ESTIMATED IMPACTS OF CLIMATE WARMING ON CALIFORNIA WATER AVAILABILITY UNDER TWELVE FUTURE CLIMATE SCENARIOS[1]

Tingju Zhu, Marion W. Jenkins, and Jay R. Lund[2]

ABSTRACT: Spatially disaggregated estimates of over 131 stream-flow, ground water, 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 alone.
(KEY TERMS: climate change; precipitation; temperature; runoff; water supply; California.)

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 percent of annual precipitation of 584 mm occurs between November and March, while urban and agricultural demands are highest during the summer and lowest during the winter. Spatially, more than 70 percent of California's 88 billion cubic meters (bcm) average annual runoff occurs in the northern part of the state. However, about 75 percent 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 (Stine, 1994; Haston and Michaelsen, 1997; Meko *et al.,* 2001). 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 (Wigley and Raper, 2001; Snyder *et al.,* 2002). 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 (Lettenmaier and Gan, 1990; Lettenmaier and Sheer, 1991; Cayan *et al.,* 1993; Gleick and Chalecki, 1999; 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 (Snyder *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 (Lettenmaier and Gan, 1990; Lettenmaier and Sheer, 1991;Cayan *et al.,* 1993; Carpenter *et al.,* 2001; Miller *et al.,* 2003; Brekke *et al.,* 2004; Dettinger *et al.,* 2004; Vanrheenen *et al.,* 2004). Such studies are not of sufficient breadth or detail for understanding how management of California's vast integrated surface and ground water system might adapt to climate change. Water management analysis across California's complex highly integrated and inter-tied (interconnected) 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, ground water 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 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.

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
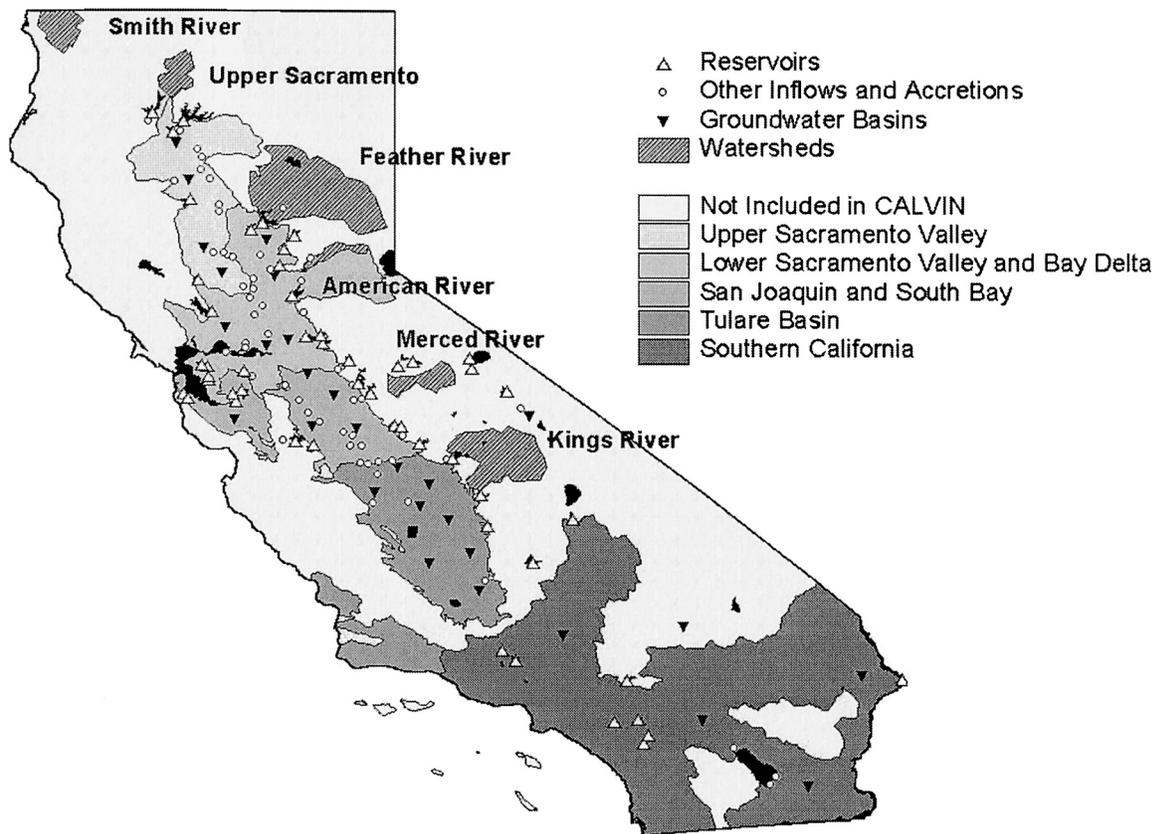
Figure 1. Index Basins and Hydrologic Components of CALVIN.

