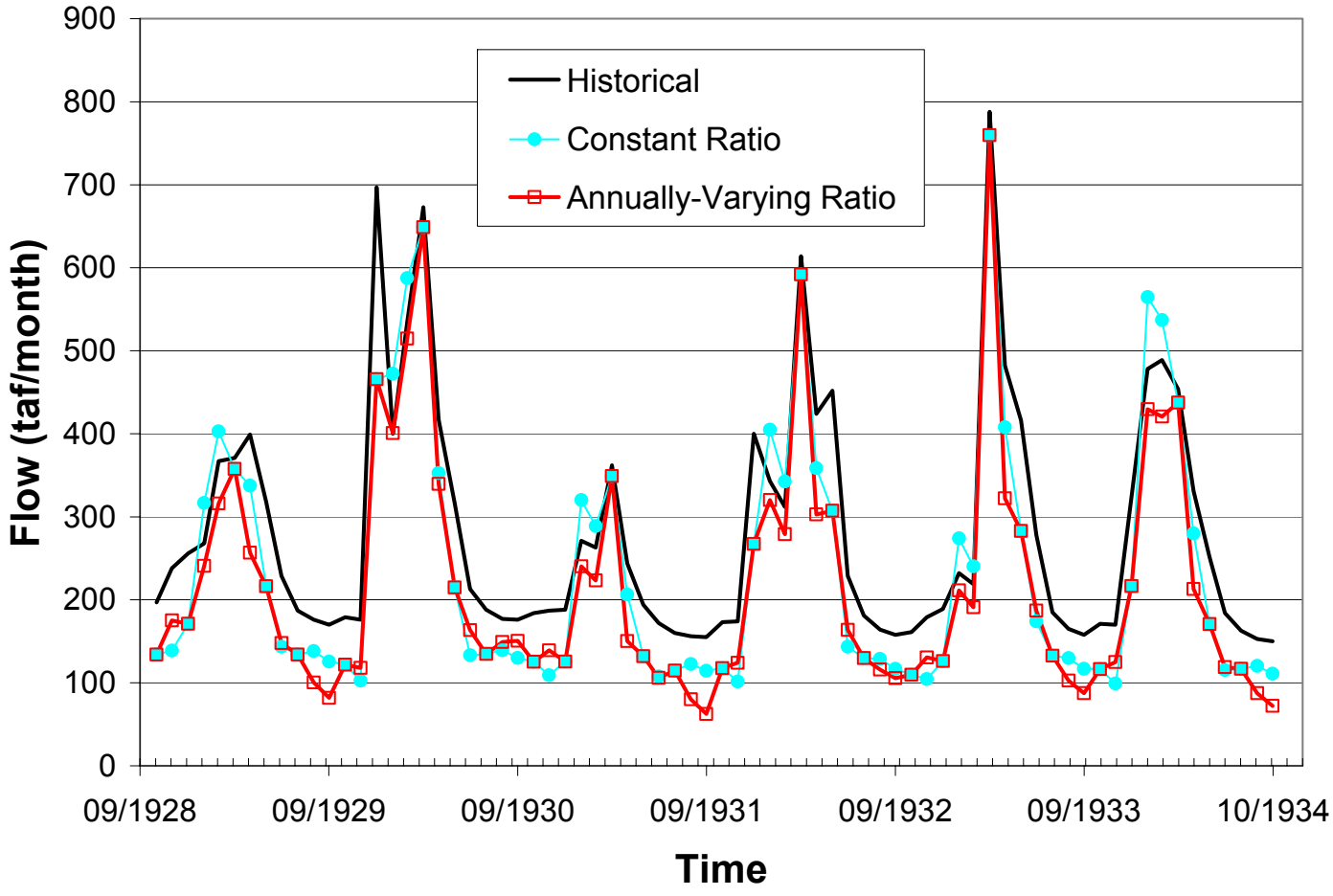

Figure 7. Sacramento River monthly flows under PCM2050 scenario during the drought period from 1928 through 1933 water years.

