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ANALYSIS OF POTENTIAL HYDROLOGICAL RESPONSES TO CLIMATE CHANGE WITHIN THE SAN JOAQUIN RIVER BASIN

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Abstract Data representing climate change projections were input to the NWS calibrated versions of the NOAA NWS Sacramento Soil Moisture Accounting Model with the Anderson Snow Model with the aim of assessing the potential impacts on water resources. The application area was 6 subcatchments of the Sacramento - San Joaquin drainage extending from the northwest and northern Sierra Nevada region to the southern Sierra Nevada region.

One relatively warm and wet projection ensemble member from the HadCM2 (Hadley Centre Climate Model Version 2), and one relatively cool and dry projection ensemble member (B06.06) from the PCM (DOE NCAR Accelerated Climate Prediction Initiative Parallel Climate Model), were used in this study to encompass the range of potential impacts. Statistically downscaled output from the two AOGCM baseline (1962-1991) and projection (1994-2100) model runs were used to calculate the average monthly changes in precipitation (ratio) and temperature (absolute) for 3 projected periods relative to the baseline. These monthly changes were imposed onto the observed 1962-1991 (baseline) precipitation and temperature time series and used as input forcing to the hydrologic simulations. The projected periods were selected to represent mean 2025 (2010-2039), 2065 (2050-2079), and 2090 (2080-2099) projected climate change.

To further assess the range of possible impacts, a range of fixed temperature (+1.5-+5^{o}c) and precipitation (70% - 130%) changes were superimposed on the historic data and used as input.

Simulated ranges of changes in streamflow amount and timing, annual peakflow, snow relative to elevation, and the likelihood of extreme events are discussed. The resulting streamflow changes were used as input to water demand and agro-economic models for a comprehensive set of San Joaquin River Basin subcatchments by assuming similar response sub-regions.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (Intergovernmental Panel on Climate Change, 2001) reports that climate model projections with a transient one percent annual increase in greenhouse gas emissions show an increase in the global mean near-surface air temperature of 1.4 to 5.8 ^{O}C, with a 95% probability interval of 1.7 to 4.9 ^{O}C by 2100 (Wigley and Raper 2001). This global mean is not uniform and the magnitudes of projected changes vary across the globe. In terms of California, signs of warming have already been noted, including a long-term decrease in the proportion of streamflow occurring in spring and summer, annual snowmelt occurring earlier, and increased salinity in the San Francisco bay delta. Downscaled data from the GCM projections suggest that California’s warming trend is likely to continue.

It is important to assess the potential impacts of these changes. There have been a number of investigations of California hydrologic response focused on changes in streamflow volumes or timing due to climate change (e.g. Revelle and Waggoner 1983, Gleick 1987, Lettenmaier and Gan 1990, Jeton et al. 1996, Miller et al. 1999, Wilby and Dettinger 2000, Knowles and Cayan 2001). Many of these studies suggest a continuing trend for earlier snowmelt, therefore a larger proportion of the streamflow occurring earlier in the year. A large proportion of the Sacramento-San Joaquin drainage is from snowmelt, and the snowpack during spring is often considered to represent the water resources available for the summer. Therefore these changes could affect the Sacramento-San Joaquin drainage in terms of water resources, salinity, water quality, and ecology.

This study focuses on possible streamflow changes resulting from climate change, and a companion paper (Hidalgo et al., this issue) shows the potential impacts of these changes on the Sacramento-San Joaquin drainage.

METHODOLOGY

Due to the large uncertainty in the magnitude of future changes in climate it is necessary to evaluate the impacts from a range of changes. The approach of this project was to compile a range of precipitation and temperature datasets representing potential future climate. These precipitation and temperature data were used as input to a hydrological model, and the outputs from the model runs give a range of possible future streamflow scenarios.

Study watersheds

The study watersheds were chosen to represent a range of elevations and hydrological regimes in the Sacramento-San Joaquin basin. The aim was that the responses could be used for other hydrologically similar basins for our collaborators to evaluate the effects on the Sacramento-San Joaquin drainage. Subbasins range from the low elevation coastal Smith, to the high elevation Merced in the Sierras (figure 1). All the basins excepting the Smith have significant snow accumulation, and therefore a large proportion of the annual streamflow is snowmelt. Due to the variation within the basins, the snow producing basins were divided into upper and lower subbasins (table 1) with separate forcings for the hydrological modeling.

