POTENTIAL IMPLICATIONS OF PCM CLIMATE CHANGE SCENARIOS FOR SACRAMENTO–SAN JOAQUIN RIVER BASIN HYDROLOGY AND WATER RESOURCES

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Abstract. The potential effects of climate change on the hydrology and water resources of the Sacramento–San Joaquin River Basin were evaluated using ensemble climate simulations generated by the U.S. Department of Energy and National Center for Atmospheric Research Parallel Climate Model (DOE/NCAR PCM). Five PCM scenarios were employed. The first three were ensemble runs from 1995–2099 with a 'business as usual' global emissions scenario, each with different atmospheric initializations. The fourth was a 'control climate' scenario with greenhouse gas emissions set at 1995 levels and run through 2099. The fifth was a historical climate simulation forced with evolving greenhouse gas concentrations from 1870–2000, from which a 50-year portion is taken for use in bias-correction of the other runs. From these global simulations, transient monthly temperature and precipitation sequences were statistically downscaled to produce continuous daily hydrologic model forcings, which drove a macro-scale hydrology model of the Sacramento–San Joaquin River Basins at a $1/8$-degree spatial resolution, and produced daily streamflow sequences for each climate scenario. Each streamflow scenario was used in a water resources system model that simulated current and predicted future performance of the system. The progressive warming of the PCM scenarios (approximately 1.2 °C at midcentury, and 2.2 °C by the 2090s), coupled with reductions in winter and spring precipitation (from 10 to 25%), markedly reduced late spring snowpack (by as much as half on average by the end of the century). Progressive reductions in winter, spring, and summer streamflow were less severe in the northern part of the study domain than in the south, where a seasonality shift was apparent. Results from the water resources system model indicate that achieving and maintaining status quo (control scenario climate) system performance in the future would be nearly impossible, given the altered climate scenario hydrologies. The most comprehensive of the mitigation alternatives examined satisfied only 87–96% of environmental targets in the Sacramento system, and less than 80% in the San Joaquin system. It is evident that demand modification and system infrastructure improvements will be required to account for the volumetric and temporal shifts in flows predicted to occur with future climates in the Sacramento–San Joaquin River basins.

1. Introduction

Among the various environmental and socio-economic sectors influenced by climate variability and potentially by climate change, water resources are of particular

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Climatic Change **62:** 257–281, 2004.

concern (Frederick and Major, 1997). In a review of over 1000 relevant peer-reviewed studies, Gleick et al. (2000) concluded that 'in many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to our water systems'. The effects of global warming on United States hydrology and water resources are expected to be most profound in the western U.S., where the runoff cycle is largely determined by snowmelt (Cohen et al., 2000). In the mid-latitudes, snow accumulation and melt patterns are sensitive to small shifts in temperature. Many previous studies indicate that the effects of warmer climates on the seasonality of runoff in such regions will likely shift the timing of snowmelt to earlier in the year (Smith and Tirpac, 1989; Piechota and Dracup, 1996; Piechota and Dracup, 1997; Lettenmaier et al., 1999; IPCC, 2001). The western U.S. would be negatively affected by such shifts in runoff seasonality; and although many streams in the region are heavily regulated, snowpack represents significant water storage that helps to augment low streamflows during relatively dry summers (Hamlet and Lettenmaier, 1999).

Among western states, California is particularly vulnerable. At 1995 levels of development, the State of California estimates that water demands exceed supplies by 2.0 billion cubic meters (BCM) (1.6 million acre-feet [MAF]) in average years and 6.3 BCM (5.1 MAF) in drought years (DWR, 1998). Furthermore, by 2020 the state's population is expected to grow by more than 15 million, increasing urban water use by more than 30%. In addition, estimated water shortages are projected to increase to 3.0 BCM (2.4 MAF) and 7.6 BCM (6.2 MAF) in average and drought years, respectively (DWR, 1998). Compounding the problem, the warmer temperatures associated with climate change will reduce snowpack and alter the seasonality and volume of seasonal hydrographs (Cohen et al., 2000).

The Sacramento–San Joaquin River Basin makes up most of California's Central Valley (CV). It is home to some of the country's most productive cropland and may be significantly impacted by climate-related alteration of flow regimes. In fact, the potential for climate change to adversely affect the current hydrologic condition is sufficiently serious that state water officials will include an extensive discussion of climate change and likely impacts in the next California Water Plan in 2003 (DWR, 2002).

The climate change projections for this study were produced by the DOE/NCAR Parallel Climate Model (PCM), a coupled land-atmosphere-ocean General Circulation Model (GCM) (Washington et al., 2000; Dai et al., this issue; Pierce et al., this issue). This study, like companion studies in the Columbia River basin (Payne et al., this issue) and the Colorado River basin (Christensen et al., this issue), utilized a statistical downscaling approach for translating climate model outputs into hydrologic model inputs. A hydrology model translated the PCM climate scenarios into daily streamflow sequences at selected locations within the study domains. A water resources management model, operating at a monthly timestep, calculated the potential impacts of the global warming scenarios on system operations in the CV. The model's outputs are reservoir levels and releases, from which

Table I

Parallel Climate Model simulations used in this study

Run	Description	Period
B06.28	Historical (greenhouse CO_2 + aerosols forcing)	1870–2000
B06.45	Climate Control (CO_2 + aerosols at 1995 levels)	1995–2048
B06.44	Climate Change (BAU, future scenario forcing)	1995–2099
B06.46	Climate Change (BAU, future scenario forcing)	1995–2099
B06.47	Climate Change (BAU, future scenario forcing)	1995–2099

the predicted performance of the system with respect to such operating criteria as instream flows for fish, water quality, flood control, hydropower production, agricultural and municipal diversions, and navigation was calculated.

2. Methods

2.1. PCM SCENARIOS

PCM simulates climate and its dependence on greenhouse gas (GHG) concentrations (Washington et al., 2000). We used an ensemble of three PCM ‘business as usual’ (BAU) future climate scenarios and one current climate ‘control’ scenario, as described in Dai et al. (this issue) and Pierce et al. (this issue). The predicted western U.S. warming in the 21st century for these scenarios is approximately 2 °C relative to the control run (1995 conditions). The climate control run reflects observed late 20th century (1995) conditions and is approximately ½° warmer than the recent historical period. To derive statistics needed for bias-correcting the PCM control and climate change runs, we used a 50-year segment of a 130-year historical simulation, in which GHG emissions evolve from pre-industrial to current levels (although the PCM historical scenario is not itself downscaled as are the others). These runs are listed in Table I.

The future scenario results (for the period 2000–2098) are partitioned into three 30-year periods, termed Periods 1, 2, and 3, respectively: 2010–2039, 2040–2069, 2070–2098. These periods are consistent with those used in companion analyses of the Columbia River basin (Payne et al., this issue) and the Colorado River basin (Christensen et al., this issue). Although many results are averaged within these period, the underlying continuity of the daily hydrologic and monthly water resources modeling analyses preserves the consequences of variability from seasonal to interannual and lower frequencies, and in this respect our analysis is more general than the more common quasi-stationary analyses (e.g., Lettenmaier et al., 1999). The method for downscaling the PCM outputs (monthly temperature and precipitation) to drive hydrologic simulations at ⅛-degree spatial resolution is discussed by Wood et al. (this issue) and Wood et al. (2002), where a similar method was previously applied to downscaling seasonal climate model forecasts.

2.2. STUDY AREA VIC MODEL APPLICATION

We used the Variable Infiltration Capacity hydrology model (VIC) of Liang et al. (1994, 1996). The VIC model has been applied to simulate continental river basins and is well documented (see, e.g., Nijssen et al., 1997; Maurer et al., 2001). In this study, the VIC model was implemented at a ⅛-degree latitude/longitude resolution for a hydrologically-defined domain (shown in Figure 1 of Wood et al., this issue) that covers the State of California and drainage areas extending slightly into the State of Oregon (2,906 grid cells in all, each about 150 km^2). For the parts of the domain draining to river gauging stations that are collocated with water resources system inflow nodes, runoff from model grid cells was routed through a flow network to produce streamflow estimates (Figure 1). The VIC model application is similar to that given a fuller description in Payne et al. (this issue), with the main differences being the domain and finer spatial resolution (⅛- vs. ¼-degree) used.

