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Global Climate Change: Potential Effects on the Sacramento–San Joaquin Watershed and the San Francisco Estuary

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Introduction

In light of mounting evidence of anthropogenic warming of the Earth's oceans and atmosphere (NRC 2001) the consequences of projected future global and regional warming for the Bay-Delta estuary and its watershed need to be carefully evaluated. California's heavy dependence on reservoirs and snowpack for flood prevention and freshwater storage makes it especially vulnerable to projected hydrologic changes.

From December through March, the Bay-Delta watershed receives an average 30 to 40 km^3 (about 24 to 32 maf[1]) of freshwater as rain and snow. California depends on artificial storage (reservoirs) and natural storage (snowpack) to help make this supply last the rest of the year. Snowpack alone delays an average of 40% of the annual supply until after April 1 (Roos 1989). 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.

1. million acre-feet.

Warmer conditions would reduce the volume of the snowpack, contributing to higher flood peaks during the rainy season and reduced warm-season flows after April. Possible precursory signs of a warming trend include a long-term decrease in the fraction of bay inflows arriving in the spring (Roos 1991; Aguado and others 1992; Wahl 1992; Dettinger and Cayan 1995), earlier onset of spring plant blooms and of the initial spring snowmelt runoff pulse (Peterson and others 2000; Cayan and others 2001), and increased spring salinity in the estuary (Peterson and others 1995; Knowles 2000).

A sustained warming trend would alter hydrologic conditions throughout the watershed, consequently changing the annual salinity cycle of the estuary. The amount of snowpack reduction would determine the level of effect on the economies and ecosystems that depend on this freshwater supply. This article presents new estimates of warming-induced changes in snowpack and streamflow throughout the watershed, and of changes in estuarine salinity, for the remainder of this century.

Methods

The Parallel Climate Model (PCM) is a numerical model of the global climate system that couples atmospheric, land surface, oceanic and sea-ice components (Washington and others 2000). It has recently been shown to accurately reproduce an observed long-term rise in the temperature of the world's oceans (Barnett and others 2001) and otherwise produces climate simulations that compare favorably to observations. In California, this model 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. This is a relatively small warming in comparison to most other climate models (see Gleick 2000).

While there is a consensus among global models in 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 (Figure 1). During the recent National Climate Change Impacts Assessment (Felzer 1999), however, other models have forecasted increases. Thus, the magnitude and even the direction of possible precipitation changes in California remains an area of considerable uncertainty. Because of the great uncertainty shrouding precipitation projection at present, we focus here solely on the effect of temperature change on the Bay-Delta estuary and watershed, with the implicit assumption that the PCM forecast of (essentially) no precipitation trend is accurate.

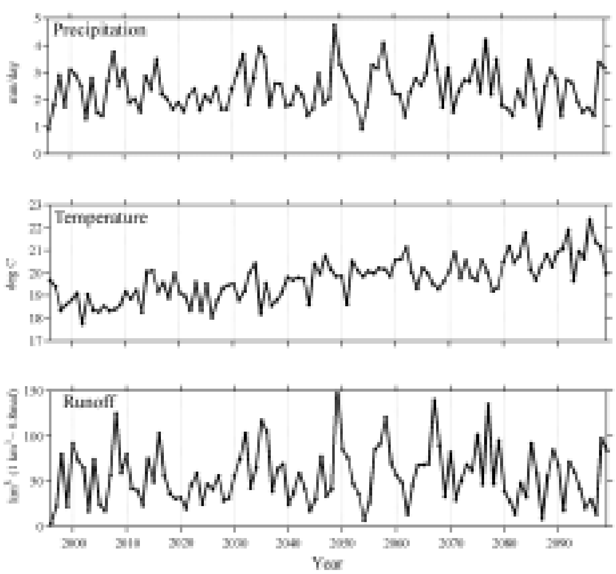

Figure 1 Downscaled PCM-simulated watershed-averaged precipitation and temperature and simulated total watershed runoff for WY 1995-2099

To isolate the effects of temperature increase, simulated temperatures from a 1995–2099 PCM run were used to generate monthly temperature anomalies averaged over the periods 2020–2039, 2050–2069, and 2080–2099, relative to 1995–2005 monthly averages. The resulting values represent estimates of average monthly temperature changes over the Bay-Delta watershed for the years 2030, 2060 and 2090, relative to present conditions. These 3 sets of 12 monthly mean anomalies were added separately to historical temperature data from water years (WY) 1965–1987. Along with the adjusted temperature time series, historical (unchanged) precipitation data from the same 1965–1987 period were used as forcing input to a hydrologic model of the Bay-Delta watershed, resulting in three simulations of watershed snowpack and streamflow representing the watershed's hydrologic behavior under 2030, 2060, and 2090 temperature regimes. A fourth control simulation was performed using unchanged WY 1965–1987 precipitation and temperature to represent the watershed's present hydrologic regime.