	Smith	Sacramento	Feather	American	Merced	Kings
Area sq. km	1706	1181	9989	950	891	4292
Gage Lat.	41° 47’ 30”	40° 45’ 23”	39° 32’ 00”	38° 56’ 10”	37° 49’ 55”	36° 49’ 55”
Gage Lon.	124° 04’30”	122° 24’ 58”	121° 31’ 00”	121° 01’ 22”	119° 19’ 25”	119° 19’ 25”
Percent Upper	0	27	58	37	89	72
Upper Centroid		1798	1768	1896	2591	2743
Lower Centroid	722	1036	1280	960	1676	1067

Table 1. Basin Area, stream gauge coordinates, percent subbasin area and elevation.

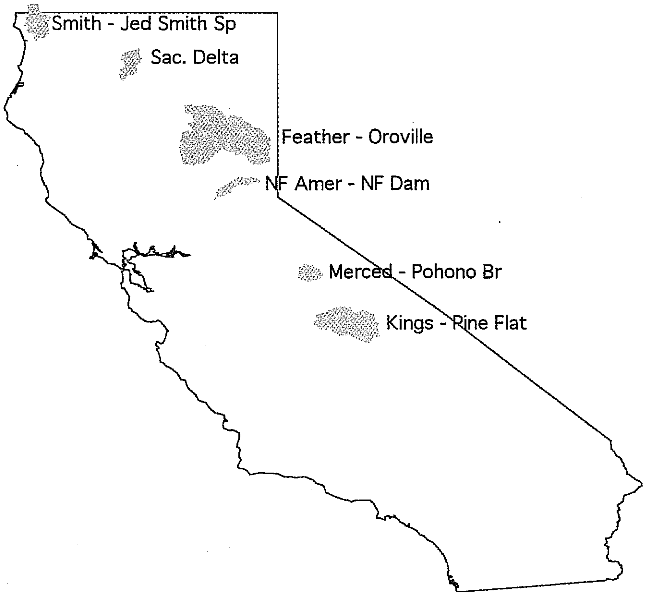

Figure 1 Location of the six study basins (Smith-at Jed Smith, Sacramento at Delta, Feather at Oroville Dam, North Fork American at North Fork Dam, Merced at Pohono Bridge, and Kings at Pine Flat).

GCM projections

The GCM projections chosen were the NCAR parallel climate model run to be referred to as PCM, and Hadley Centre run, to be referred to as HCM. These projections are relatively cool and dry, and relatively warm and wet respectively, compared to the range of projections for California from the IPCC report. They were chosen to represent the extremes of the range of potential changes from the GCM runs included in the IPCC report (IPCC TAR, 2001). The scale of GCM grid squares is far larger than the scale at which data are required for hydrological modeling; therefore it is necessary to downscale the GCM outputs. The precipitation and temperature data used here were statistically downscaled to the 10km scale using the PRISM technique (Daley et al. 1999), and the areal mean of these downscaled data were used for each catchment.

Many GCMs do not accurately represent historical and current climate, therefore it could be assumed that these biases also exist in the projections. To remove this bias it is necessary to calculate the change in climate between historical and future GCM runs, and superimpose these changes on historical measured data. Therefore differences between downscaled GCM outputs from these projection periods and the historical periods were computed, then superimposed on the National Weather Service measured 6 hourly data from the baseline period.

Both GCM projections give a significant increase in temperature (figure 2) but the Hadley model increase is more extreme. Changes also tend to be higher further East. The PCM model suggests an increase of 2.4C by the last period, whereas the HCM suggests a larger increase of around 3.3C.

