

ELEVATIONAL DEPENDENCE OF PROJECTED HYDROLOGIC CHANGES IN THE SAN FRANCISCO ESTUARY AND WATERSHED

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Abstract. California's primary hydrologic system, the San Francisco Estuary and its upstream watershed, is vulnerable to the regional hydrologic consequences of projected global climate change. Previous work has shown that a projected warming would result in a reduction of snowpack storage leading to higher winter and lower spring-summer streamflows and increased spring-summer salinities in the estuary. The present work shows that these hydrologic changes exhibit a strong dependence on elevation, with the greatest loss of snowpack volume in the 1300–2700 m elevation range. Exploiting hydrologic and estuarine modeling capabilities to trace water as it moves through the system reveals that the shift of water in mid-elevations of the Sacramento river basin from snowmelt to rainfall runoff is the dominant cause of projected changes in estuarine inflows and salinity. Additionally, although spring-summer losses of estuarine inflows are balanced by winter gains, the losses have a stronger influence on salinity since longer spring-summer residence times allow the inflow changes to accumulate in the estuary. The changes in inflows sourced in the Sacramento River basin in approximately the 1300–2200 m elevation range thereby lead to a net increase in estuarine salinity under the projected warming. Such changes would impact ecosystems throughout the watershed and threaten to contaminate much of California's freshwater supply.

1. Introduction

California's largest hydrologic system comprises San Francisco Estuary and its upstream watershed (Figure 1), and is one of the most highly managed hydrologic systems in the world. A heavy dependence on artificial (reservoirs) and natural (snowpack) freshwater storage creates a particular susceptibility to the effects of potential global warming.

The San Francisco Estuary is the third largest in the United States, supporting a wide variety of flora and fauna, including many endangered species. The delta of the Sacramento and San Joaquin Rivers, which provide nearly all the estuary's freshwater, is also the hub of California's freshwater management infrastructure. This freshwater storage and transport system is vital to the State's economy, providing water to meet agricultural, municipal, industrial, and environmental demands.



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Figure 1. The San Francisco estuary and its watershed, with major geographic features indicated. The inset shows the watershed's location within California.

Annually, the Sacramento–San Joaquin watershed generates an average 30–40 km³ (~24–32 maf) of freshwater runoff derived from rain and snow. The Sacramento River is sourced in the moderate-altitude Cascades and northern Sierra, while San Joaquin flows are generated in the high southern Sierra. California depends on artificial and natural storage to make this supply last the rest of the year. Snowmelt runoff accounts for at least 40% of the annual supply, as indicated by discharge occurring after April 1st (Roos, 1989). Total artificial storage in the watershed's major reservoirs is about 35 km³, roughly the size of the average annual freshwater endowment. Highly variable winter and spring runoff is managed as a flood hazard, meaning it is released from reservoirs as quickly as necessary to maintain sufficient flood control storage space. After April, the management goal is reservoir recharge, accumulating the steady stream of snowmelt runoff for distribution later in the year. Approximately 80% of California's 'non-environmental' water use is due to agricultural irrigation, which is highly peaked in the summer (CDWR, 1998).

Many studies have shown that the effects of a warmed climate in this system would include reduced snowpack storage, higher flood peaks during the rainy season, and reduced warm-season flows after April (Gleick, 1987; Roos, 1989; Lettenmaier and Gan, 1990; Jeton et al., 1996; Gleick and Chalecki, 1999; Snyder

et al., 2002; Knowles and Cayan, 2002; Dettinger et al., 2004, this issue), adversely impacting many who depend on California's freshwater supply infrastructure. These hydrologic changes would propagate downstream to the estuary, resulting in an altered salinity regime (Knowles and Cayan, 2002). During the spring and summer, the lower streamflows and increased salinities would impact many species that depend on the estuary and rivers. The risk of contamination of freshwater supplies by salinity intrusion would also be greater.

While such studies have offered some insight into the spatial distribution of hydrologic change, a detailed exploration has been lacking. One relationship that may be exploited to refine our estimation of spatial detail is the strong dependence of hydrologic impacts of climate warming on elevation. It is generally understood that a warming trend would have stronger hydrologic impacts at moderate altitudes than at higher, colder ones or than at lower elevations with less snowpack. The present study attempts to refine this understanding by developing quantitative estimates of the elevational dependence of hydrologic change in the watershed of the San Francisco Estuary. Further, the dependence of downstream estuarine impacts on the elevational distribution of upstream changes is investigated.

This study builds on the results and methods of previous work (Knowles and Cayan, 2002), which provided estimates of the impact of warming on snowpack and streamflow throughout the watershed, and on salinities in the estuary. A strong elevational dependence of the hydrologic response was evident in that work, but was not the focus of investigation. Here, new hydrologic and estuarine modeling capabilities allow water parcels to be tracked through the system to understand what elevations are most sensitive to a projected climate warming, and how hydrologic changes at various elevations propagate through the system and could potentially affect estuarine inflows and salinity. This more detailed understanding of the hydrologic and estuarine effects of potential climate change could be useful as water managers and others attempt to understand and prepare for possible changes.

2. Methods

A revised version of the approach of Knowles and Cayan (2002) is used, wherein projected temperature changes from the Parallel Climate Model are used to drive a hydrologic model of the watershed, the Bay-Delta Watershed Model, which in turn drives a model of the San Francisco Estuary, the Uncles-Peterson Model.