2.3. WATER RESOURCES MODEL

The Central Valley of California is one of the largest multi-purpose water storage and conveyance systems in the world. The State Water Project (SWP) and the Central Valley Project (CVP) coordinate operations of a system of 20 major dams and reservoirs with a combined storage capacity of nearly 21 BCM (17 MAF), as well as 13 major hydropower plants, over 1010 km (630 mi.) of major canals and aqueducts, and various related facilities. Locally-owned reservoirs of significance provide an additional 4.9 BCM (4 MAF) of storage, bringing the total CV surface water storage to nearly 25.9 BCM (21 MAF).

For purposes of this study, we developed a simulation model of the system, termed CVmod (Central Valley Model), which operates at a monthly timestep and represents the major projects and operational features of the Sacramento–San Joaquin basin. CVmod simulates the movement and storage of water within the basin given current operational policies. Table II lists the operational purposes and operator of each major component in CVmod.

The primary hydrologic input to CVmod is monthly streamflow, which comes either from observed naturalized streamflow (for studies of past climate) or from the VIC simulations. CVmod was used to explore system performance and reliability given various operating policies and alternative climate and operating scenarios. The model's outputs are reservoir levels and releases, from which the predicted performance of the system with respect to such operating objectives as water quality, flood control, hydropower production, agricultural and municipal diversions, navigation, and instream flows for fish was calculated. As is common in planning

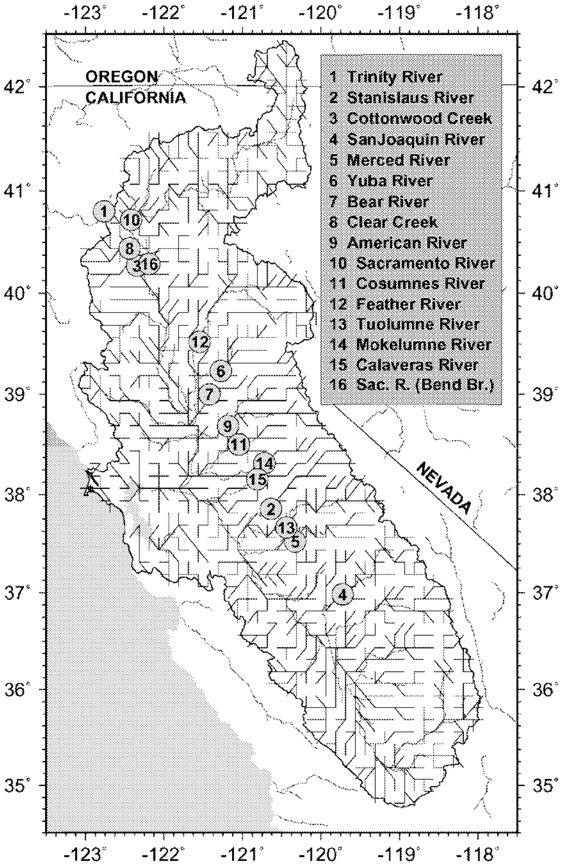

Figure 1. Central Valley 1/8-degree routing network with streamflow routing points corresponding to water resources system inflow nodes.

studies, future inflows were assumed to be known, that is, the model had perfect foresight of future inflows for purposes of determining reservoir releases.

2.4. WATER RESOURCES SYSTEM ALTERNATIVES

Several alternatives were developed to evaluate the ability of the combined SWP/CVP system to mitigate the impacts of climate change. The hydrologic simulations (Section 3.3) indicate that future inflows will differ in magnitude and timing from current inflows. This paper identifies alternatives to current flood control rules and inflow forecasting methods that could assist in mitigating the impacts of climate change related to hydrograph timing and volume. The alternatives considered are:

- Current operations (CO) – Uses current operating rules, as defined by the governing authorities, the California Department of Water Resources (DWR) and

Table II

Listing and principle purposes and operators of major components incorporated in CVmod. Abbreviations: Bureau of Reclamation (USBR), California Department of Water Resources (DWR), East Bay Municipal District (EBMUD), Merced County (MC), Turlock Irrigation District (TID), US Army Corps of Engineers (COE)

CVmod component	Principle purposes by priority	Operator
North of Delta Components:		
Lake Shasta	Flood control, navigation, fish conservation	USBR
Lake Trinity	Water supply, hydropower, fish conservation	USBR
Whiskeytown Reservoir	Flood control, hydropower	USBR
Lake Oroville	Flood control, water supply, hydropower, water quality, environmental conservation	DWR
Folsom Lake	Flood control, water supply, hydropower	USBR
South of Delta Components:		
Pardee/Camanche Reservoirs	Flood control, water supply	EBMUD
New Hogan Reservoir	Flood control, water supply	COE
New Melones Reservoir	Flood control, water supply, water quality, hydropower	USBR
New Don Pedro Res./Lake McClure	Flood control, water supply	TMID, MC
Millerton/Eastman/Hensley	Water supply, recreation	USBR, COE, COE
Other:		
Sacramento–San Joaquin Delta	Water supply, water quality	Jointly operated: USBR, DWR
San Luis Reservoir	Water supply, hydropower	Jointly operated: USBR, DWR

the United States Bureau of Reclamation (USBR) (CSWRCB, 2000; DWR, 1998, 2000, 2001, 2002; USBR, 1999a,b).

- 1-Month Shift (1-Mo Shift) – Flood control rules are adjusted such that all reservoirs in the system refill one month earlier than for CO. This alternative is designed to mitigate the earlier snowmelt and associated earlier runoff simulated by the hydrology model for the future climate scenarios (see Section 3.3).
- 2-Month Shift (2-Mo Shift) – Like 1-Mo Shift, this alternative mitigates the earlier snowmelt and associated earlier runoff simulated by the hydrology model for the future climate scenarios, however, reservoirs can refill two months earlier than the current rules dictate.
- Volume Shift (Vol Shift) – This alternative mitigates the seasonal timing shifts in flow magnitude that occur for many of the streamflow sequences for future climate (Section 3.3). Cumulative distributions were developed for future monthly inflows and compared to control climate scenario monthly inflows to determine differences in 50th percentile flows. New flood control curves were regressed from these predicted distribution differences, and simulations were performed using the new curves. In most cases, existing flood control rules were adjusted to increase flood control space earlier in the season.
- Comprehensive Management (CM) – Through sensitivity analysis, the best alternative from CO, 1-Mo Shift, 2-Mo Shift, and Volume Shift was selected for each reservoir. The criteria used for selection included environmental and flood control reliability, hydropower production and spilling. In general, each reservoir was evaluated on its ability to meet agricultural and municipal demands, environmental targets, flood control targets, and to produce hydropower. A thorough description of the alternative analyses and results is given in Section 3.5. Table III lists the alternative selected for each reservoir for inclusion in the CM alternative, along with the principle operational effects of the selected alternative.
- Water Year Shift (WY Shift) – DWR and USBR use an inflow-based water year classification system in the Central Valley (CSWRCB, 2000). This system classifies years – as critically dry, dry, below normal, above normal, or wet – for the Sacramento and San Joaquin Valleys using linear regression equations with the predictor variables of forecasted October–March inflows, observed April–July inflows, and a surrogate value for carry-over reservoir storage. Many rules for environmental targets, reservoir releases, and demand levels are predicated on a given year's water year type. Since the predicted system inflows (presented in Section 3.3) are lower than control inflows, the distribution and type of future water years, which are predominantly 'critically dry', are very different from those in the control run, which are predominantly 'wet'. The WY Shift alternative modifies the thresholds within the classification such that the predicted 2010–2098 water year types are distributed to reflect the control water year type distribution.