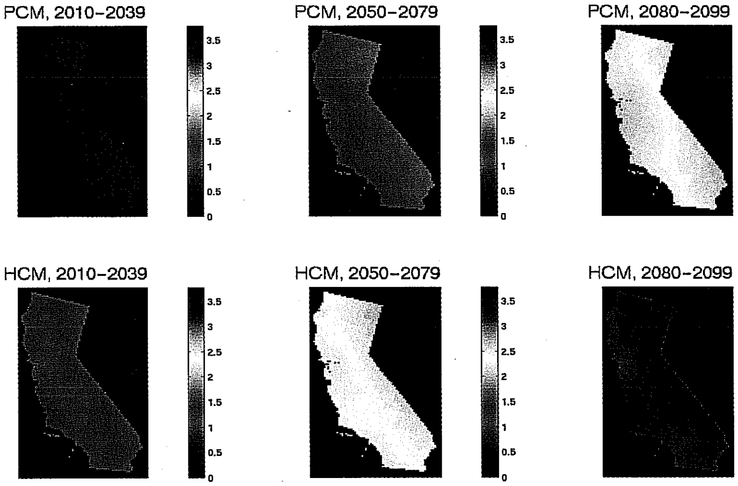

Figure 2 California climatological temperature shifts (°C) for PCM and HadCM2 averaged over the time periods 2010-2039, 2050-2079, and 2080-2099.

The precipitation changes are expressed in terms of a ratio (figure 3). The PCM suggests that there will be a decrease in precipitation that will reach 90% on average by the 2090 period. In contrast the Hadley projections suggest a large increase in precipitation. This varies spatially and is as high as doubled precipitation near the coast.

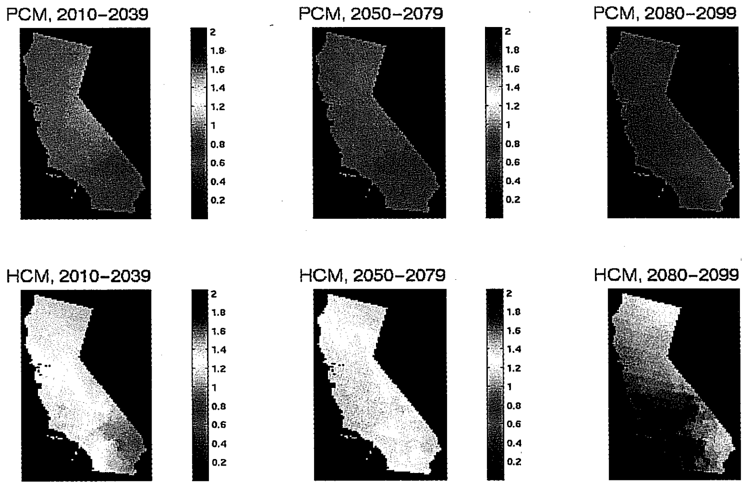

Figure 3 California mean-area climatological precipitation ratios for PCM and HadCM2 averaged over the time periods 2010-2039, 2050-2079, and 2080-2099.

For each projected period, the average temperature for each calendar month averaged over all the years was calculated. The average monthly temperature for the baseline period was subtracted to result in monthly temperature shifts. There is little seasonal variation in temperature changes, although the Hadley changes tend to be higher in January for the 2090 period. These monthly shifts were added to the 6 hourly measured data from the baseline period, to give the climate change input data for hydrological modeling.

The 6 hourly climate change precipitation data were calculated in a similar manner, except that the monthly changes were calculated as a ratio. The precipitation changes show a lot more seasonal variation, and those seasonal variations show different trends for the different periods and models (figure 4).