In California, the Parallel Climate Model (Dai et al., 2001) projects a near-surface air temperature increase of just over 2 °C during the course of the 21st century, in response to a hypothesized 'business-as-usual' buildup of greenhouse gases in the atmosphere. While there is a consensus among global models on the occurrence and approximate magnitude of temperature increase, precipitation is a much more variable process. In response to the projected 21st century greenhouse-

gas buildup, the PCM projects relatively little overall change in the amount of precipitation California receives. During the recent National Climate Change Impacts Assessment (Felzer, 1999), however, other models have forecast increases. Thus, the magnitude and even the direction of possible precipitation changes in California remains an area of considerable uncertainty. Because of the uncertainty shrouding global change effects on patterns, intensity and seasonality of precipitation, we focus here solely on the effect of temperature change on the San Francisco estuary and watershed, taking the position that the PCM forecast of (essentially) no precipitation trend is a good starting position for these experiments. As in Knowles and Cayan (2002), in this paper the precipitation is simply prescribed from historical (time-varying) values, while the temperature is given as historical values plus a monthly adjustment for the projected climate change component.

To isolate the effects of temperature increase, simulated mean monthly maximum (T_x) and minimum (T_n) daily temperatures from a 1995–2099 PCM run were averaged over the watershed to generate 12 mean monthly T_x and T_n anomalies for the period 2050–2069 relative to 1995–2005 mean monthly values. Averages over the 2050–2069 period are hereafter referred to as the conditions for 2060. The resulting anomalies represent estimates of mean monthly T_x and T_n changes averaged over the Sacramento–San Joaquin watershed for the year 2060, relative to ‘present conditions’, which are approximated by the 1995–2005 values. Inspection showed that the values thus obtained are representative of the warming trend in all of the PCM ensemble members and are not significantly influenced by the interdecadal variability present in these runs.

These 12 monthly mean anomalies were added separately to historical daily temperature (T_x and T_n) time series distributed over the watershed from water years (WY) 1965–1987. This 23-year period was chosen for its complete coverage of required model input data. Along with the adjusted temperature time series, daily historical precipitation (amounts unchanged but rain/snow partitioning consistent with adjusted temperatures) data from the same period were used as inputs to a hydrologic model of the watershed, resulting in simulations of watershed snowpack and streamflow representing the watershed’s hydrologic behavior under the projected 2060 temperature regime. A control simulation was also performed using unchanged WY 1965–1987 precipitation and temperature to represent the watershed’s present hydrologic regime.

The historical temperature and precipitation series used in conjunction with the PCM-generated temperature anomalies to generate meteorological forcing were derived using a spatial interpolation method combined with a study of elevational lapse rates throughout the watershed (Knowles, 2000). Also accounted for was the influence of orography on rising air parcels through adiabatic and pseudoadiabatic processes, using the method of Georgakakos and Bras (1984). The resulting meteorological fields and simulated hydrology agreed well with measurements throughout the State. In particular, comparison with snowpack observations indicated that critical, high-elevation meteorological and snowpack processes are

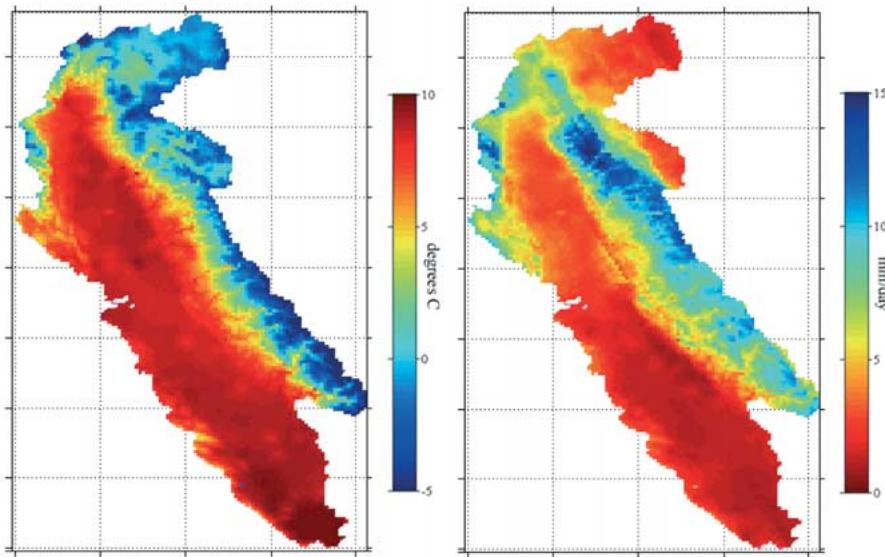


Figure 2. Spatial distributions of average winter (DJF) surface air temperature (left) and precipitation (right) throughout the watershed.

represented with reasonable accuracy, a particular challenge given the paucity of high-elevation meteorological observations in California. The resulting spatial distributions of winter temperature and precipitation are shown in Figure 2. The mean monthly values of precipitation and temperature corresponding to recent (1965–1987) historical and a 2060 changed climate are shown in Figure 3.

In the approach used here, the historical temperature and precipitation data represent natural meteorological variability throughout the watershed at daily to decadal time scales. The century-scale effects of global warming are included by superposition of the PCM-generated monthly watershed-wide temperature anomalies on the historical temperatures. A recent analysis of PCM outputs suggest that the background of anthropogenic change is largely uncorrelated with more quickly varying climate modes such as ENSO and PDO (Dettinger et al., 2004, this issue), supporting the validity of this superposition. This approach provides a simple method of evaluating the impacts of the projected long-term warming trend while retaining the robust representation of fine-scale spatial and temporal variability afforded by the interpolation methods described above. By using 23 years of historical data (WY 1965–1987) as the basis for daily to decadal climate variability, we also include a large range of hydrologic conditions in the projections.