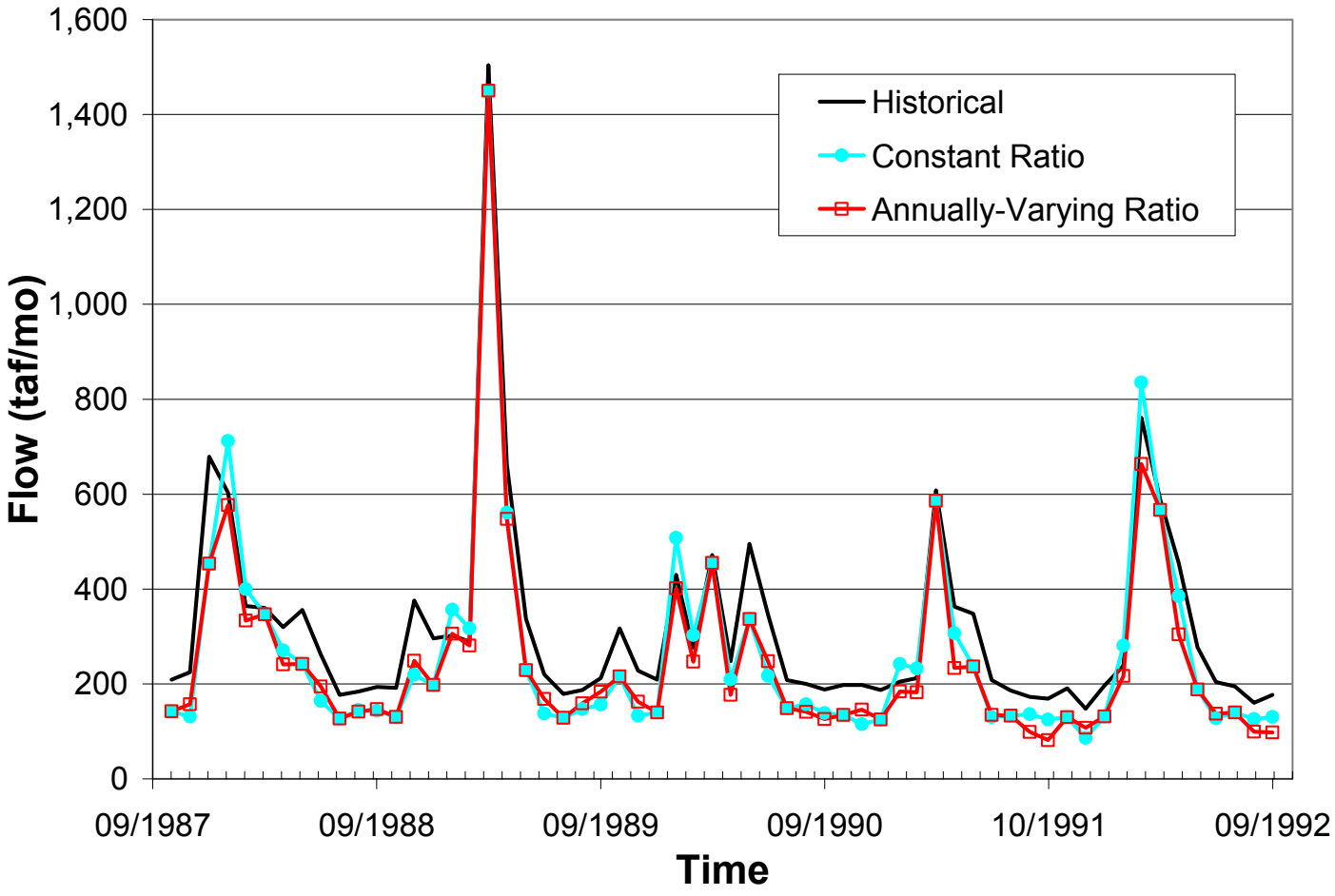

Figure 8. Sacramento River monthly flows under PCM2050 scenario during the drought period from 1987 through 1991 water years.