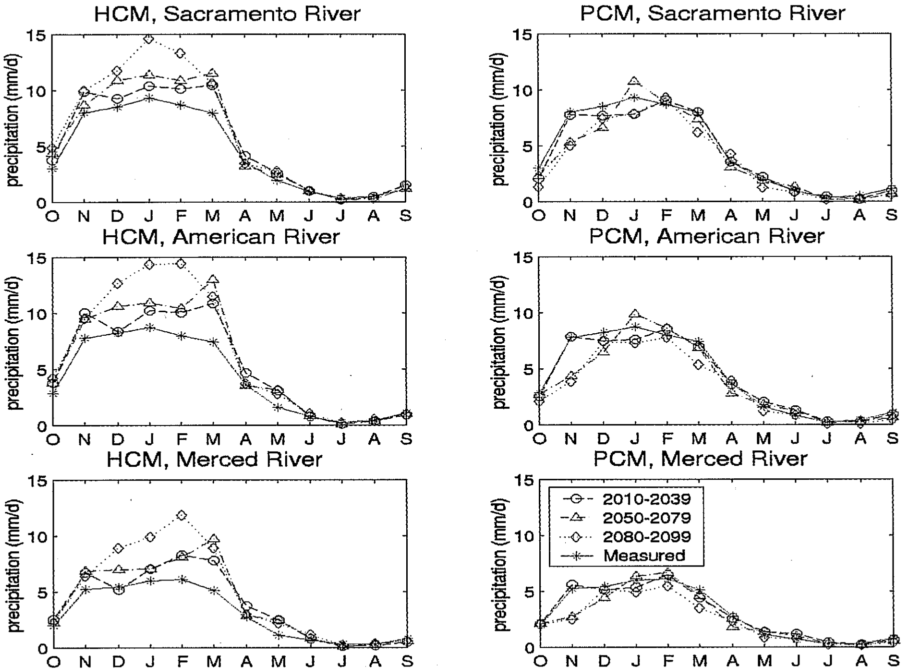

Figure 4 HadCM2 (HCM) and PCM precipitation ratios imposed on the NWS observed temperatures at the Sacramento, American, and Merced study basins.

Specified changes

To further evaluate the range of potential outcomes a range of temporally and spatially uniform changes were also simulated. Although the magnitude of the change is uncertain, all GCM projections seem to imply an increase in temperature in California, therefore a range of temperature increases was selected, up to 5 °c. In terms of precipitation both the direction and magnitude of the change is uncertain, therefore a range of +/- 30 % was simulated.

Hydrological Model

The temperature and precipitation time series with these changes imposed were input to the Sacramento soil moisture accounting model coupled to the Anderson snow model. The Sacramento soil moisture accounting model consists of soil moisture storage in, and movement between 5 compartments (figure 5, Burnash et al., 1973). The Anderson snow model is also termed SNOW-17, and represents the dominant processes affecting snow accumulation and ablation (Anderson, 1973). The parameter set used by the National Weather Service for flood forecasting was used. The model was run with historical data from the baseline period and the outputs compared well with measured streamflow. These data are termed the baseline or verification set and were used for comparison.

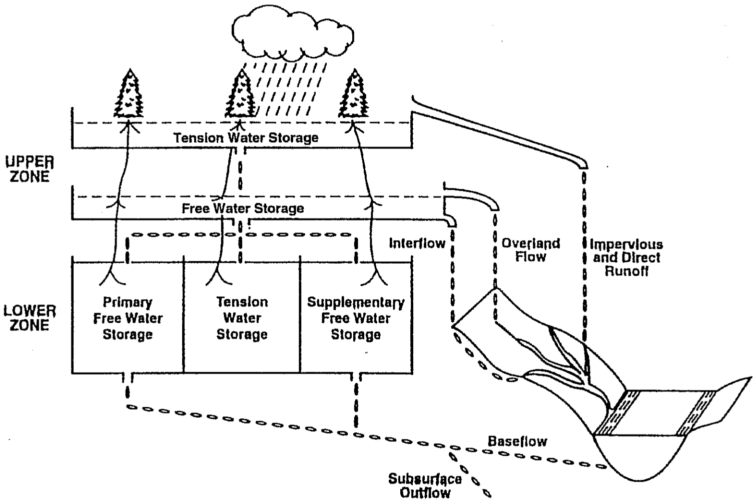

Figure 5 Schematic of Sacramento Soil moisture accounting model

RESULTS

GCM projections

The average monthly streamflow corresponding to the GCM derived precipitation and temperature changes show that in all cases an increased temperature has led to a larger proportion of streamflow occurring earlier due to snowmelt (Figure 6). This could have implications for flooding in the snowmelt periods, particularly in the case of the Hadley model where some average monthly flows are more than doubled. The PCM results suggest that low flows later in the season could be a problem.