The Bay-Delta watershed model (BDWM) used for these simulations is a physically based, soil moisture accounting model with a daily time step and a horizontal resolution of 4 km (Knowles, 2000). The snow component of this model is the Utah Energy Balance (UEB) snow model (Tarboton and Luce, 1996), which has been shown to accurately reproduce Sierran snowpack variability. Based on work by

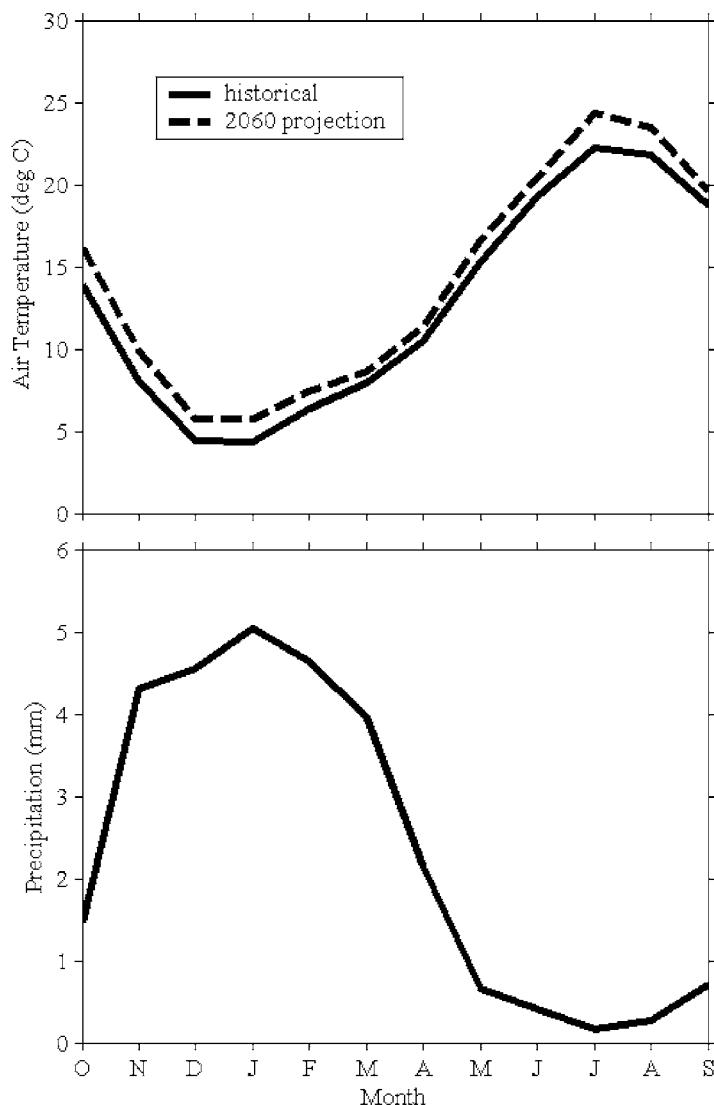


Figure 3. Mean monthly watershed-averaged temperature (top) and precipitation (bottom). Both historical and projected 2060 temperatures are shown; precipitation is not changed from historical values in the 2060 projection.

the U.S. Army Corp of Engineers (1956), the UEB model determines precipitation partitioning into rain and snow based on near-surface air temperature (precipitation is all snow if $T < -1^{\circ}\text{C}$, all rain if $T > 3^{\circ}\text{C}$, a linearly varying mix of snow and rain in between) then simulates the evolution of the snowpack's energy budget to determine melt patterns. Different methods and threshold temperatures for determining precipitation partitioning were evaluated; comparison of simulated snow

water equivalent with observations throughout the Bay-Delta watershed verified that UEB's current approach provides good agreement.

The BDWM routing component is based on work by Georgakakos et al. (Georgakakos and Bras, 1982; Georgakakos and Baumer, 1996). The BDWM reproduces observed streamflow variations throughout the watershed with sufficient accuracy to indicate that it contains a reasonably valid representation of the physical processes generating this variability. A particular feature of the BDWM used in the present study is its ability to track a water parcel from its source. Specifically, the model categorizes runoff from each of approximately nine thousand 16 km² grid elements into thirty-eight 100-m elevation bins and tracks the water that originates in these elevation ranges as it progresses through the hydrologic system. This allows the composition of simulated watershed outflow to be quantified in terms of its distribution by source elevation.

In order to more realistically simulate the elevational composition of watershed outflow, it was necessary to incorporate a representation of management effects in the watershed into the BDWM. Present-day watershed outflow patterns are changed significantly from the 'undisturbed' state by alterations including reservoirs and freshwater pumping, which reduce April–June outflow by ~45%. These effects must be accounted for when propagating climate-induced changes from the headwaters to the estuary. This was accomplished by building on the results of an earlier analysis (Knowles, 2000) that quantified effects of reservoirs and freshwater exports on watershed outflow. There, release and recharge rates for ten major reservoirs were estimated using flow data from the U.S. Geological Survey and the California–Nevada River Forecast Center.

Historical reservoir actions over the 1965–1987 period are used in the simulations conducted here. All simulated runoff above a given reservoir was assumed to enter that reservoir's storage pool, determining the composition of the pool according to source elevation. In both the control and the climate change runs, releases from the reservoir are identical to historical releases (reservoirs never fully emptied in either scenario). Releases from a reservoir were assumed to draw from a well-mixed (with regard to elevational composition) pool, thus determining the elevational composition of daily outflows from each reservoir.