Besides the differences discussed above, the hydrologies developed in this study share the major characteristics with the previous climate warming hydrology study (Zhu et al., 2003). In general, the HCM2050 scenario would lead to a much wetter (high flow) hydrology while the PCM2050 would result in a drier (low flow) hydrology[11]. Both climate change scenarios would significantly shift the peak runoff of catchments where the annual hydrograph is currently dominated by spring snowmelt. Much more runoff would occur in winter and less in spring and summer. Therefore, reservoirs would have to maintain more empty space to maintain current levels of flood protection from increased winter storm runoff[12]. This empty space would then be less likely to refill at the end of the flooding season, because of reductions in snowmelt after the storm season's end.

CONCLUSIONS

Climate change rim inflows are estimated using annually-varying response ratio equations of index basin streamflows under two climate warming scenarios, HCM2050 and PCM2050. Those results are compared with rim inflow results in the previous climate change hydrology study. The following conclusions are drawn:

(1) There are significant correlations between monthly hydrologic response ratios and annual flow frequencies for a few months for the six index basins, based on the study by Miller et al. (2003). Therefore, annual variability of mountain streamflows is a factor that influences hydrologic response (surface flow) to

[11] The HadCM2 climate warming scenario projected significantly wet and warm climate, leading to much more water availability and serious flooding problems, while this scenario is not very reliable (Miller, 2004, personal communication). The HadCM3 is a better scenario for warmer and wetter climate.

[12] Analysis of daily flows of the same climate warming scenarios indicates that daily flood flows will be bigger for large events.

climate change. The influence of this factor should be considered in developing climate change rim inflows with empirical method such as the "Delta" method used in this and other studies (Zhu et al., 2003; Brekke et al., 2004).

(2) While there are some differences in average rim inflow quantities for the long period (1921 to 1993) generated with or without consideration of inter-annual variability of perturbation ratios, the differences are relatively small. Overall, the year type ratio method results in more flow than does the constant ratio method. This needs further research.

(3) The differences of drought year flows between the two methods are significant. Most of these differences occur in dry season. Compared to the results calculated with the constant ratio method, the year type ratio method results have more flow augmentation in HCM2050 scenario and less flow reduction with PCM2050 scenario. Those have water management implications in adaptation to climate change. Again, further research is suggested towards these findings.

(4) Similar to the previous climate warming hydrology study, this study shows HCM2050 scenario will lead to higher flows while the PCM2050 will leads to much lower flows, and both climate change scenarios would significantly shift the peak flow, with much more runoff would occur in winter and less in spring and summer.