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 ground water basin centroids.

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. These future periods are labeled by their midpoints: 2025, 2065, and 2090. 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). 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 changes in incremental temperature (shifts) and precipitation (ratios) 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 their dependence on only precipitation and temperature.

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

1. 1.5°C temperature increase and 0 percent precipitation increase (1.5 T; 0 percent P).
2. 1.5°C temperature increase and 9 percent precipitation increase (1.5 T; 9 percent P).
3. 3.0°C temperature increase and 0 percent precipitation increase (3.0 T; 0 percent P).
4. 3.0°C temperature increase and 18 percent precipitation increase (3.0 T; 18 percent P).
5. 5.0°C temperature increase and 0 percent precipitation increase (5.0 T; 0 percent P).
6. 5.0°C temperature increase and 30 percent precipitation increase (5.0 T; 30 percent P).
7. HadCM2025 (1.4 T; 26 percent P).
8. HadCM2065 (2.4 T ; 32 percent P).
9. HadCM2090 (3.3 T ; 62 percent P).

10. PCM2025 (0.4 T; -2 percent P).
11. PCM2065 (1.5 T; -12 percent P).
12. PCM2090 (2.3 T; -26 percent 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 magnitude of annual high flow days.

METHODS

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

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 had 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 12) 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 through March and April through September, respectively) between each rim inflow and each index basin. The best index basin (when wet and dry seasons were 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 regimes and rainfall dominant runoff regimes. Thus, for each of 37 rim inflows the best matched index basins for wet and dry seasons are obtained, resulting in a 37 (rim inflow) by 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, requires that 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.

Ground Water and Local Runoff

To estimate climate change impacts on ground water inflows and local runoff, precipitation changes were partitioned into local runoff and deep percolation portions for each ground water subbasin. These changes were then added to corresponding historical ground water 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 ground water subbasin (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 to 1990 period (USBR, 1997). Deep percolation changes were then estimated for each ground water subbasin 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 ground water basins and had peak plateaus that 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 ground water subbasin.

Natural ground water inflows or recharge, excluding recharge from operational deliveries to agricultural and urban demand areas, for each ground water subbasin in the Central Valley from CVGSM can be represented as

$$GW = DP + SA + BF + SS + LS + AR \qquad (1)$$

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 subbasin from subsurface flows across basin boundaries, LS denotes seepage from lake beds and bedrock in the subbasin, and AR is seepage from canals and artificial recharge, all in bcm per month (bcm/mo). Assuming other components of ground water inflow are unchanged, changes in ground water inflow are equivalent to changes in deep percolation from changes in rainfall over each ground water subbasin, that is

$$GW^P = GW + \Delta DP \qquad (2)$$

where GW^P represents perturbed ground water inflow for the ground water subbasin, and ΔDP is change in deep percolation, both in bcm/mo.

To connect ground water inflow with local runoff, each ground water subbasin is associated with a local accretion area that coincides with the ground water subbasin. Local runoff associated with a ground water subbasin can be represented as

$$LR = R + AG \qquad (3)$$

where LR represents net local runoff, R denotes direct runoff, and AG is gain from the aquifer, all in bcm/mo. Incremental local runoff over a ground water subbasin equals incremental precipitation minus incremental deep percolation, so that

$$LR^P = LR + \Delta P - \Delta DP \qquad (4)$$

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

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.

RESULTS

Rim Inflows

There are 37 major inflows into the Central Valley. Historically, these rim inflows average 34.8 bcm/yr, accounting for 72 percent 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 percent more than historical under the wettest scenario, HadCM2090, and 25.5 percent 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, inflows

TABLE 1. Overall Rim Inflow Quantities and Changes.

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

increase much more significantly in winter than in summer, resulting in an overall shift in annual runoff from the dry season to the wet season in all scenarios except PCM2025.

Monthly mean total rim inflows for the 12 climate scenarios and historical inflows are plotted in Figure 2. It shows that 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.

Regional analyses show that rim inflows increase relatively more in the south than in the north with the extreme warm and wet climate in 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 decrease relatively more in the north than in the south during the dry season. These regional conclusions should be tempered by considering the

relatively poorer fit to index basins for more southerly locations, where there were fewer index basins.