Historical (1965–1987) diversions below the major reservoirs are also included in these simulations. The combined effect of historical in-stream diversions and groundwater contributions in the Sacramento and San Joaquin Valleys were inferred as the difference between simulated and observed historical runoff contributions from these local basins. This contribution is added to or removed from, depending on its sign, each day's reservoir outflows to yield Valley outflows. This approach uses U.S. Geological Survey flow data (<http://waterdata.usgs.gov/ca/nwis/sw>) and is described further in Knowles (2000). In the climate change run, if historical demand exceeds the altered supply, only available water is withdrawn, at a rate equal to historical reservoir outflow. The remaining demand is assumed to be unmet under the warmed climate.

The final management effect that was accounted for when tracking water parcels to the watershed outflow was diversions within the Delta region. Pumps in this region export freshwater into aqueducts that transport the water to distant regions of need. Knowles (2002) provides estimates of in-Delta diversions, based on data from the California Department of Water Resources (CDWR, 1999). Such diversions, as with reservoir releases and in-stream Valley diversions, were assumed to draw evenly from all elevational components flowing into the Delta.

After accounting for reservoirs, in-stream Valley diversions, and in-Delta withdrawals, the BDWM provides estimates of the elevational composition of daily historical watershed outflows for the period 1965–1987. This approach is not intended to constitute an operations modeling component, merely to account for historical patterns of reservoir operations and freshwater manipulations when routing watershed runoff to the estuary. An advantage of this approach is that it provides a daily accounting of freshwater manipulations, whereas most operations models use a monthly time increment. A distinct disadvantage is that it does not account for potential management adaptations or altered demand patterns in response to future changes. The results will nonetheless be shown to provide insight into management possibilities and monitoring needs. VanRheenen et al. (2004, this issue) present a discussion of alternate management scenarios.

The final step in these simulations was to use simulated watershed outflow magnitude and elevational composition from the 23-year BDWM (a) control and (b) climate change simulations to drive simulations of the estuarine response in the San Francisco Bay-Delta. The Uncles-Peterson (U-P) estuarine model, an advective-diffusive intertidal box model of the San Francisco estuary with a daily time step, was used to perform the estuary simulations. This model has been applied in several previous studies of the estuary and has been shown to accurately reproduce salinities at weekly to interannual time scales over a wide range of flow regimes (e.g., Peterson et al., 1995; Knowles et al., 1998). Possible effects from sea level changes are not included in these simulations. Like the BDWM, the U-P model possesses the capability to track water parcels throughout the estuary (see Knowles et al., 1997); this capability is exploited here in conjunction with the BDWM output to estimate changes in the elevational composition of freshwater in the San Francisco Estuary resulting from projected climate warming.

3. Results

3.1. SNOWPACK AND RUNOFF CHANGES

In present day, snow accumulation peaks around April 1. Knowles and Cayan (2002), using the same forcing and modeling framework, found that the combination of warmer storms and earlier snowmelt caused April watershed-total snow accumulation to drop to 95% of present levels by 2030, 64% by 2060, and 48%

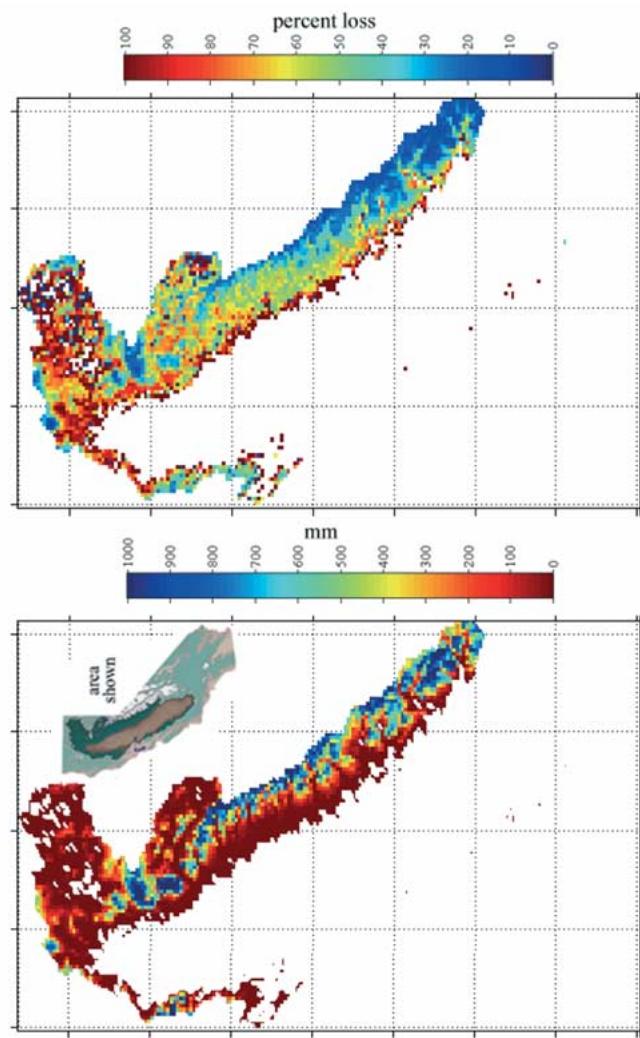


Figure 4. Projected 2060 snowpack changes in the Bay-Delta watershed resulting from climate warming. Left: Present-day April snow water equivalent in mm. Right: Percent SWE lost by 2060.

by 2090. Simulated snowpack under warmed conditions for the 2060 time frame (Figure 4) depicts a severe loss of snow as indicated by relative changes in the April snow water equivalent (SWE) throughout the watershed. A PCM-predicted average surface air temperature increase over the watershed of 1.6°C by 2060 causes the loss of about one-third of the total April snowpack (by water volume). This relative loss is focused in mid to lower elevations, since snowpack there is more sensitive to temperature changes than at higher, colder elevations. Note that since overall precipitation is conserved in this projection, the lost snowpack appears instead as early runoff. In general, the loss of snowpack from the imposed climate warming results in higher runoff peaks prior to April and reduced snowmelt-driven flows in subsequent months.