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 an adaptation of the Utah Energy Balance (UEB) snow model (Tarboton and Luce 1996), which has been shown to accurately reproduce Sierran snowpack variability. The BDWM reproduces observed streamflow variations throughout the watershed with sufficient accuracy to indicate that it contains a valid representation of the physical processes generating this variability. An important feature of the model is that it is not calibrated to any particular historical hydrologic regime, making it particularly well suited for studies of climate change.

The final step in these simulations was to use output from the BDWM runs to estimate changes in total watershed outflow (Delta outflow) in 2030, 2060 and 2090, relative to present conditions. These simulated changes in Delta outflow were added to historical, observation-based estimates of outflow (DWR 1999) to generate estimates of freshwater inflows to the estuary that would occur under the projected increases in temperature. The implicit assumption that management effects on Delta outflow would be the same under the projected warmed conditions as they have been under recent historical conditions is of course an oversimplification; limitations of this assumption are addressed below. Adjusted Delta outflow time series were used to drive 3 simulations of estuarine salinity from WY 1965–1987. These simulations correspond to the three climate change simulations of the watershed; a corresponding fourth control simulation using unchanged 1965–1987 inflows was also performed.

The Uncles-Peterson (U-P) estuarine model, an advective-diffusive intertidal box model of San Francisco Bay with a daily time step, was used to perform these simulations. This model has been applied in several previous studies of the San Francisco Bay and has been shown to accurately reproduce salinities at weekly to interannual time scales over a wide range of flow regimes (Peterson and others 1995; Knowles and others 1997; Knowles and others 1998). The simulated salinity values provide a rough estimate of the effect of the projected temperature change on estuarine salinity in 2030, 2060, and 2090, relative to present conditions.

Results

Interannual Variability

Before examining the broad trends that result from the simulations described above, it is useful to first consider the interannual variability present in the climate simulation. Statistically downscaled PCM precipitation and temperature were used to drive the BDWM model over the period WY 1995–2099. The downscaling method used was developed by M. Dettinger (personal communication) and is a simple but robust means of translating the approximately 250 km PCM output onto the 4 km grid of the 140,000 km^2 BDWM domain. The resulting watershed-averaged precipitation and temperatures and total watershed outflow (Figure 1) reveal strong interannual variability of the same magnitude observed in California historically (Namias 1978; Cayan and others 1999). Among the PCM's distinguishing features is its high-resolution treatment of the tropical ocean, which gives a relatively realistic depiction of the El Niño-Southern Oscillation process and other interannual variability (Washington and others 2000). The long-term rise in temperature associated with anthropogenic change is also clearly evident (Figure 1, middle). Though no long-term trend in precipitation is apparent, decadal to interdecadal variability is evident (Figure 1, top), also consistent with observed historical behavior (Cayan and others 1998; Dettinger and others 1998).

Thus these simulations suggest strong interannual and decadal variability (including very wet years, droughts, and relatively cold and hot years), will continue to occur in the coming century much as has been observed to occur in California in the instrumental record. The subject of the present study, however, is the background of slower hydrologic change that would underlie these variations.

Snowpack Changes

Simulated snowpack under warmed conditions depicts a severe loss of snow as indicated by changes in the snow water equivalent (SWE) by 2090 (Figure 2). By 2030, the watershed-averaged temperature is projected, under the business-as-usual scenario, to rise by about 0.6 °C, resulting in a minor reduction in snowpack at lower elevations. April SWE, typically the snowpack's annual apex, is reduced by only 5% compared to present conditions. However, an increase of 1.6 °C by 2060 causes the loss of over one-third of the total April snowpack. This loss is focused in mid to lower elevations, since snowpack there is more sensitive to temperature changes than at higher, colder elevations. Regionally, this means that the northern Sierra and Cascades experience the greatest loss. Note that since overall precipitation is conserved in this projection, the lost snowpack appears instead as early runoff.