Table III

Alternatives selected for each reservoir to compose the Comprehensive Management (CM) alternative. Sensitivity analysis was performed on each reservoir to determine the alternative giving the best performance

Reservoir	Alternative selected	Principle impact
Lake Shasta	1-month Shift	Minimize storage losses and fish endangerment
Lake Trinity	2-month Shift	Minimize storage losses and spilling
Whiskeytown	Current Operations	No change from control
Oroville	1-month Shift	Jan–May storage increases 5–30%; improved demand satisfaction
Folsom	Volume Shift	Minimize storage losses and fish endangerment; improved demand satisfaction
San Luis	Current Operations	Minimize storage losses; improved demand satisfaction
Pardee/Camanche	2-month Shift	Minimize storage losses
New Hogan	Current Operations	Minimize storage losses
New Melones	1-month Shift	Minimize storage and water quality losses; improved demand satisfaction
New Don Pedro/Lake McClure	Current Operations	Minimize storage losses; improved demand satisfaction
Millerton/Eastman/Hensley	Current Operations	Minimize storage losses; improved demand satisfaction

3. Results

3.1. CLIMATE CHANGES

Figure 2 shows the downscaled, basin-averaged mean annual precipitation and temperature time series from the control run and averaged simulations from the BAU ensembles, as well as the control run average and the observed long-term (1950–1999) average. The control run average temperature is slightly warmer than the observed average (reflecting warming that has occurred in the last 50 years),

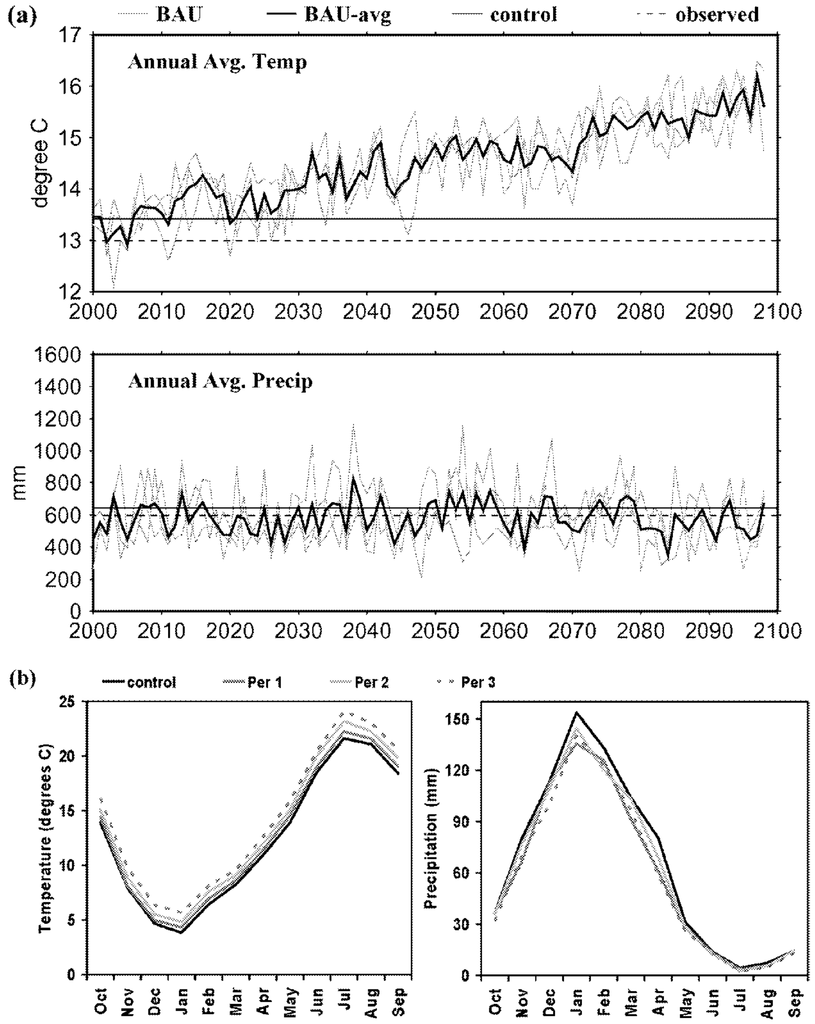

Figure 2. Downscaled PCM Central Valley annual precipitation and temperature: (a) time series and (b) monthly averages for Periods 1–3.

while the observed and control run averages for precipitation are nearly equivalent. In Periods 1–3 (i.e., 2010–2039, 2040–2069, and 2070–2098), the BAU ensemble averages are warmer than the control by 0.5, 1.2 and 1.9 °C, respectively, and the increases are slightly greater in summer than in winter (Figure 2b). Despite the presence of a distinct warming trend, however, the degree of warming varies significantly at the decadal timescale, leading to departures from the long-term warming trend, such as a relative cooling in the 2020s and 2060s (the latter followed by a sharp increase in the following decade). The BAU precipitation is moderately lower than the control run precipitation, and the time series exhibits decadal and interannual variability with distinctive features, such as low precipitation in the beginning in 2020 and 2080, and more or less normal precipitation in the decade of 2050. In Period 2, spring precipitation is closer to the historic and control than in Periods 1 and 3. Figure 2a shows an apparent increase in annual variability (for the individual BAU runs) after about 2030, and Figure 2b shows that BAU ensemble precipitation is, on average, reduced (with changes of 10 to 25% in the basin average) in winter and spring for all periods, relative to the control run.

3.2. SNOWPACK CHANGES

Spring (represented by April 1) snow water equivalent (SWE), a critical factor for water resource management, is significantly affected by the temperature changes of the BAU scenarios. For the CV (Figure 3), the BAU-ensemble averaged April 1 SWE declines by 26, 38 and 52% in Periods 1–3, respectively. Note that while the 30-year average SWE declines shown in Figure 3 are relatively large, the annual and decadal variability in precipitation results in even more substantial SWE anomalies in snow water storage (not shown here) on these shorter time scales. The decrease in spring SWE (as a percentage) is greatest in the region of the Sacramento River watershed, at the north end of the CV, where snowpack is shallower than in the San Joaquin River watersheds to the south. The large SWE percentage changes on April 1, late in the snow season, are clearly due to reductions in winter precipitation and the temperature increases, but also reflect the rapid melt of spring snowpack, which leads to large percentage reductions (up to 100% in shallow snowpack areas), when the melt season shifts earlier in the year.

3.3. RUNOFF AND STREAMFLOW CHANGES

Figure 4a shows the period-averaged changes in annual runoff relative to the control run averages. Figure 4b shows control run and BAU ensemble-average aggregate streamflow (i.e., routed runoff) for the Sacramento River system (combined inflows at Lake Shasta, Folsom Lake, Lake Oroville, and Yuba River) and the San Joaquin River system (combined inflows at New Melones Reservoir, New Don Pedro Reservoir, Lake McClure, and Millerton Reservoir). These streamflow locations are regarded by the DWR as representative of runoff for each basin, and hence portray the effects of the BAU scenarios for the northern and southern halves of the Central Valley drainage areas.