An important property of the relative snowpack reductions depicted in Figure 4 is a strong dependence on elevation. Figure 5 (right) shows the relative 2060 SWE losses from the Sierra region plotted against elevation. The elevational dependence appears clearly. These reductions act upon the present-day April snowpack distribution, shown versus elevation in Figure 5 (left). At elevation zones below 2000 m, more than half of the snowpack water volume is lost. Comparing these two plots depicting the elevational distribution of snowpack and relative snowpack reduction resulting from projected warming, we see that for moderate altitudes, significant relative reductions occur in zones that have historically accumulated significant snowpack, making these altitudes maximally sensitive to climate change. In fact, a plot of total snowpack volume lost in 2060 relative to present conditions (Figure 6) suggests that the largest reductions in SWE volume would occur at elevations between approximately 1500 and 2000 m as a result of the projected warming.

Figure 6 also demonstrates another factor that affects the changes in total SWE volume – the distribution of area with elevation. The northern headwaters exhibit a strong maximum in this distribution around 1500 m, while the southern headwaters are more evenly distributed with significantly more area above 2000 m. Consequently, the most significant losses occur at higher elevations in the southern Sierra than in the more moderate-altitude northern Sierra. In the northern Sierra, 85% of the SWE losses occur between 1300 and 2200 m, while in the southern Sierra, 85% of the losses occur between 1800 m and 3300 m. Total projected 2060 reduction in April SWE volume is about 38% in the northern headwaters and 23% in the southern headwaters.

These snowpack changes cause changes in the simulated outflow from the Sierran and Cascade headwater basins as shown in Figure 7. By 2060 both the northern (Sacramento) and the southern (San Joaquin) headwaters show the effect of reduced snowpack, with the largest streamflow impacts in the north. The April–July fraction of total annual flow in the northern headwaters is reduced from 0.36 in 2030 to 0.26 in 2060. Combined with a smaller reduction in the south, this represents over 3 km^3 ($\sim 2.5\text{ maf}$) of runoff shifting from April–July to pre-April 1 flows.

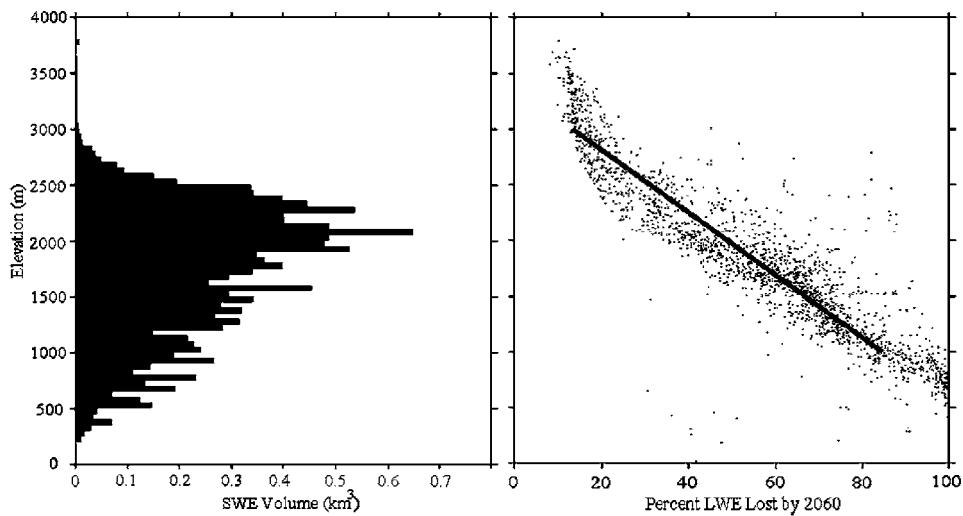


Figure 5. Left: Distribution of present-day April snow water equivalent volume versus elevation, in 50 m bins. Right: Percent of April snowpack lost due to projected global warming by 2060, versus elevation, for the Sierra-Nevada region.