The state of California water resources is sometimes quantified in terms of the snowpack on April 1st. Figure 7 shows the average snow water equivalent over the basins at the end of each month relative to the current day. According to both GCM projections, the April 1^{st} snowpack could be reduced to 50% of that of current day by the 2090 period, except for the case of the high elevation Merced.

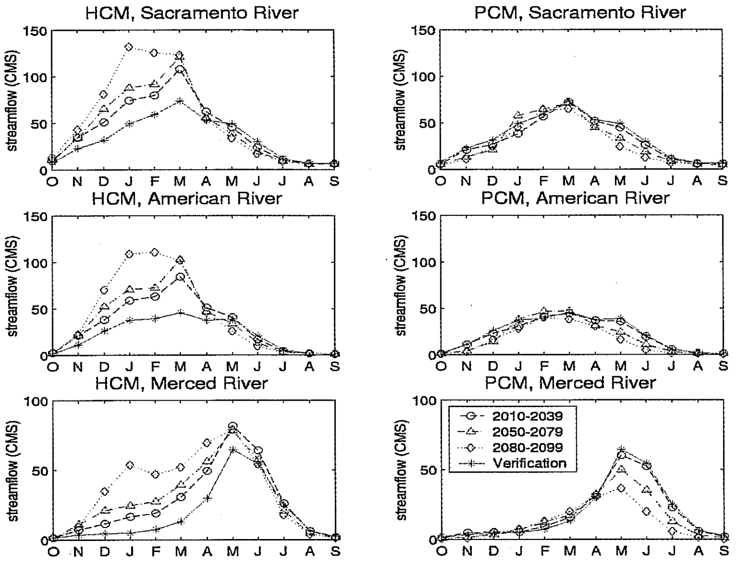

Figure 6 Streamflow monthly climatological averages based on the HadCM2 (HCM) and the PCM.

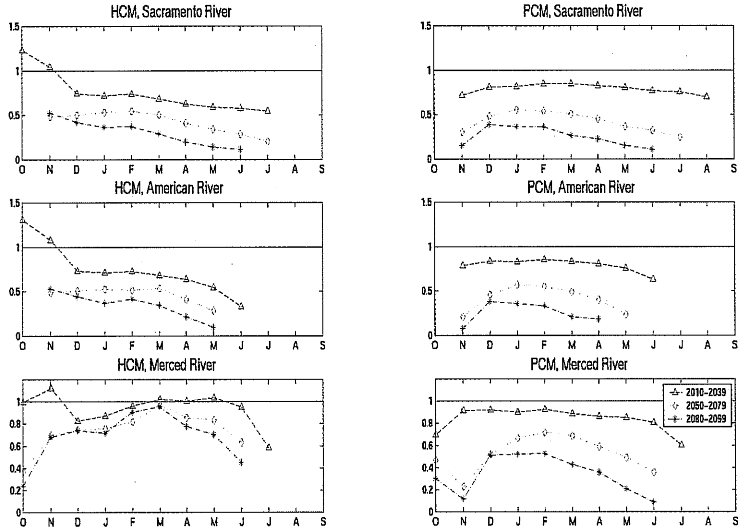

Figure 7 Ratio of climate change to baseline mean-monthly Snow Water Equivalent (SWE) for each basin.

Climate change could also lead to changes in the likelihood of extreme events. The GCM projections suggest a significant increase in the likelihood of high flow events, even in the case of reduced precipitation (figure 8).