The BAU ensemble exhibited runoff declines that are most severe in the Sierra Nevada mountain range and the coastal mountains in the northwest, where snow plays a large role in the water balance. There are much smaller decreases in the drier areas of southeastern and northeastern California (both areas which do not drain into the Central Valley and expect little or no snow). The primary change in streamflow, consequently, both in the north (Sacramento River) and south (San Joaquin River), for the BAU ensemble is a reduction of streamflow volume, which is larger in Periods 1 and 3 than in Period 2 (which is consistent with the runoff results). In the north, there does not appear to be a significant change in seasonality

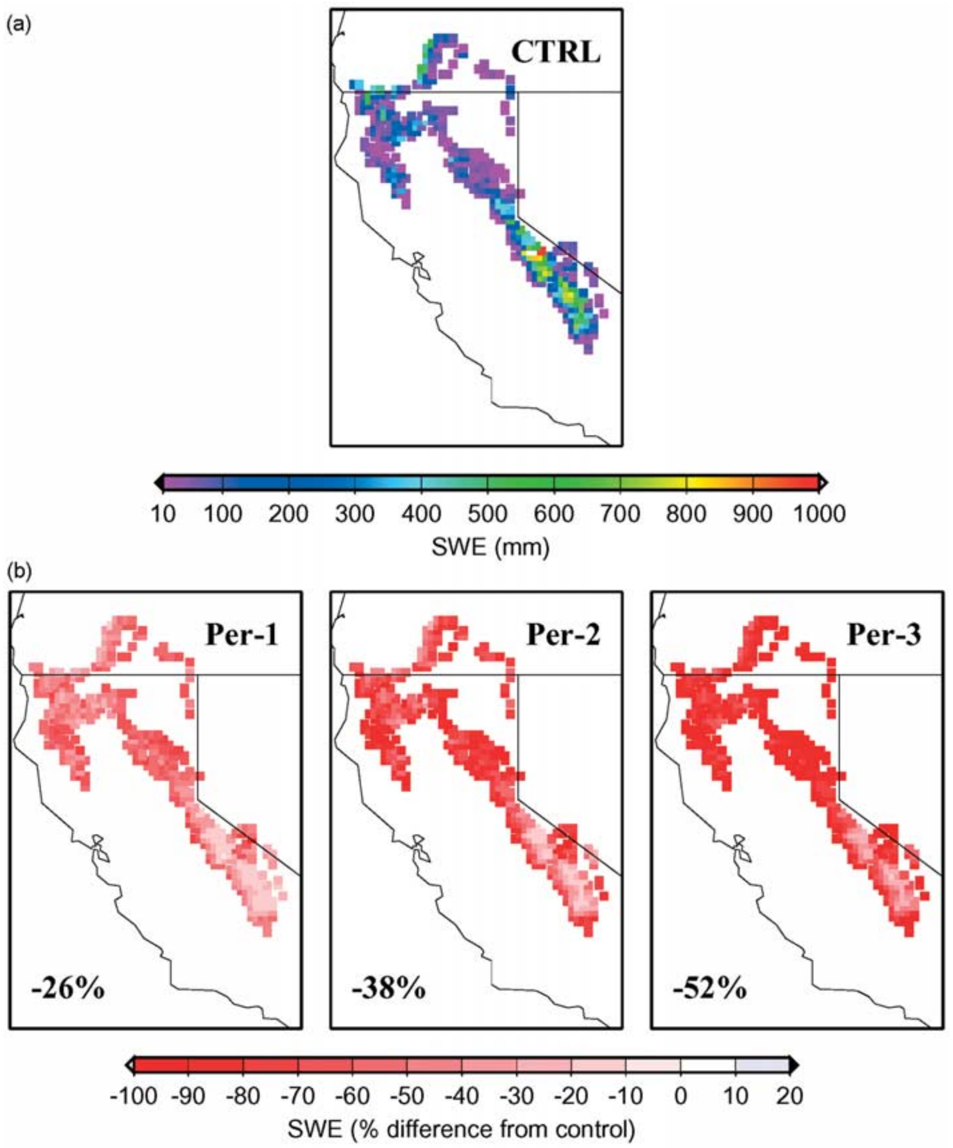

Figure 3. (a) Average Central Valley April 1 snow water equivalent (SWE) for the control climate; and (b) the percent change in BAU ensemble-average April 1 SWE for Periods 1–3.

(a shift in runoff toward earlier in the year, due to earlier melt), although the volume reductions are greater in the spring (the melt period) than in the winter. In the south, a seasonality shift is evidenced by an increased severity of the summer streamflow reduction, although for Period 1 monthly variations in precipitation and temperature complicate this general seasonal response. Overall, the volume reductions are more severe in the southern portion than in the northern portion of the basin.

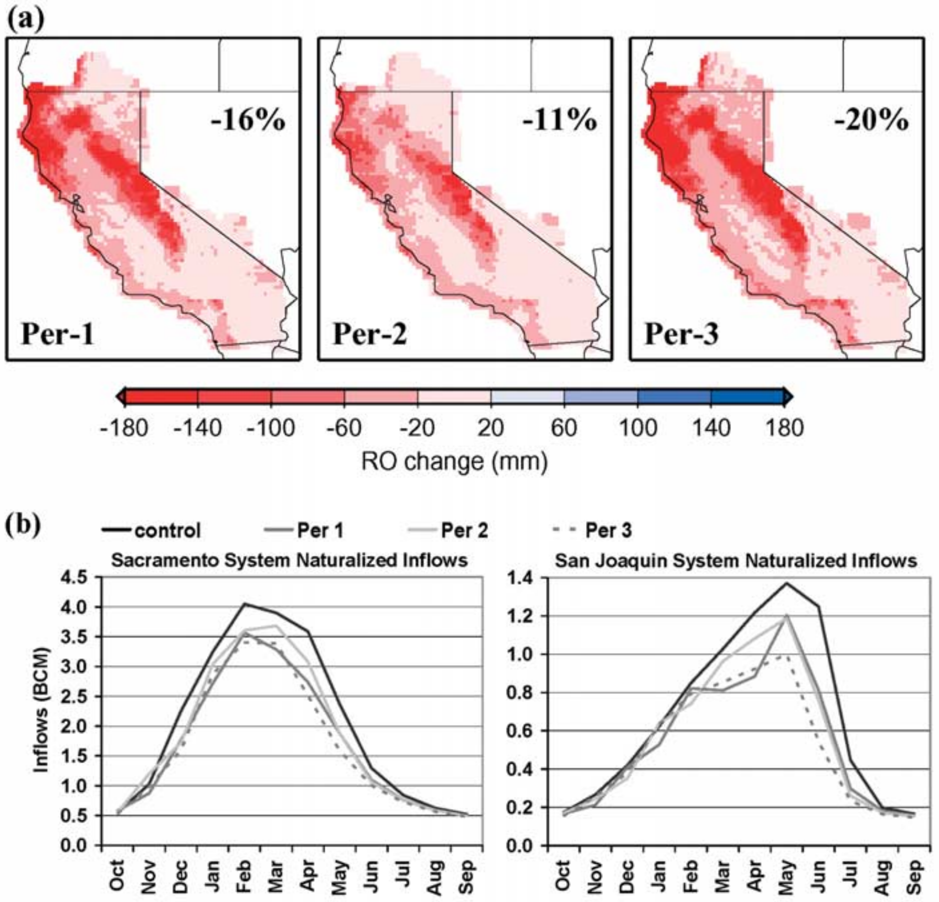

Figure 4. (a) Simulated change in average future Period 1–3 annual runoff relative to the control run average; and (b) mean monthly hydrographs for the control run and BAU runs for the Sacramento and San Joaquin River systems.

3.4. WATER RESOURCES SYSTEM EFFECTS UNDER CURRENT OPERATIONS

The effects of the predicted changes in streamflow on the water resources of the Central Valley were evaluated using CVmod. This section addresses the impact of these climate-altered hydrologies on the system, assuming no adaptive changes in operations from those currently in use.