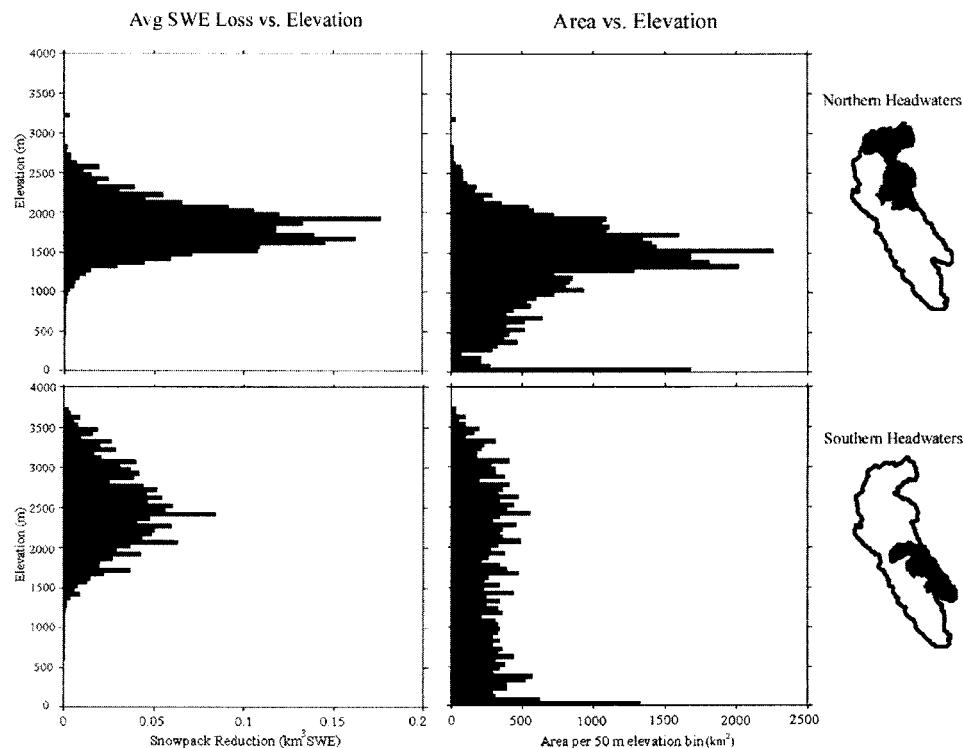


Figure 6. Reduction in April snow water equivalent volume versus elevation for the northern and southern headwater regions for 2060 relative to the historical period. Also shown is the distribution of area versus elevation for each region. Plots were generated using 50 m elevation bins.

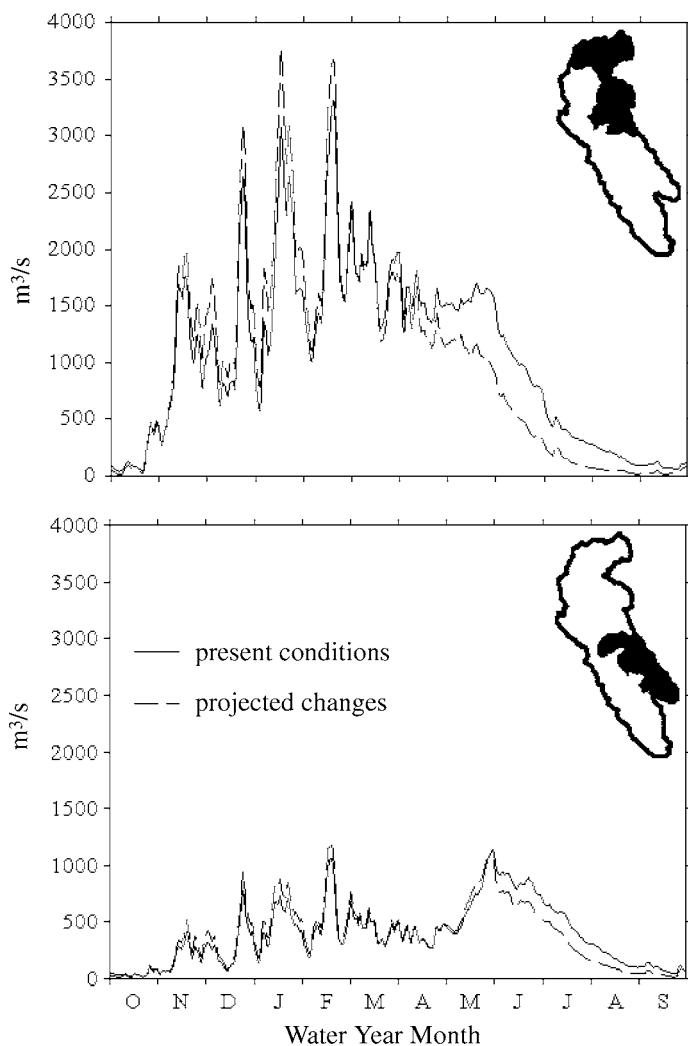


Figure 7. Projected changes in the mean annual cycle of runoff by 2060 from the northern Sierra and Cascades headwater basins (top) and from southern Sierra headwater basins (bottom).

3.2. CHANGES IN ESTUARINE INFLOWS AND COMPOSITION

After including historical influences from reservoir operations, in-stream diversions in the Sacramento and San Joaquin Valleys, and Delta pumping as described earlier, the net effect of the upstream hydrologic changes on estuarine inflows is as shown in Figure 8. This figure shows the mean annual cycle of daily estuarine inflows for present conditions and the relative change by 2060. The shading represents the distribution of the flows in terms of their original runoff source elevation.

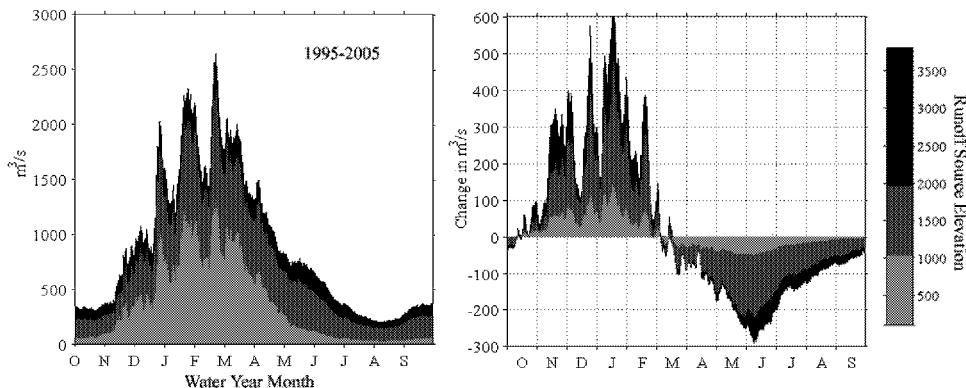


Figure 8. Mean annual cycle of freshwater inflow to the estuary for present conditions (left), and the relative change by 2060 (right). The shading represents the distribution of flows in terms of their original runoff source elevation.