Figure 2 illustrates the range of hydrological responses to climate change in California for mean monthly rim inflows across the 12 climate change scenarios. 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 percent) 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 that could induce additional evapotranspiration effects of climate change.
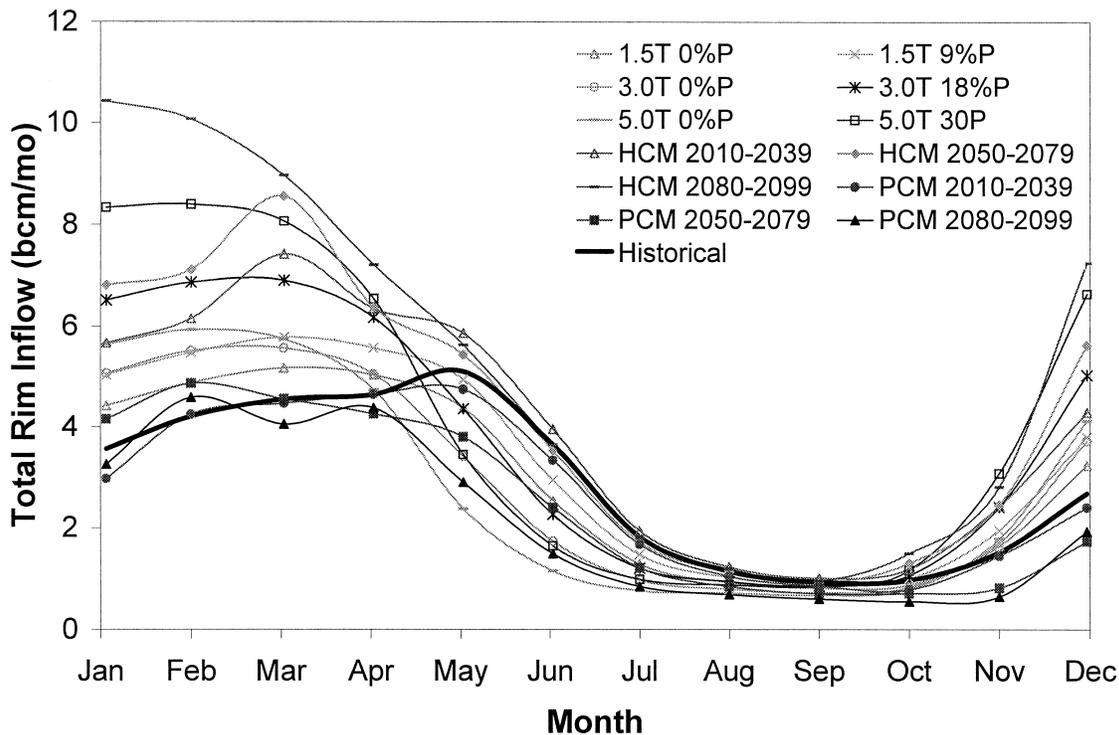
Figure 2. Mean Monthly Total Rim Inflow for 12 Climate Change Scenarios and Historical Record.

Ground Water and Local Runoff

The CALVIN model has 28 ground water inflows and 35 local runoff inflows (Figure 1). Due to limited data, the seven ground water subbasins outside the Central Valley are not studied, although these tend to have relatively small natural inflows. The 21 ground water subbasins and 21 corresponding nodes of local runoff in the Central Valley have been perturbed for climate warming. Total ground water 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 percent and 11 percent, respectively, of all inflows. Deep percolation of rainfall accounts for about 2.1 bcm/yr of the total 8.4 bcm/yr of average ground water inflow in the Central Valley. Under the historical climate, this volume represents only about 12 percent of precipitation falling over ground water subbasins in the Central Valley. Figure 3 shows quantity and changes of average annual ground water inflows over the modeled subbasins and average annual changes in local runoff.

For all the three GCM periods, ground water 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 infiltra-

tion capacity limits deep percolation. On average, local runoff in the wet season accounts for 80 percent of annual local runoff. Winter season ground water inflow accounts for 53 percent of annual ground water inflow. The proportions of winter season local runoff and ground water inflow increase with more-precipitation scenarios (parametric changes and HadCM2) and decrease with less precipitation scenarios (PCM).