As described in Section 2.4, the DWR water year type (critically dry, dry, below normal, above normal, or wet) defines how water will be allocated to various purposes each year. Figure 5a shows the control water year types (comparable to historical) and climate change water year types for Periods 1–3. Whereas ‘wet’ years occurred in more than 35% of years in the control scenario and occurred more than any other type by a margin of 12%, by Period 3 ‘critically dry’ years increased from 18% occurrence in control years to more than 40%. Also, by Period 3

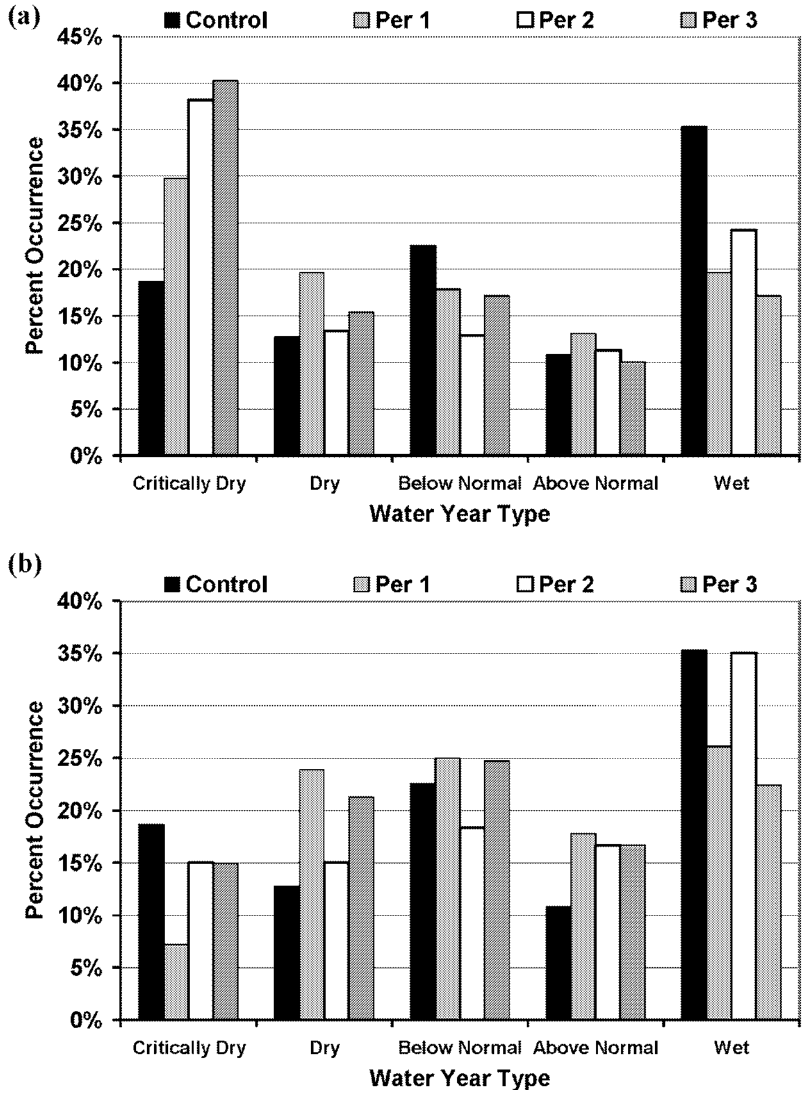

Figure 5. (a) Frequencies of water year types in the Sacramento and San Joaquin watersheds of control and BAU climate inflows over Periods 1–3 using current water year type definitions; and (b) using type definitions designed to preserve the control climate water year distribution.

the occurrence of ‘wet’ years was only 17%. The change in percent occurrence of ‘dry’, ‘below normal’, and ‘above normal’ between the control and climate change scenarios is comparatively small, ranging from 1 to 6%. Figure 5b shows the frequency of water year types used in the WY Shift alternative, in which the water year type definition was altered to distribute the predicted 2010–2098 water year types similarly to the control climate water year type distribution.

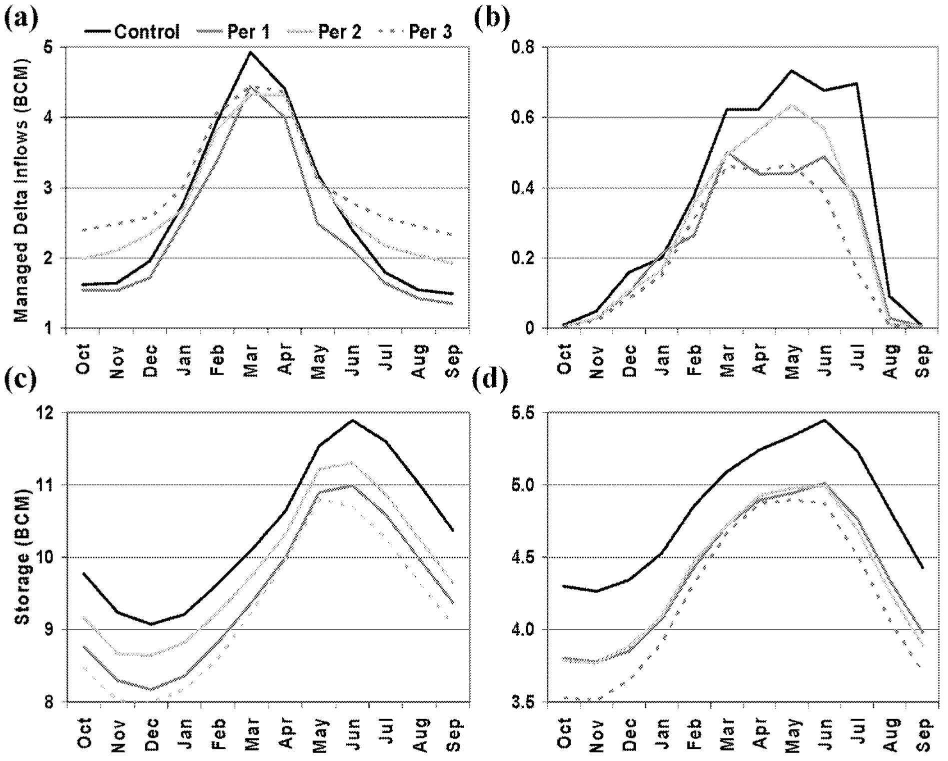

Figure 6. Predicted 2000–2098 mean monthly regulated Delta inflows and Sacramento and San Joaquin total storages given current operating rules and year 2001 demands and hydrologic development: (a) Regulated flows at the mouth of the Sacramento River and (b) at the mouth of the San Joaquin River; (c) total reservoir storage north of the Delta (i.e., Sacramento River System) and (d) south of the Delta (i.e., San Joaquin River System).

The regulated maximum monthly inflows into the Sacramento–San Joaquin Delta from the Sacramento River varied widely over time when system performance was averaged over the BAU ensemble (Figure 6a). Period 1 maximum inflows decreased by 11%, whereas the Period 2 and 3 maximum inflows increased by 11 and 25%. June–December regulated maximum inflows had a similar negative-positive-positive pattern for the 3 periods; however, Period 2 and 3 increases were much more pronounced, with increases of 23 and 44%. January–May maximum inflows were consistently below control levels, with average decreases of 13, 4, and 1% for the three periods. Regulated mean inflows into the Delta from the San Joaquin River decreased in every month for each period (Figure 6b). The mean annual inflow decreased by 33, 29, and 44%.

Predicted mean storage in reservoirs in the Central Valley generally decreased with the climate-altered hydrologies. Storages for reservoirs north of the Delta (in the Sacramento River System) decreased by 9, 5, and 11% releative to control storages during the three periods (Figure 6c); similarly, reservoirs south of the

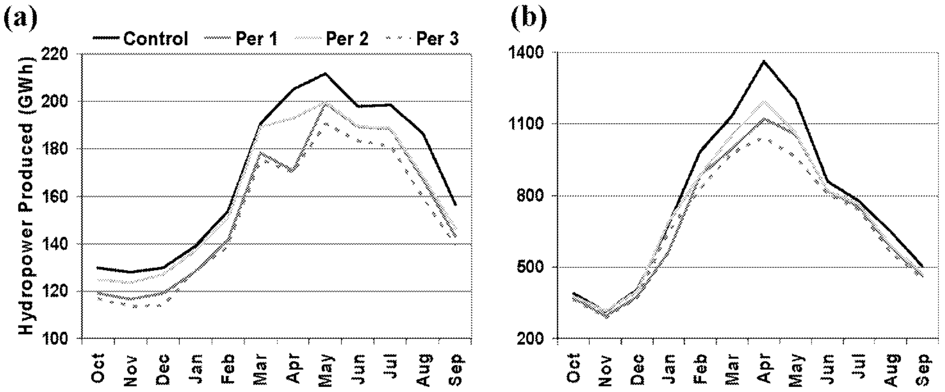

Figure 7. Predicted 2000–2098 hydropower production for (a) Lake Shasta and (b) Central Valley given current operating rules and year 2001 demands and hydrologic development.