From October through February, estuarine inflows from the Sacramento–San Joaquin watershed are projected to increase an average of approximately $240 \text{ m}^3/\text{s}$, or 20%, and from March through September flows are reduced $\sim 120 \text{ m}^3/\text{s}$, or about 20%. On the whole, total annual flow is very nearly conserved, with winter gains approximately balancing spring–summer losses. The shading of these plots reveals that a large portion of the projected changes occurs in runoff at moderate elevations.

Figure 9 presents plots analogous to those of Figure 8, but showing the effects of the inflow changes on the composition of estuarine waters. Higher winter inflows result in slight increases in the amount of watershed runoff present in the Bay during winter months, but it is the reduced inflows in the spring and summer that have the largest impact on the estuary's waters, reducing the amount of watershed runoff in the Bay by a maximum of 8% by late June. The reason for the disparate response to inflow changes is the low rate of flushing of Bay waters in the spring and summer relative to winter. The high flows of the winter months do not allow the effects of winter inflow anomalies to persist and accumulate in the estuary, while the lower spring–summer inflows allow the inflow reductions to have a cumulative impact on the composition of the estuary's waters.

Since the lost freshwater is replaced by seawater, these changes translate into higher spring–summer salinities in the estuary. Corresponding to the changes shown in Figure 9, the average May–August salt content of the estuary of about 100 million metric tons increases by nearly 5.7 million metric tons. This change would manifest more strongly in the northern reach of the estuary due to its proximity to the watershed outflow. Average May–August salinity in the northern reach is projected to increase by 2.2 psu.

As discussed in Knowles and Cayan (2002), these impacts can vary quite strongly depending on the character of the water year. For example, considering only the 5 driest years of each the two 23-year runs corresponding to present and

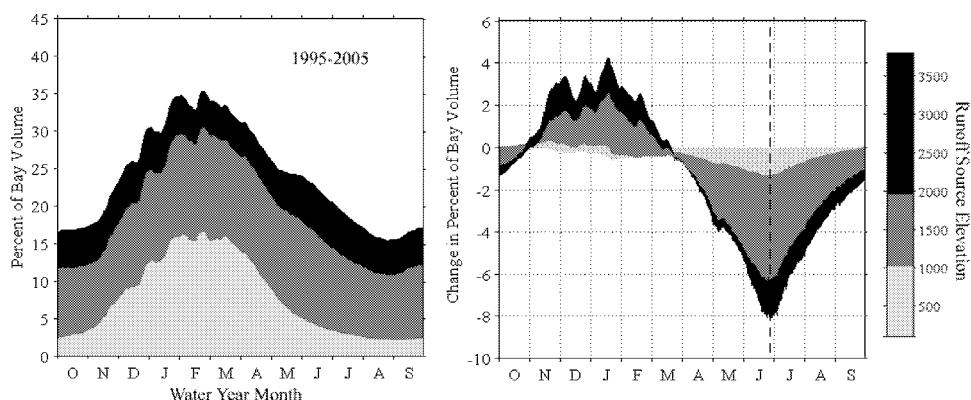


Figure 9. Mean annual cycle of percentage of estuarine volume composed of runoff from the watershed for present conditions (left), and the relative change by 2060 (right). The shading represents the distribution of the freshwater in term of its original source elevation. The largest reduction totals 8%, in late June (Figure 10). Note that seawater constitutes the dominant fraction of estuarine water volume, but is not explicitly represented.

2060 temperature conditions yields relatively small salinity changes. With very low flows to begin with, runoff changes in these dry years have a small impact in the estuary. In these years, average May–August salt content of the estuary increases by only 2.8 million metric tons, and average May–August northern reach salinity increases by 1.2 psu. Conversely, considering the 5 wettest years, the corresponding increases are larger – 6.8 million metric tons of salt and an average salinity increase in the northern reach of 2.5 psu for May–August.

Beyond the interannual variability in impacts, the general result of a warmer climate and the associated changes in the seasonality of outflow is to raise salinity in the San Francisco Estuary, regardless of whether the water year is dry or wet. Though the total annual inflow is conserved, the spring–summer reductions have a stronger influence in the estuary than the winter increases, due to longer spring–summer residence times as discussed above. As in Figure 8, the shading of the change in composition of estuarine waters (Figure 9) reveals that changes in the timing of inflows that originated as runoff in mid-elevations have a disproportionately large impact in the estuary.