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APPENDIX A-1. FITTING CURVES TO PERTURBATION RATIOS

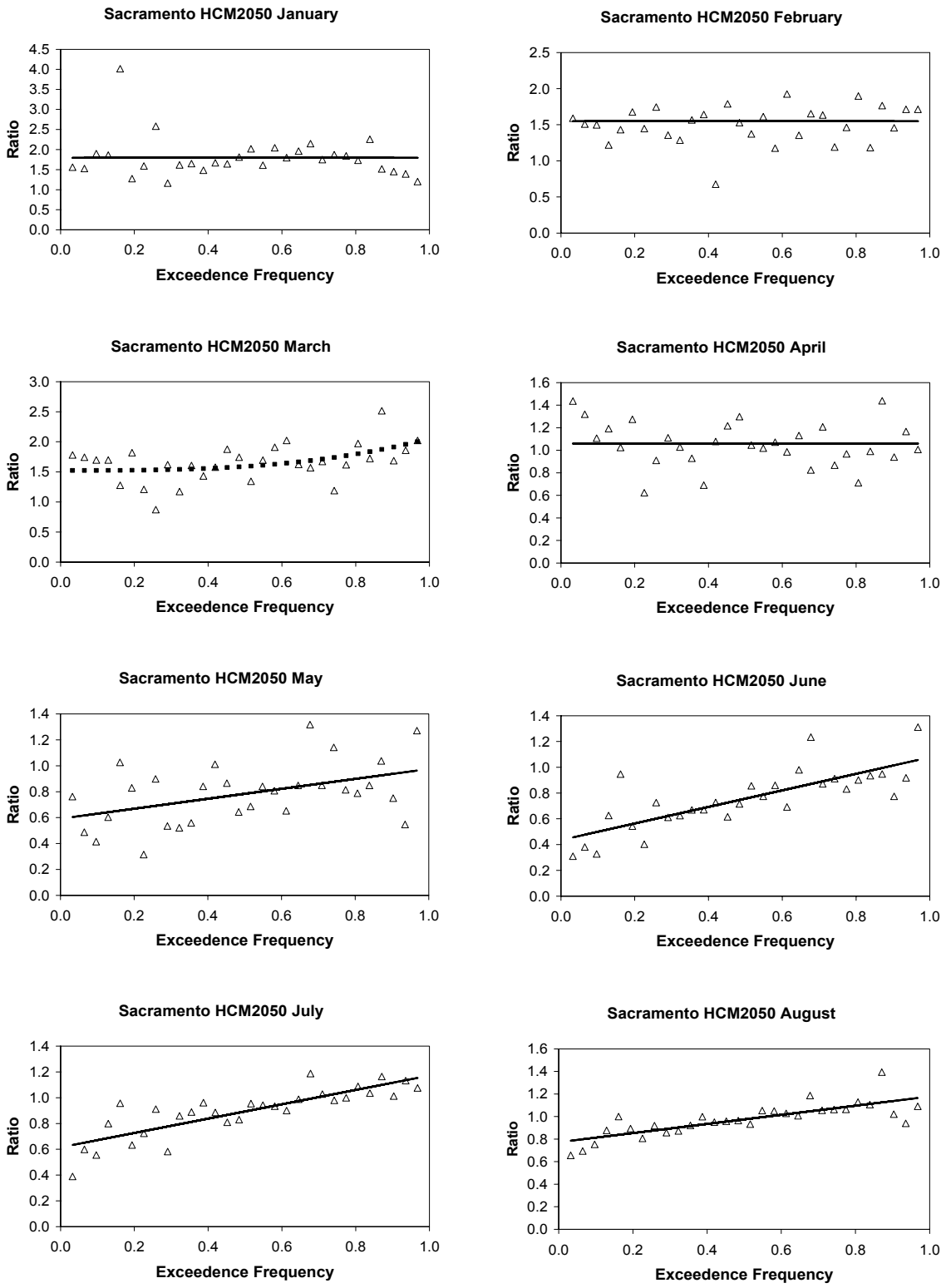

Figure 9. Fitting polynomial functions to Sacramento River monthly perturbation ratios.