Delta (in the San Joaquin River System) decreased by 9, 10, and 13% during the periods (Figure 6d).

Hydropower production (a function of reservoir storage) for the Central Valley generally decreased. Lake Shasta hydropower production, for example, decreased by 8, 4, and 11% during the three periods (Figure 7a). The entire Central Valley system showed a similar hydropower response, decreasing by 10, 6, and 12% (Figure 7b).

A key measure of water resources system performance is functional reliability, the probability that a primary function of a system is met (Hashimoto et al., 1982). Figure 8 shows mean annual reliabilty for the control and BAU climate simulations for seven system performance targets. In general, the reliability of future fish and environmental targets was lower for the BAU scenarios than for the control, due to reduced summer reservoir inflows and reservoir stsorage, while flood control reliability increased due to lower future storages.

Annual reliability measures can be somewhat misleading, however, as monthly to seasonal hydrologic and system variability is not clearly reflected. While the annual reliability of the Shasta (b)(2) target (a comprehensive minimum flow requirement that combines both fish and water quality requirements) decreased 14, 9, and 25% from control climate levels during BAU Periods 1–3 (Figure 8), seasonal decreases give a much different picture. Figure 9 shows that January–June Shasta (b)(2) reliability was within 10% of control reliability levels, with the greatest reduction during Period 3 (9%), whereas June–December reductions in reliability were much greater: 25, 19, and 40% during Periods 1–3.

Oroville fish target reliability is also better characterized using monthly means (Figure 9). At Oroville, however, the greatest decreases in fish flow reliability occured from December–March, when rules designed to prevent large changes in monthly releases are implemented. During the rest of the year dynamic rules are in place to modify monthly targets based on forecasted annual system inflows

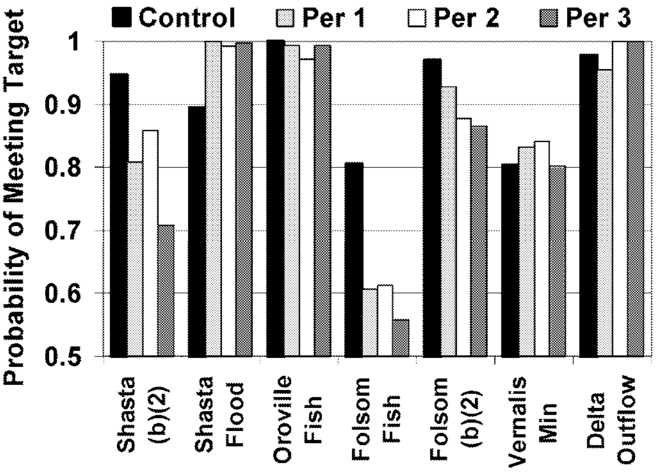

Figure 8. Reliability of meeting operational targets throughout the Central Valley System, given current operating rules and year 2001 demands and hydrologic development, for the control and Period 1–3 climate scenarios; (b)(2) requirements (Shasta and Folsom) are rigorous joint fish and water quality objectives, whereas fish requirements (Oroville and Folsom) are generally fish species-specific; Shasta flood represents the flood control rule; *Vernalis min* is the minimum flow requirement at the mouth of the San Joaquin River; delta outflow is the minimum flow required to prevent salt water intrusion to the Delta.

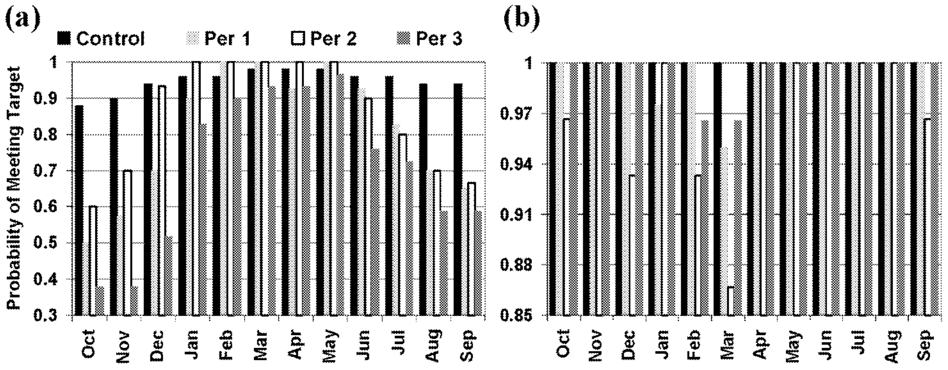

Figure 9. Mean monthly reliabilities of meeting (a) Lake Shasta (b)(2) environmental targets and (b) Lake Oroville fish targets, given current operating rules and year 2001 demands and hydrologic development, for the control and Period 1–3 climate scenarios.

(USBR, 1999a). To examine more clearly the interaction between climate and fish target modification, monthly fish targets were fixed as described in Section 3.7.

To better demonstrate the effect of dynamic (forecast-based) operating rules, we evaluated future system performance relative to current performance by adapting the method of Miller et al. (1999), in which modeled inflows are expressed as the ratio of control inflows to modeled inflows. Here we expressed future scenario reliability as a fraction (loosely termed ‘ratio’) of the control scenario reliability.

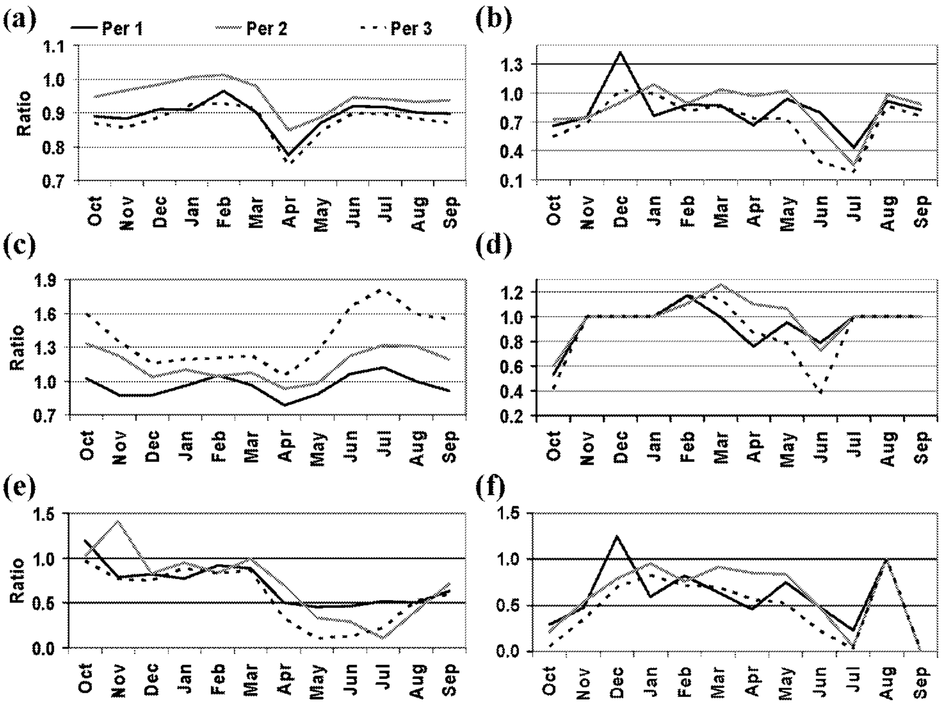

Figure 10. Ratios (Periods 1–3 to control climate) of mean monthly Sacramento System and San Joaquin System reliabilities for fish target satisfaction (a and b, respectively), water quality target satisfaction (c and d, respectively), and of spill volumes (e and f, respectively), given current operating rules and year 2001 demands and hydrologic development.