The maximum change in estuarine composition occurs in late June, indicated by a vertical dashed line in Figure 9. Figure 10 illustrates the dependence of this change on runoff source elevation in more detail. The elevational distribution of the maximum change in Bay waters has a clear peak around 1500 m, where about 0.05 km³ per 100-meter elevation band are lost. Also, nearly all of the change is a result of shifts in Sacramento River runoff patterns. In part, this reflects the relatively small contribution of the San Joaquin River to spring–summer estuarine inflows, as well as the smaller magnitude of hydrologic change in response to warming in the San Joaquin headwaters as compared to the Sacramento head-

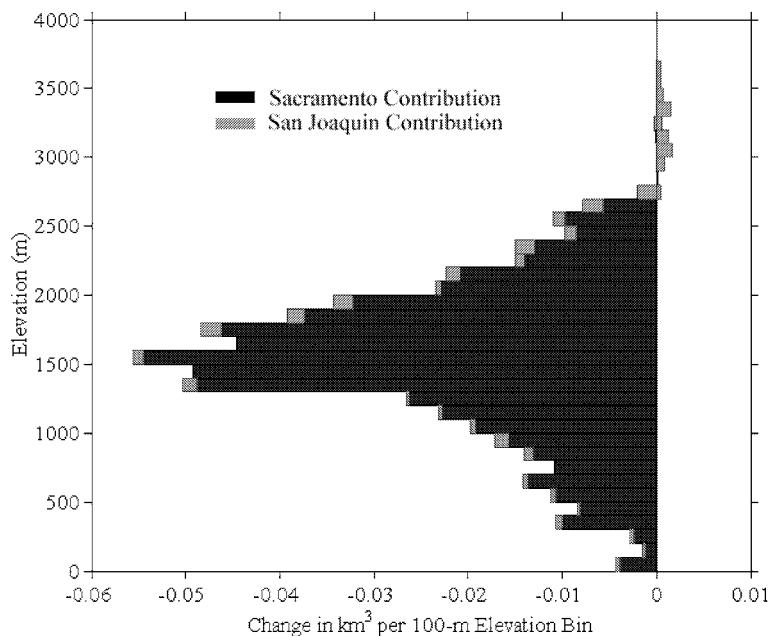


Figure 10. Breakdown of the maximum change by 2060 in the mean annual cycle of estuarine composition (in late June, see Figure 9) by source elevation. Contributions from the Sacramento and San Joaquin Rivers are also distinguished with shading. The changes were calculated using 100-m elevation bins.

waters. Additionally, much of the reduction in spring-summer San Joaquin River flow manifests as unmet demand for in-stream diversions in San Joaquin Valley rather than propagating to the estuary. As a result, hydrologic changes in the San Joaquin headwaters would have a much smaller impact in the estuary than changes in the northern headwaters, under present-day freshwater management and demand patterns.

4. Discussion

Thus, the change in estuarine composition (Figure 10) has a pattern that is dependent on elevation. This is a result of two main factors – the hydrologic sensitivity at mid-level altitudes to climate warming, seen earlier, and the fact that Bay waters in the summer are largely composed of reservoir releases of spring-summer snowmelt runoff. These mid-altitude-sourced waters are particularly important to the managed watershed/estuary system, and climate-induced shifts in their behavior manifest as shifts in the timing of watershed outflow and as changes in spring-summer estuarine salinity. In particular, two-thirds of the projected maximum change in composition of Bay waters, and therefore two-thirds of the maximum change in salinity, is attributable to changes in snowpack in the region

between 1300 m and 2200 m in the Sacramento River basin. Freshwater management in this specific region is therefore likely to play a key role in attempts to mitigate the effects of climate warming, particularly with regard to its effects on the San Francisco Estuary.

As mentioned earlier, the treatment of management effects in this study assumes that historical reservoir, in-stream diversion, and Delta pumping demands are met when possible. The projected changes presented here do not, therefore, account for any attempts at mitigation. They do, however, give an indication of the effects that such attempts must be designed to counter, and which specific regions and elevation ranges will likely be involved. Other factors will also have to be considered, such as changes in municipal and agricultural freshwater demands, which will also have a large impact on estuarine inflows. Another critical influence on estuarine conditions will be sea level rise, which is projected to proceed at a rate of 50 cm over the next 100 years (IPCC, 2001), an acceleration of the recent historical rate of 23 cm/century (Flick and Cayan, 1984). This effect is likely to add to the salinity increase seen in the simulations presented here (Williams, 1985). The increased possibility of levee failure that would result from higher wet-season flows and increased sea level could have additional impacts. Changing runoff patterns could also alter streamflow temperatures, potentially impacting downstream ecosystems including valuable fish populations.

In addition to assessing possible impacts and guiding mitigation planning, understanding which elevations are most sensitive to climate warming has other benefits. It delineates which mountain and riparian ecosystems are most likely to be altered by hydrologic changes such as significant loss of snow cover. Changes in the water balance will likely have profound effect on the ecology of mid-elevation mountain zones. Changes in vegetation and land cover could produce a secondary effect that further alters the hydrologic balance. These results can also serve as a guide to effective monitoring of climate change. Monitoring stations should be installed at locations that are projected to experience the most rapid and detectable changes, rather than waiting for signals to become apparent at current locations which are heavily weighted toward low elevations.

It is important to recognize that this study represents one possible climate change scenario. As discussed earlier, there is general consensus regarding the occurrence of a temperature increase. However, the range of warming estimates from the various climate models is large – from 1.4–5.8 °C over the next 100 years (IPCC, 2001). The PCM estimates are therefore among the most conservative of climate models in terms of temperature increase. Even more uncertainty is associated with the disposition of changes in precipitation that may result from global climate change. Nonetheless, studies such as this provide useful information on the sensitivity of a complex managed watershed/estuary system to potential climate changes. A different rate of temperature increase, for example, would have the same consequences as presented here, but in a different time span. Many of the

results presented here are therefore transferable to other possible climate change scenarios.

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