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 percent 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 percent and 41.3 percent.
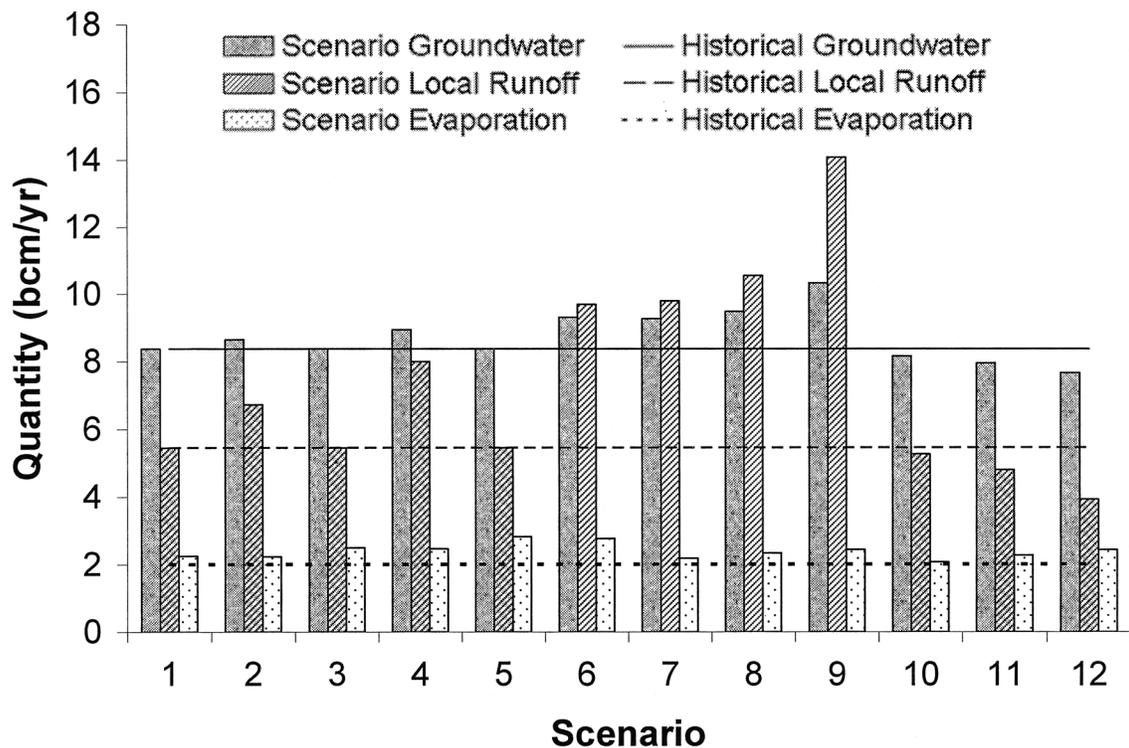
Figure 3. Average Annual Quantities of Ground Water Inflow, Local Runoff, and Surface Reservoir Evaporation.

Statewide Annual and Seasonal Inflows

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

TABLE 2. Overall Water Quantities and Changes.

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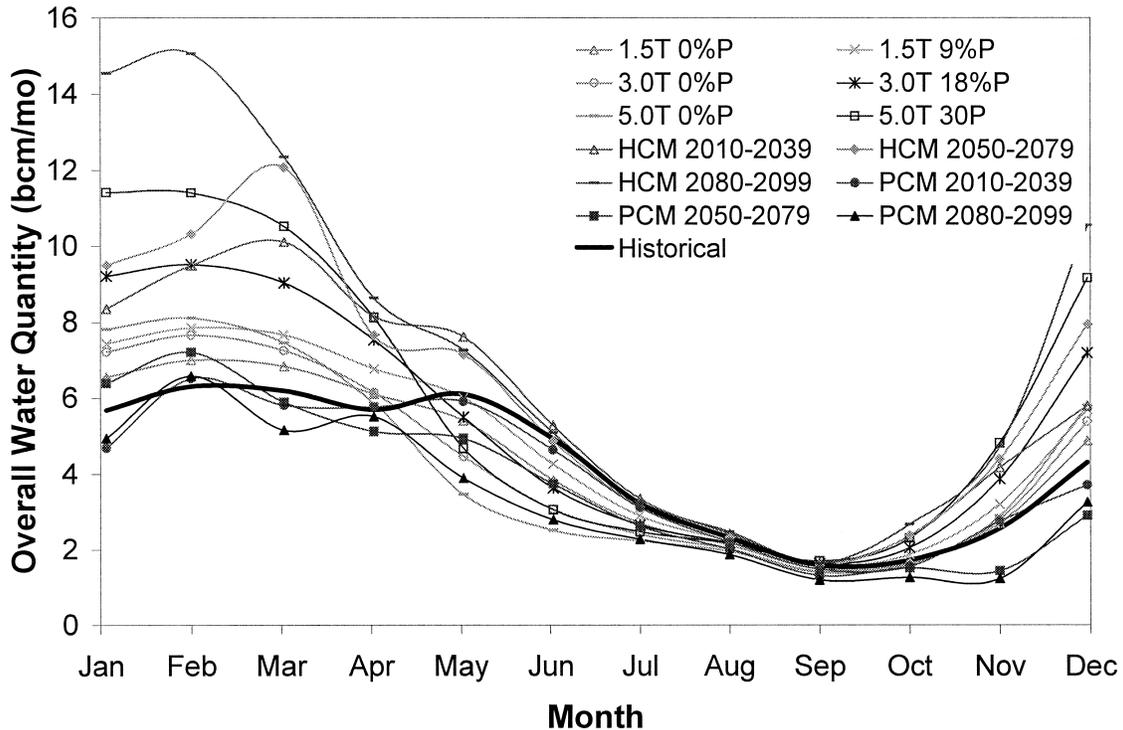
Figure 4. Mean Annual Overall Water Quantity for 12 Climate Change Scenarios and Historical Record.