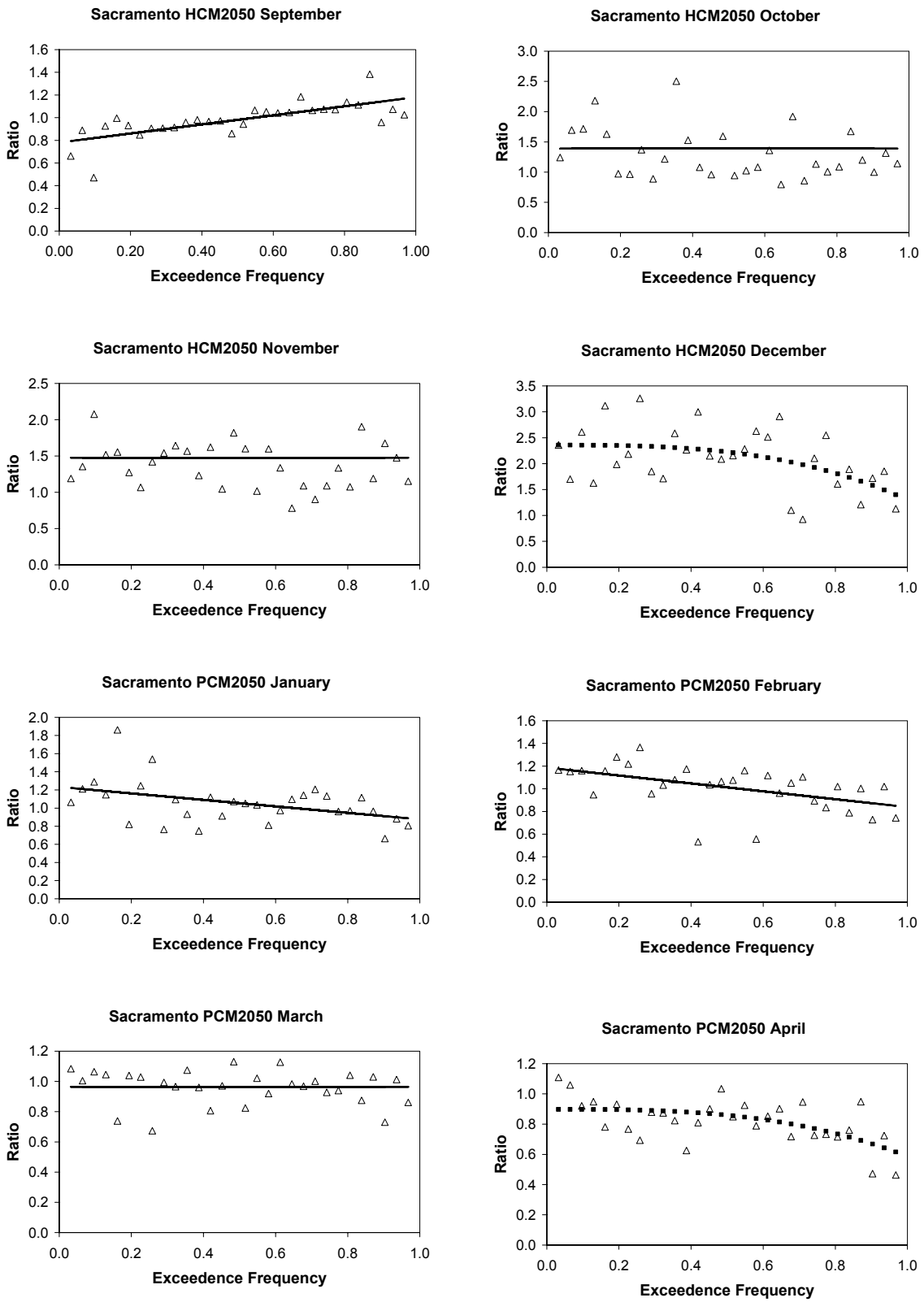

Figure 10. Fitting polynomial functions to Sacramento River monthly perturbation ratios (continued).