By 2090, average temperatures are projected to have increased 2.1 °C, resulting in a loss of one-half of the watershed's total April snowpack. Again, the loss is most severe in the northern Sierra and Cascades, which would lose 66% of their April snowpack, but the southern Sierra would also be strongly affected, losing 43% of their April snowpack.

Outflow Changes

The loss of snowpack indicated above would have large effects on streamflows throughout the watershed. The mean annual (water year) hydrographs of the total outflow from the northern and southern headwaters (Figure 3) for 2030, 2060, and 2090 reflect the changing flow patterns in these two regions. In general, the loss of snowpack results in higher runoff peaks before April and reduced snowmelt-driven flows in subsequent months.

As with the relatively unchanged 2030 snowpack, projected 2030 outflows are very similar to present conditions. By 2060, both the northern (Sacramento) and the southern (Cosumnes, Mokelumne, and San Joaquin) headwaters show the effect of reduced snowpack, with the largest effect in the north. The April–July fraction of total annual flow is reduced from 0.36 in 2030 to 0.26 in 2060. Combined with the smaller reduction in the south, this represents over 3 km^3 (about 2.5 maf) of runoff shifting from post-April 1 to pre-April 1 flows.

By 2090, both regions show significantly affected hydrographs, with a loss of 1.2 km^3 April–July runoff in the south and 4.4 km^3 in the north, for a total loss of 5.6 km^3 (about 4.5 maf). This lost snowmelt runoff appears instead as increased flood peaks during the earlier portions of the hydrographs.

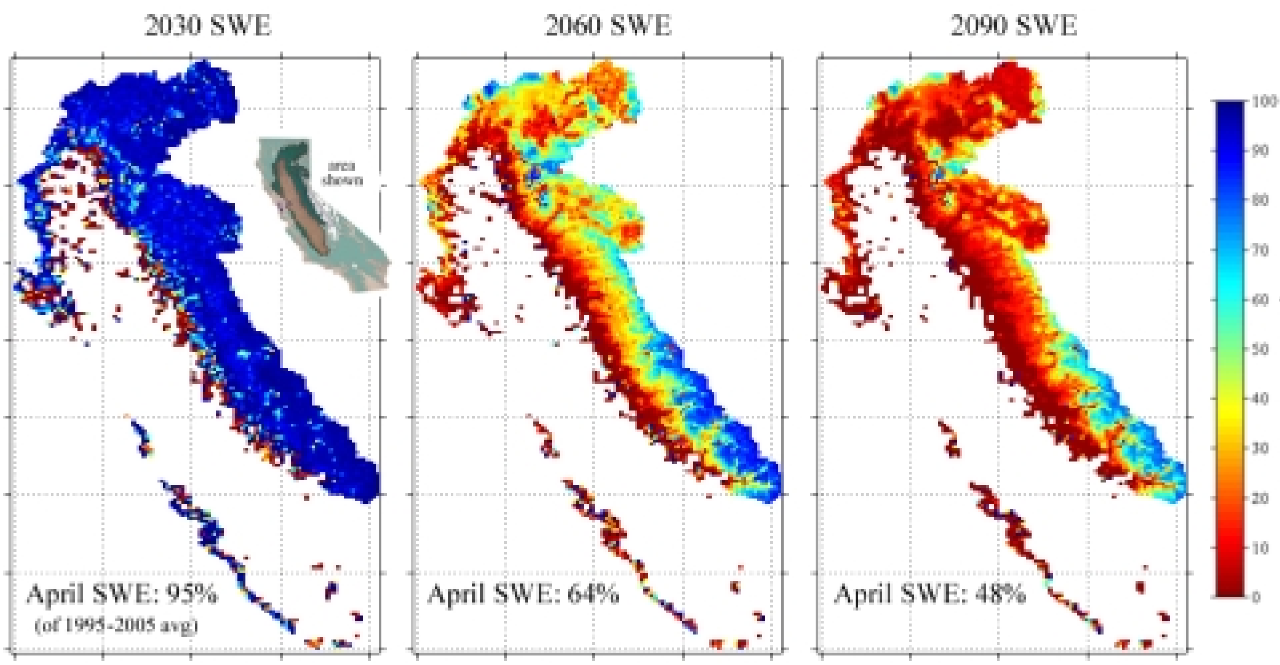

Figure 2 Simulated snow water equivalent (SWE) under a projected temperature increase for the periods 2020-2039, 2050-2069 and 2080-2099, expressed as a percentage of average 1995-2005 SWE