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 that less water will be available and conditions will worsen with time. Compared with the historical average, drought years (1928 to 1934, 1976 to 1977, and 1987 to 1992) are expected to experience serious water decreases under the climate warming scenarios, though the HadCM2090 scenario shows only moderate reductions.

Figure 5 shows annual exceedence 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 that 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.
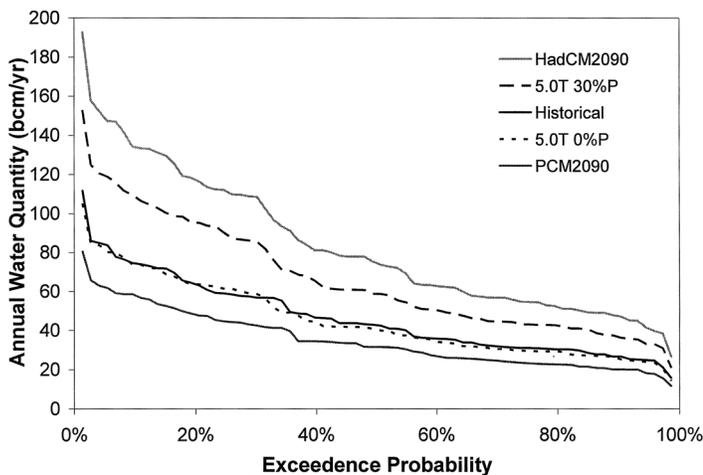
Figure 5. Overall Water Quantity Exceedence Probability.

Statewide Water Supply Availability

Approximate water supply changes with climate warming are estimated without modeling facility operations (Table 3). It is assumed that (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 ground water inflows directly affect water supply availability because they directly

affect ground water 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.

TABLE 3. Estimated Raw Water Supply Availabilities and Changes.

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

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.

Assuming that most wet season ground water inflows can be stored for dry season consumption, the relative decrease in water availability in the dry season, when combined with wet season ground water inflows, is much less significant than the relative decrease in either dry season rim inflows or overall water availability under the parametric and PCM scenarios that produce serious dry season water decreases. This indicates ground water inflow helps to dampen overall fluctuations in water availability.

Efficient ground water management such as conjunctive use and ground water banking could be crucial to meet increasing water demand under climate change conditions.

LIMITATIONS

By including multiple hydrologic components (particularly many rim inflows, local inflows, ground water inflows, and reservoir evaporation) over the entire system, this work provides 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, ground water inflow and local inflows are estimated solely based on deep percolation changes, with other influencing factors treated as unchanging. Furthermore, deep percolation for each ground water subbasin 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 significantly affect the results presented here. However, for drought years, this observed nonlinearity in hydrologic response lessens 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.

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 by 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 and expensive and would embody uncertainties in many hydrologic details as well as the significant uncertainties in the climatic boundary conditions driving any hydrologic representation of the system including the methods used herein. 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, that is, with a greater number of important hydrologic components and 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 nontechnical advantage of employing permutation of the 72-year historically derived time series as the 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).

TABLE 4. Rim Inflow Average Drought Year Statistics.

| Scenario | Method | Annual | | October to March | | April to September | |
		Quantity (bcm/yr)	Change (percent)	Quantity (bcm/yr)	Change (percent)	Quantity (bcm/yr)	Change (percent)
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

CONCLUSIONS

Inflows to California's entire intertied water system are estimated over a range of annual hydrologic conditions, represented by a systematic modification of the historical period covering water years 1922 through 1992. 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. Ground water 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 are 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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