Because high reliabilities generally are desireable, for most objectives ratio values greater than 1 indicate superior (and values less than 1, inferior) performance relative to control (or current) scenario levels. In the case of spill volumes, however, ratios lower than 1 indicate a performance improvement.

Figure 10 shows the ratio of future to control scenario system reliability for Sacramento and San Joaquin fish targets (Figures 10a,b), water quality requirements (Figures 10c,d), and spill volumes (Figures 10e,f). In the Sacramento system, the fish target ratio was lowest in April during all three periods, when it was 23, 16 and 30% below control fish targets during each period. The San Joaquin system's ability to meet fish targets was severely degraded in every month but December, when the reliability was 33 and 4% greater than the control scenario reliability during Periods 1 and 2; during Period 3, the reliability was 20% below the control scenario reliability. In July, the system suffered large decreases in the ability to meet fish targets: the ratios reflect reliability reductions of 60, 76, and 84% during Periods 1–3.

The effect of climate-altered inflows on satisfying water quality targets is counterintuitive, particularly in the Sacramento System (Figure 10c). However, water quality targets, as currently defined in the system, are determined by forecasted system inflows. Future releases are thus only nominally governed by future water quality targets because the targets are decreased to adapt to potential system inflow decreases. As a result, reliability ratios for water quality targets were generally greater than one, even while future scenario flows were lower than control scenario flows. In instances where water quality targets govern releases, as in June in the San Joaquin System, the ratio is more directly indicative of the changes in system inflows (Figure 10d).

Figures 10e,f show the monthly ratios (e.g., quotients) of projected spill volumes to control volumes. In the CV system, the projected decrease in water availability decreased overall system storage and generally decreased the severity of spilling. Spill volumes often decreased by a factor of 5 or more from control spills in the Sacramento (Figure 10e) and San Joaquin (Figure 10f) systems. In the San Joaquin system, spills in Period 3 were reduced by as much as a factor of 40.

3.5. WATER RESOURCES SYSTEM ALTERNATIVE ANALYSIS

Figure 11 shows the performance of the current operations (CO), 1-month flood control shift (1-Mo Shift), water year type reclassification (WY Shift), probabilistic inflow-driven flood volume shift (Vol Shift), and comprehensive management (CM) alternatives with respect to fish target satisfaction and hydropower production. While each adaptive alternative (e.g., all but CO) generally improved performance relative to CO for all or most of the year in both the Sacramento and San Joaquin Systems, the CM alternative provided the best combination of fish target satisfaction and hydropower production, spill reduction, demand satisfaction, and monthly reliability improvements (not shown). However, despite improvements in performance relative to CO, even for the CM alternative, the reliability ratios were still less than one for all months for hydropower, and for most months for fish targets. The water year type alternative (WY Shift) did not perform well in this scenario because demands were not proactively reduced, and because flood curve-driven releases are not affected by water year type.

System operation requirements for fish have changed significantly over the last several decades in response to the listing of at least six native fish species by the Endangered Species Act (ESA) as endangered or threatened (winter-run and spring-run chinook salmon, coastal chinook, coho salmon, steelhead trout, and Delta smelt) (DWR, 1998). While the degree to which future ESA listings and altered environmental flow objectives may affect system operations is uncertain, we investigate the robustness of alternate operating responses to possible changes in fish targets. Tradeoff curves showing the performance of the CM alternative with respect to 5, 10, and 20% increases in current fish flow targets are shown in Figure 12. In general, any increase in fish targets beyond 5% produced a similar response in the system's ability to meet a given target. While summer and fall target increases did not strongly affect the system's ability to meet targets (since releases

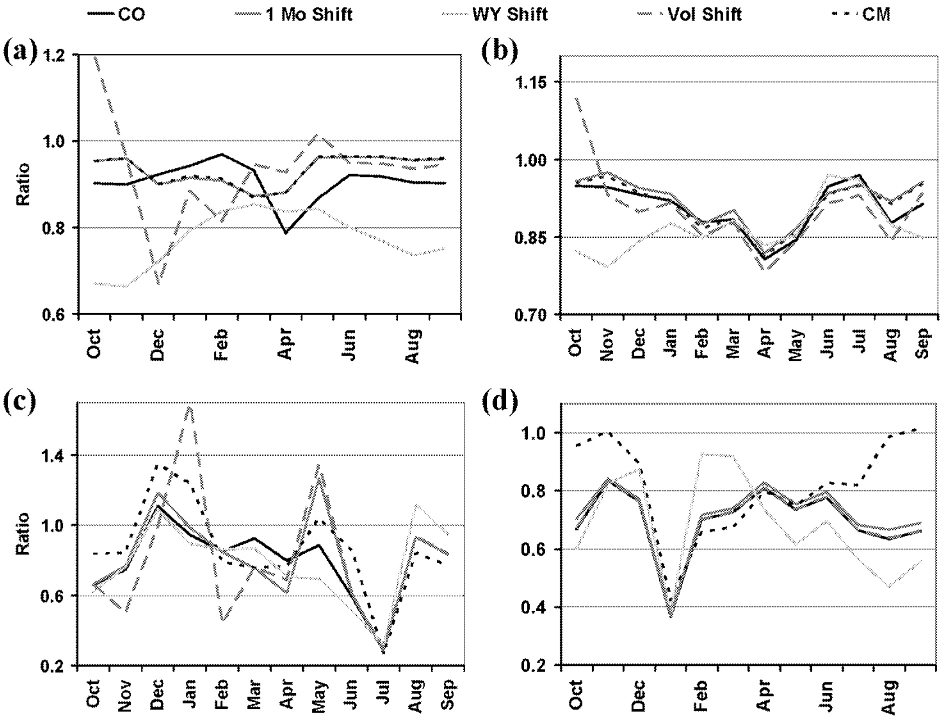

Figure 11. Ratios (2000–2098 to control climate) of fish target satisfaction and hydropower production for various alternatives: (a) Sacramento System fish target satisfaction; (b) Sacramento System hydropower production; (c) San Joaquin System fish target satisfaction; (d) San Joaquin System hydropower production. Abbreviations: CO – current operations; 1 Mo Shift – 1-month flood control shift; WY Shift – water year determination change; Vol – volumetric shift of flood control rules; CM – comprehensive management.

for demands predominate during this period), spring target increases could not be met on a consistent basis. Spring is a particularly sensitive season for both environmental targets and reservoir refill, hence meeting increased fish targets during this period is unlikely.

Also important is the effect of demands and demand management on system performance. The DWR and USBR currently utilize a complicated demand and delivery allocation scheme that optimizes the distribution of forecasted inflows given operational constraints, system objectives and current water year type (DWR, 2001). To simulate the severity of curtailments that might occur with BAU inflows, we performed sensitivity analyses of system performance given varying demand reduction levels (up to 50, 75, and 95% in critically dry years in demand modification scenarios 1–3). Figures 13a,b show fish flow target satisfaction ratios and hydropower production, respectively, given each demand curtailment level. While demand reduction improved the system's ability to satisfy fish targets overall, it did not have an appreciable positive impact on hydropower production (relative to

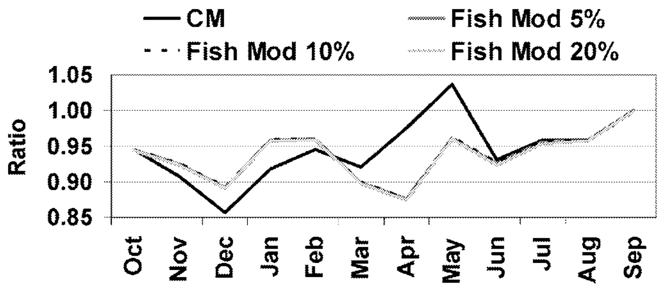

Figure 12. Tradeoff ratios (2000–2098 to control climate) of mean monthly fish target satisfaction, for CM alternative operations and CM operations with three hypothetical flow target increases.