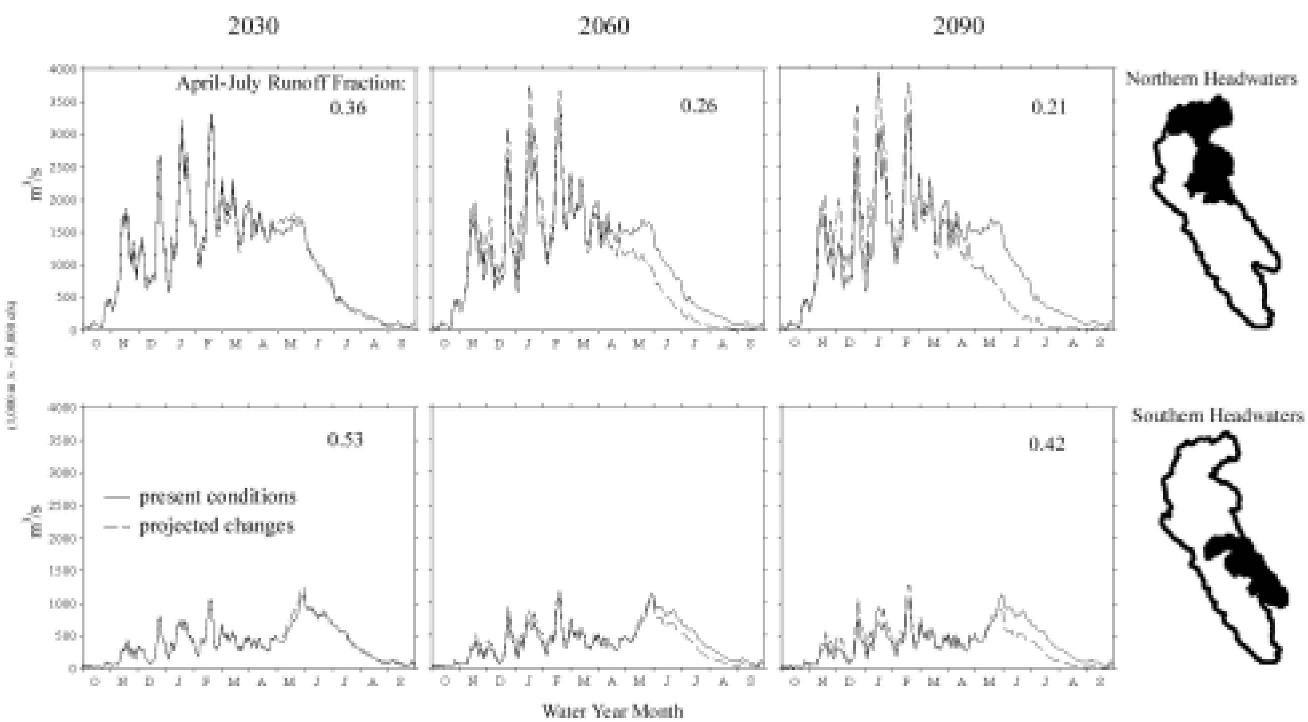

Figure 3 Simulated mean annual hydrographs of northern and southern headwater regions for the same periods as Figure 2

Salinity Changes

Seasonal to interdecadal variations in San Francisco Bay salinity can be explained almost entirely by variations in freshwater inflow from the watershed (Knowles 2000). Among the factors associated with global change, changing inflow patterns are likely to have a large effect in the estuary. With the simplifying assumption that reservoirs would not change their operating procedures in response to climate change, and neglecting the effects of sea level rise, the simulated changes in total watershed outflow were used to model the effect of warming on salinity in the estuary.

While increased December–March runoff would lead to a fresher estuary, reduced snowmelt runoff in the subsequent months would allow tidal action to mix seawater into the estuary more quickly, resulting in higher salinities during late spring, summer, and fall. The mean annual cycle of simulated San Pablo Bay salinity for present and projected future conditions (Figure 4) indicate that average salinities could be 2 to 5 psu higher for May through September.