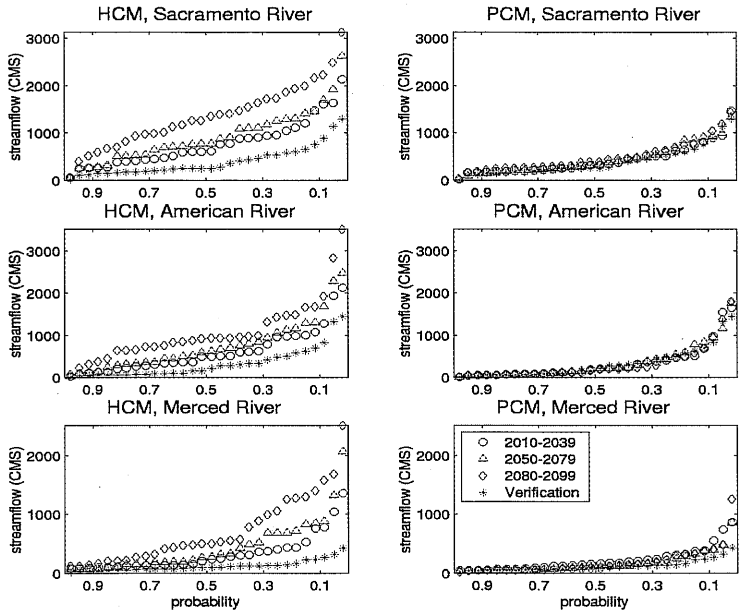

Figure 8 Exceedance probabilities of the daily flow for each climate change scenario

Specified Changes

The incremental precipitation and temperature change data are useful for analyzing precipitation and temperature effects. The monthly streamflow effects of increased precipitation and temperature increases of 1.5, 3 and 5 degrees are shown in figure 9.

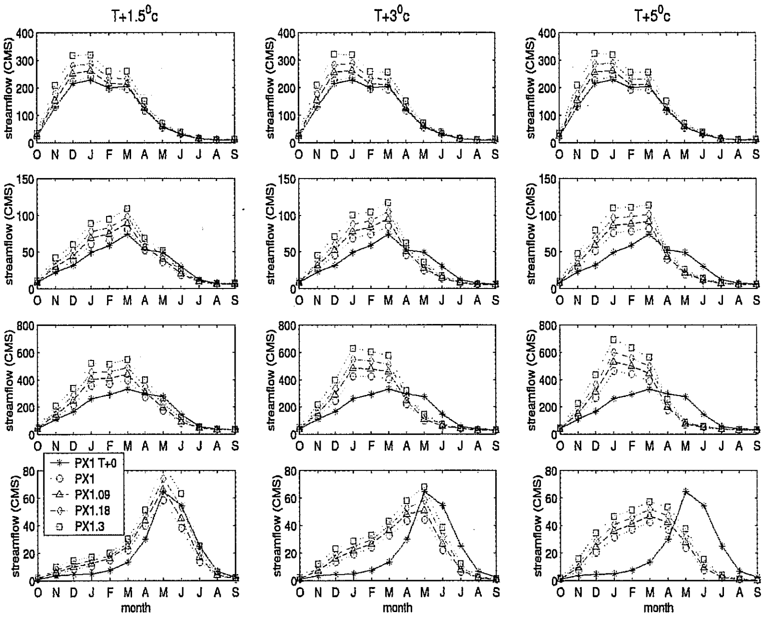

Figure 9 Streamflow monthly climatologies based on the specified changes for (top to bottom) Smith (722m), Sacramento (1242m), Feather (1563m), and Merced (2490m) with temperature increases (1.5C, 3 C, and 5C, left to right) for increasing precipitation.

The Smith, at 722m has little snow accumulation, therefore the increase in temperature has little effect on streamflow timing, and the proportional increase in streamflow is fairly uniform seasonally. For the higher elevation snow accumulating basins, as the temperature increases the snowmelt tends to occur earlier. The timing shift is not too extreme in the Sacramento where there is less snow accumulation than in the higher basins. It is fairly extreme in the Feather, and the high elevation Merced requires a higher temperature increase to lead to a significant snowmelt timing shift because the high elevation temperatures are so much below freezing under present day conditions.

With reduced precipitation and the equivalent increases in temperature, again a higher proportion of streamflow occurs earlier in the year, but in this case it leads to more extreme low flows later in the season (figure 10). This could lead to significant problems in terms of water resources, salinity and ecology.