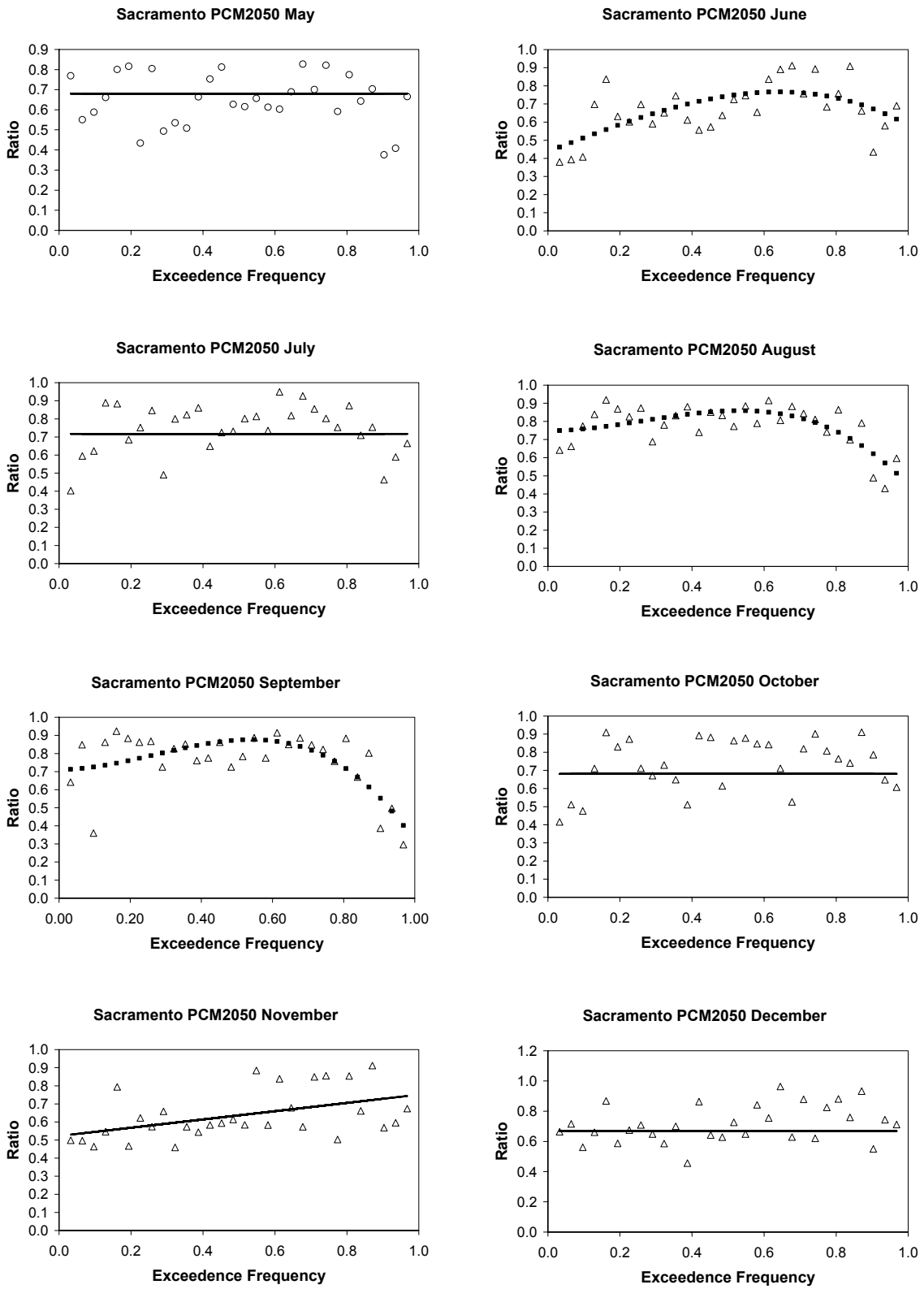

Figure 11. Fitting polynomial functions to Sacramento River monthly perturbation ratios (continued).

APPENDIX A-2. CALVIN RIM INFLOW CHANGES (IN TAF)

Table 7. Flow changes on each CALVIN rim inflow locations.

TRINITY RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	27.8%	71.6%	-14.5%
PCM2050	-17.8%	-8.1%	-27.2%
Historical	1217	598	619

CLEAR CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	22.3%	30.5%	2.6%
PCM2050	-11.1%	-11.6%	-9.9%
Historical	263	186	77

SACRAMENTO RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	39.2%	69.7%	-8.8%
PCM2050	-15.3%	-9.4%	-24.6%
Historical	5525	3379	2147

STONY CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	19.6%	28.6%	1.5%
PCM2050	-7.4%	-6.6%	-9.1%
Historical	396	265	131

COTTONWOOD CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	23.2%	29.9%	2.1%
PCM2050	-9.7%	-9.7%	-9.8%
Historical	554	421	133

LEWISTON LAKE INFLOW			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	46.2%	105.6%	-12.1%
PCM2050	-15.2%	2.8%	-32.9%
Historical	46	23	23

M & S FORK YUBA RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	54.3%	103.9%	-14.0%
PCM2050	-18.5%	-7.7%	-33.5%
Historical	426	247	179

FEATHER RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	51.5%	104.2%	-12.3%
PCM2050	-10.2%	1.9%	-24.7%
Historical	3900	2137	1763

N AND M FORKS AMERICAN RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	53.5%	100.4%	-8.1%
PCM2050	-18.9%	-9.9%	-30.7%
Historical	1374	780	594

S FORK AMERICAN RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	46.3%	101.4%	-13.8%
PCM2050	-14.8%	-0.2%	-30.7%
Historical	1311	684	627

Table 8. Flow changes on each CALVIN rim inflow locations (continued).