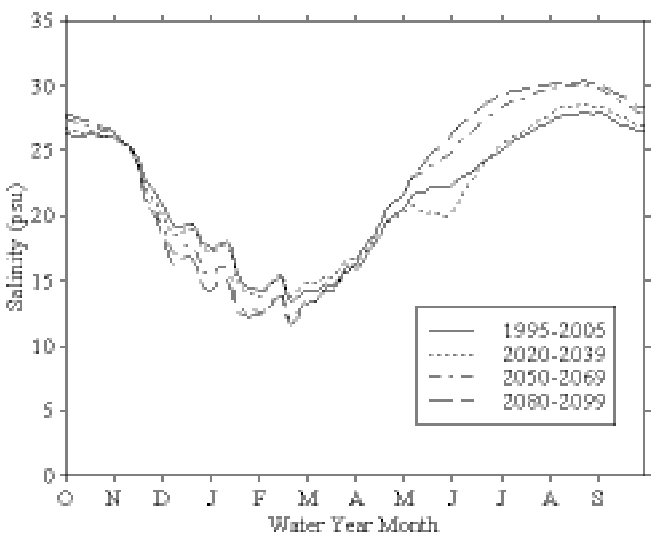

Figure 4 Simulated San Pablo Bay mean annual salinity cycles for periods 1995-2005, 2020-2039, 2050-2069 and 2080-2099. Differences result from changes in total watershed outflow simulated by the watershed model as depicted in the hydrographs of Figure 3.

However, actual salinity changes resulting from the projected temperature increase might in fact be quite different than those shown here, since these estuarine simulations incorporate historical Delta outflows (see "Methods") which are adjusted by the simulated Delta outflow changes resulting from higher temperatures. The resulting outflow time series used in these simulations contain the effects of historical management strategies, which would invariably differ from future management strategies intended to mitigate the hydrologic effects of warming.

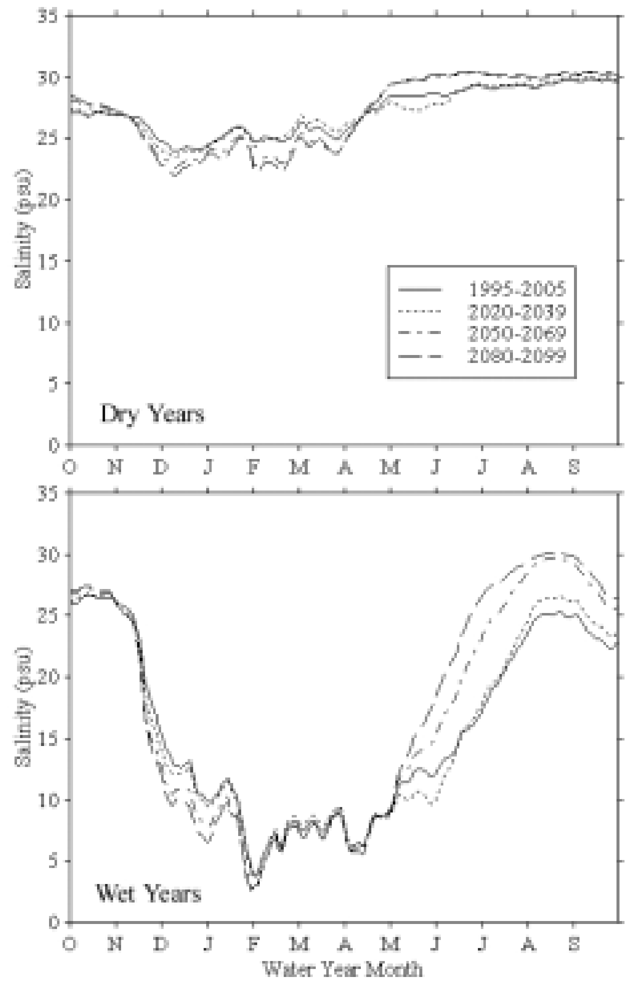

Figure 5 Simulated warming-induced changes in San Pablo Bay mean annual salinity cycle for extreme wet and dry years

To permit a more comprehensive assessment of the potential changes, composites were produced of the 5 wettest and driest years of the simulations used to generate the salinity change estimates (Figure 5). In dry years (Figure 5, top), estimates of salinity change between 2000 and 2090 conditions are on the order of 1 to 3 psu. However, dry year conditions would actually leave reservoirs with more space to mitigate the hydrologic effects of temperature change. As a result, it may be likely that during dry years, salinity effects could be even less than shown by these simulations.