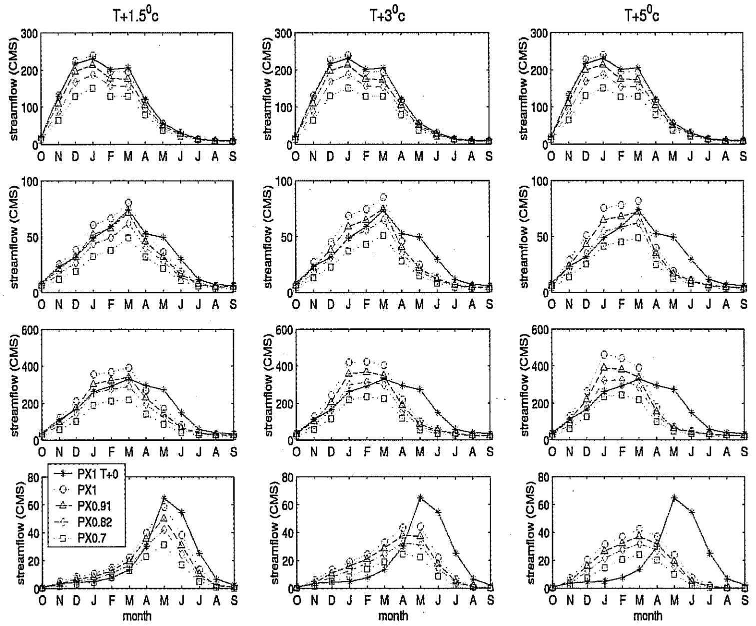

Figure 10 Streamflow monthly climatological averages based on the specified changes for Smith, Sacramento, Feather and Merced (top to bottom) with temperature increases (1.5 oC, 3 oC, and 5 oC, left to right) for decreasing precipitation

The effects that temperature has on the snowpack is clearly shown by the change in snow water equivalent. Even with a 30% increase in precipitation, temperature increases resulted in less snowpack, except for a slight increase in the high elevation Merced (figure 11). With reduced precipitation the snowpack would be even lower.

The effects of precipitation and temperature changes on high flow events varies with elevation. Figure 12 shows the mean maximum annual flow for each combination of incremental temperature and precipitation changes. An increase in precipitation leads to a higher proportional increase in high flows in each case. Therefore a situation of doubled precipitation might lead to quadrupled flood magnitudes, as the antecedent conditions would be more storage, in terms of soil moisture or snow.

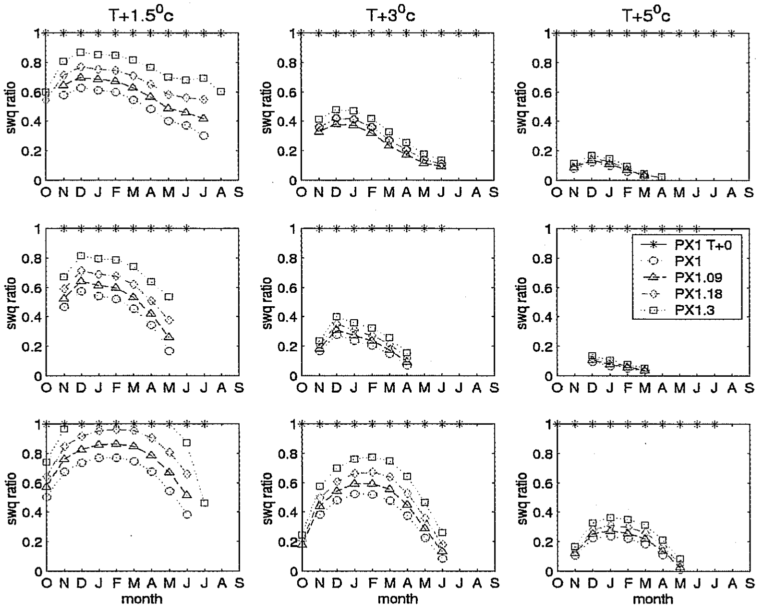

Figure 11 Ratio of climate change to baseline mean-monthly Snow Water Equivalent (SWE) for Sacramento (top), Feather (middle) and Merced (bottom) basins, increasing precipitation.