CACHE CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	20.3%	29.3%	1.4%
PCM2050	-8.6%	-8.5%	-8.9%
Historical	499	339	160

PUTAH CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	25.0%	29.0%	0.6%
PCM2050	-8.9%	-8.6%	-10.8%
Historical	372	320	52

N FORK YUBA RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	48.6%	106.7%	-16.1%
PCM2050	-13.6%	3.9%	-33.2%
Historical	1213	639	574

CALAVERAS RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	23.1%	29.3%	-0.1%
PCM2050	-9.7%	-9.6%	-10.3%
Historical	154	121	33

MOKELUMNE RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	70.2%	95.4%	50.8%
PCM2050	-8.0%	-1.6%	-12.9%
Historical	681	296	385

COSUMNES RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	64.4%	100.8%	-9.8%
PCM2050	-13.0%	-4.4%	-30.5%
Historical	366	245	120

DEER CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	24.1%	29.7%	0.8%
PCM2050	-10.3%	-10.1%	-10.9%
Historical	68	55	13

DRY CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	23.9%	29.1%	-0.7%
PCM2050	-9.7%	-9.1%	-12.5%
Historical	81	67	14

FRENCH DRY CREEK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	21.5%	30.4%	1.5%
PCM2050	-9.9%	-9.8%	-10.0%
Historical	133	92	41

GREENHORN CREEK AND BEAR RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	59.3%	101.8%	-0.3%
PCM2050	-16.4%	-6.5%	-30.2%
Historical	418	244	174

KELLY RIDGE			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	18.1%	36.5%	2.6%
PCM2050	-14.5%	-20.6%	-9.3%
Historical	126	58	68

STANISLAUS RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	74.0%	98.6%	58.6%
PCM2050	-5.2%	1.6%	-9.4%
Historical	1057	408	649

Table 9. Flow changes on each CALVIN rim inflow locations (continued).

SAN JOAQUIN RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	63.7%	93.7%	47.9%
PCM2050	-8.7%	0.2%	-13.5%
Historical	1681	580	1101

MERCED RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	71.8%	104.1%	56.1%
PCM2050	-7.8%	6.3%	-14.6%
Historical	922	301	621

FRESNO RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	18.8%	28.9%	1.0%
PCM2050	-8.8%	-8.6%	-9.2%
Historical	84	54	30

CHOWCHILLA RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	21.7%	28.5%	-0.4%
PCM2050	-8.4%	-7.6%	-11.2%
Historical	69	53	16

CLOCAL INFLOW NEWDP			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	34.7%	70.4%	-7.1%
PCM2050	-16.4%	-3.9%	-31.1%
Historical	618	333	285

TUOL RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	59.2%	268.8%	15.2%
PCM2050	-24.3%	12.3%	-32.0%
Historical	747	130	617

CHERRY & ELNOR CRK			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	56.2%	131.4%	24.9%
PCM2050	-16.0%	9.2%	-26.5%
Historical	436	128	308

SCV LOCAL			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	29.1%	33.1%	1.5%
PCM2050	-16.4%	-16.9%	-12.8%
Historical	126	110	16

KERN RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	66.1%	111.3%	48.0%
PCM2050	-10.0%	5.0%	-16.0%
Historical	684	196	488

KAWEAH RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	51.1%	113.2%	22.6%
PCM2050	-16.4%	1.1%	-24.5%
Historical	416	131	285

TULE RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	46.4%	104.7%	-18.4%
PCM2050	-12.3%	6.2%	-32.9%
Historical	132	69	62

KINGS RIVER			
Scenario	Annual	Oct-Mar	Apr-Sep
HCM2050	66.8%	116.6%	52.6%
PCM2050	-11.5%	3.7%	-15.8%
Historical	1594	354	1240

Table 10. Flow changes on each CALVIN rim inflow locations (continued).

LV-HAIWEE			
Scenario	**Annual**	**Oct-Mar**	**Apr-Sep**
HCM2050	75.4%	68.7%	77.6%
PCM2050	-2.4%	1.6%	-3.7%
Historical	292	72	220

MONO BASIN			
Scenario	**Annual**	**Oct-Mar**	**Apr-Sep**
HCM2050	79.8%	235.1%	51.7%
PCM2050	-10.5%	-0.9%	-12.3%
Historical	119	18	101

UPPER OWENS			
Scenario	**Annual**	**Oct-Mar**	**Apr-Sep**
HCM2050	46.4%	119.2%	-14.8%
PCM2050	-8.7%	12.5%	-26.5%
Historical	143	66	78