Conversely, wet years (Figure 5, bottom) bring precisely the type of conditions that would handicap the reservoirs' ability to mitigate change. The need for increased flood control capacity, combined with severely reduced snowmelt runoff, could severely limit the options of water managers. The resulting lower-than-historical dry season freshwater reserves could result in salinity increases greater than the 5 to 9 psu shown here.

Discussion

Under the business-as-usual temperature increase scenario examined here, the diminished snowpack and earlier runoff of water that is currently used to recharge California reservoirs would bring adverse effects to estuarine and watershed ecosystems and all who depend on the freshwater supply infrastructure. This water would runoff during the rainy season, greatly increasing the potential for flooding. During the dry season, lower streamflows and increased salinities would affect many species that depend on the estuary and rivers. The risk of contamination of freshwater supplies by salinity intrusion would also be greater. Also, the estuarine simulations presented here do not include the effect of 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 per century (Flick 1998). 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 effects.

The estimates of hydrologic change presented here agree well with the results of previous studies of the potential effects of climate change in this watershed (Gleick 1987; Roos 1989; Lettenmaier and Gan 1990; Jeton and others 1996; Gleick and Chalecki 1999). These results are also supported by recent simulations with much finer scale models of the upper Merced, Carson, and North Fork American rivers under the same climatic changes, which show similar losses of snowpack in those basins (M. Dettinger, personal communication).

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 to 6 °C over the next 100 years (IPCC 2001). Clearly, a smaller increase than the approximately 2 °C used in the present study would lessen the effects on snow, streamflow and salinity discussed above, while the higher increases projected by some climate models would magnify these effects. Changes in precipitation as a result of global climate change are far less certain than the change in temperature. Consequently, there is considerable uncertainty in the hydrologic consequences of climate change. Using the U.S. National Assessment scenario (HadCM2 climate model) results of a 50% increase in California precipitation over the next century, Wilby and Dettinger (2000) have shown that a precipitation increase of this magnitude would restore snowpack volume in the watershed's higher elevations to near-present conditions even with a projected temperature increase of 3 °C. The potential for rainy season flooding under this scenario, however, would be increased considerably more than in the constant-precipitation scenario presented here. Thus, a range of potential hydrologic effects could result from climate change, while some consequences, such as increased flooding potential, are quite likely under most scenarios.

This study illustrates the distribution of the very sensitive response of snowpack and streamflow throughout the watershed, and the propagation of that response into the San Francisco Bay-Delta estuary with an associated change in salinities. The hydrologic and water quality changes exhibited are substantial, even though the PCM's projected temperature change of about 2 °C per century is relatively conservative. These results emphasize that California's strong reliance on natural and artificial storage of freshwater will make adjusting to the hydrologic changes that seem likely to occur in the coming century a difficult challenge.

Acknowledgements

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Differences Among Hatchery and Wild Steelhead: Evidence from Delta Fish Monitoring Programs

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Introduction

Steelhead is the name generally used for anadromous rainbow trout, *Oncorhynchus mykiss*. The Central Valley steelhead Evolutionarily Significant Unit (ESU) was listed as threatened in 1998 (NMFS 1998). Beginning in water year 1997-98, the four Central Valley hatcheries that produce steelhead (Coleman National Fish Hatchery, Feather River Hatchery, Nimbus Hatchery, and Mokelumne River Fish Installation) began marking all hatchery steelhead with an adipose fin-clip. This permits differentiation of hatchery and wild steelhead, allowing for life history comparisons among them. For the purpose of this paper "hatchery" steelhead are defined as those lacking an adipose fin, and "wild" steelhead are those with an adipose fin present. It should be noted that these terms are approximate since small percentages of hatchery fish probably go unmarked due to human error. In addition, some wild fish are the progeny of hatchery fish that spawned naturally. This paper presents an initial exploratory analysis to address the following questions:

1. What proportion of emigrating Central Valley steelhead are of hatchery origin?
2. Are life history differences among hatchery and wild steelhead discernible in the available Delta monitoring data?
3. What factor(s) affect the salvage of hatchery and wild steelhead at the CVP and SWP fish facilities?