For all snow producing basins high flows are sensitive to temperature changes, which suggests that the high flow events are snowmelt or rain on snow events. At smaller temperature changes the mid altitude feather is most sensitive, probably because the winter temperatures for a lot of the basin area are just below freezing under present conditions. A small increase leads to temperatures above freezing, therefore less snow accumulation and earlier melting.

A larger temperature increase of 5 °C does not lead to much higher high flows in the Feather than that of 3 °C, however the Merced is very sensitive to temperature change within this range. An increase of 5 °C could lead to average annual high flows of 2 1/2 times those of present day in the Merced. The Sacramento high flows are less sensitive to temperature and more sensitive to precipitation than the other snow producing basins.

DISCUSSION

Limitations

There are a number of limitations to the current status of the assessment of climate change impacts on hydrology. The use of average monthly (or uniform) changes imposed on historical data does not give a representation of the shorter timescale changes such as shorter and more intense precipitation events, and larger diurnal temperature ranges that may be associated with climate change. However use of projected data would include bias associated with GCMs, and the hydrology model is calibrated for historical conditions.

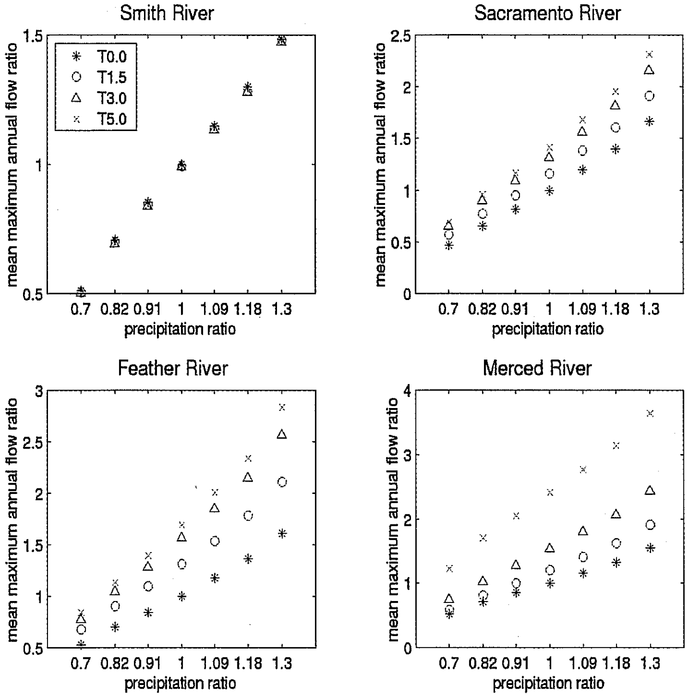

Figure 12 Ratio of mean annual high flow for changing temperature and precipitation to the baseline historical mean annual high flow for all 28 possible incremental combinations.

The assumption that the model and parameter set are applicable under changed conditions may not be valid. In particular, the Sacramento model parameter set is based on historical conditions, therefore the likely evapotranspiration changes were not modeled. This is not very significant in the winter but could affect springtime and summer results.

Despite these limitations, this study follows current practice, and gives a range of possible scenarios to evaluate potential impacts.

Conclusions

The GCM results all suggest earlier snowmelt for the snow producing basins. The Hadley suggests increased flow overall and is very extreme, whereas the PCM is less extreme and suggests reduced overall streamflow. In both cases the likelihood of higher flows increases significantly.

Temperature increases are likely to lead to a continued trend of increasing early snowmelt and streamflow. They would also lead to higher high flows, and lower flows in the spring and summer. These effects vary with elevation of the basin, and magnitude of the change. The effects of precipitation changes affect the volume rather than the timing of flows. Lower precipitation could still lead to more flooding, and higher precipitation to more extreme low flows due to the effects of temperature increases.

The main points to summarize are firstly that although potential effects are uncertain, it seems likely that increased temperatures would lead to lower water availability in spring and summer. This could affect water resources, water quality and ecology in the Sacramento-San Joaquin drainage, and these possible changes should be assessed. Secondly, there could also be more extreme high flows even if precipitation was reduced, therefore it may be necessary to think about increasing flood protection.

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