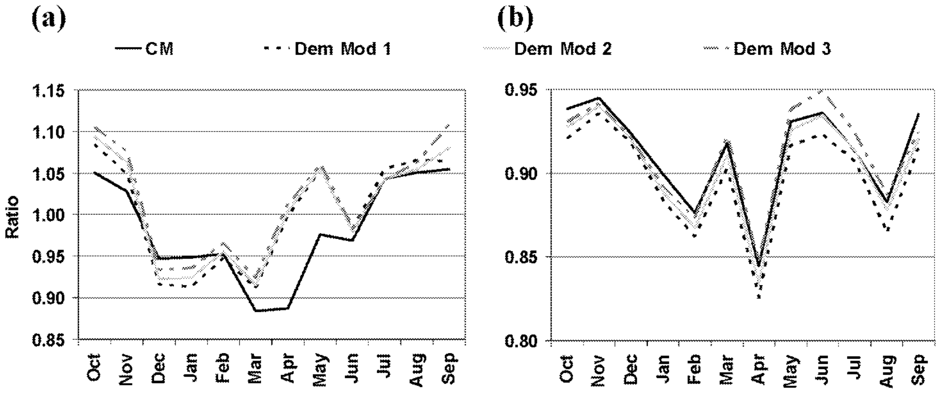

Figure 13. Tradeoff ratios (2000–2098 to control climate) of mean monthly (a) fish target satisfaction and (b) CV hydropower production, for CM alternative operations and CM operations given various levels of demand curtailment.

the ‘no demand modification’ scenario shown, CM). Also, once initial gains were made in satisfying fish targets, reducing demands further had a diminished effect, with minor additional benefit at the 95% reduction level (Dem Mod 3). The results show that the system may be unable to meet future demands sufficiently, regardless of the degree of demand curtailment.

4. Interpretation and Conclusions

The three-member ensemble of PCM transient ‘business-as-usual’ (BAU) climate change scenarios for the 21st century were compared to a current-climate control run, and the associated effects on hydrology and water resources were examined for three averaging periods representing several decades each in the early, middle and latter parts of the 21st century. With respect to climate and hydrology of the Central Valley, the primary implications of the PCM BAU simulations are:

- The BAU scenarios are initially slightly cooler than the control run, but warm by about 2.2 °C by the end of the 21st century, with mid-century warming of over 1 °C. Warming is slightly greater in the summer than in other seasons. Precipitation in the BAU scenarios is generally lower than in the control run, particularly in the winter and spring, and the reduction is greater in Periods 1 and 3 than in Period 2. Some of these differences may be attributable to natural variability among the ensembles, but the general trend of the century is almost certainly a reflection of the model's representation of greenhouse gas-related warming.
- As a result of winter precipitation reductions and warming in the BAU ensembles, the onset of the snowmelt season would be earlier, and average April 1 snowpack would progressively diminish to about half of the control scenario average in Period 3. The annual variability in precipitation and temperature (superimposed on the warming trend) would cause individual years within each averaging period to experience large snowpack reductions while other years remain at near or above normal, relative to the control climate. The spatial variability in snowpack, likewise, would cause April 1 SWE reductions to vary from 10 to 100%, with the greatest reductions generally at the lowest elevations.
- Basin-averaged monthly streamflow volumes at gage locations would significantly decrease in Periods 1–3. Smaller relative flow decreases in spring compared to those in summer (the disparity is more pronounced in the southern part of the basin) suggests a seasonality shift as well, but the overall volume decreases make this effect hard to discern.

While these results are generally consistent with the findings of previous studies, our transient, GCM output-driven analysis provided insight into the progression of climate change effects on hydrology, in particular the variability of the response over time that is not accounted for when stepwise changes in mean decadal temperature and precipitation are used in hydrologic simulations (as in many previous studies). The BAU runs exhibit decadal-scale variability in temperature that is notable relative to the eventual warming, suggesting that a compounding of two dynamics (the trend and variability in these climate indicators) will make the sequencing of periods of climate change vulnerability non-monotonic (in Figure 2, e.g., in our results the 2050s are warmer than the 2060s). Decadal and interannual scale variability in precipitation in the individual BAU ensembles also contributes to this phenomenon. On an annual level, BAU climate anomalies (hence hydrologic dry and wet periods) become more extreme, and year-to-year differences in climate and hydrology more variable than has been observed in the historic record.

Overall, BAU climate effects on hydrology would cause a progressive shift in the mode of water year type (a major determinant of CV water resources system operations) from 'wet' (for the control climate) to 'critically dry' (for Period 3), with the result that system performance would be degraded. Some mitigation of the adverse effects could, however, be achieved by changes in system operation. Specific findings related to water resources management are:

- Achieving and maintaining status quo (control) system performance in the future would not be possible, given the predicted BAU scenario hydrologies. Decreases in inflows preclude productive adaptive management techniques, given current objectives in the system. Current operating rules (CO) would be able to meet 90, 95, and 89% of fish targets and 90, 95, and 89 percent of current hydropower production levels during Periods 1, 2, and 3, respectively.
- Among the operational alternatives considered, the alternative that would best mitigate impacts to system performance is Comprehensive Management (CM), which incorporates both seasonal and volumetric shifts on a reservoir-by-reservoir basis. The CM alternative, although unable to restore control scenario performance levels, would slightly improve aggregate annual future system performance over CO levels (to 92, 98, and 92% of fish targets and 91, 96, and 89% of current hydropower production levels during Periods 1–3. For separate months and in individual systems (i.e., Sacramento or San Joaquin), however, larger impairments would occur, such as for San Joaquin system January hydropower production, which would decrease by nearly 65%.
- The most effective impact mitigation (with the CM alternative) would be possible for the hydrology of Period 2. Reservoir inflows, slightly higher than in Periods 1 and 3, increased annual Sacramento River System storages by about 5% relative to Periods 1 and 3, and resulted in larger relative improvements in system performance. Period 2, therefore, may represent the upper bound of climate-altered hydrology that is still subject to active management techniques. Changes in reservoir inflows beyond this range would create sufficient loss of system reliability so as to make non-build water mangement techniques ineffective.
- The performance of the CV system is strongly influenced by fish and water quality targets. Demand modification (reduction) would improve system performance with respect to these targets, but would have a negligible impact on overall hydropower production.

The overall conclusion of this paper is that climate change would impair the system to an extent that changes in system operation could not match past performance levels using the alternatives we considered. Although not examined here, the potential for system storage increases and other infrastructural changes to restore past performance warrants consideration.

Although the goal of this and similar studies of the impacts of climate change on water resource systems has been to suggest future management alternatives, it is naïve to assume that, as the climate changes, the economic, social, and political impacts will remain unchanged or, for that matter, be minimal. For this reason, we believe that future studies should focus on quantifying uncertainties in prediction of the range of future hydrologic conditions that may occur so as to support decision making that explicitly considers these uncertainties. This study has made one advance in this respect by considering an ensemble of climate conditions over the next century, albeit limited to three members by computational constraints.

As computing capacities increase, it will become feasible both to develop ensembles with more members that better represent within-model uncertainties, and to consider multi-model ensemble suites which represent uncertainties across models. This should help to provide a basis for representing the uncertainties in future hydrologic conditions that will face water managers in planning for the next century. Until this point is reached, however, it is unlikely that any long-term water resource management alternatives proposed to mitigate the impacts of climate change in a complex system can be implemented in a meaningful way.

Acknowledgements

The Accelerated Climate Prediction Initiative (ACPI) Pilot effort was supported primarily by the Office of Biological and Environmental Research, U.S. Dept. of Energy. The production runs of global and regional models were largely accomplished with resources of the Center for Computational Sciences (CCS) at Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Dept. of Energy. The San Diego Supercomputer Center provided dedicated machine resources for the ocean initialization component of the ACPI Pilot project. These ocean data were provided by ECCO state estimation activity at SIO. In addition to DOE support, many participating organizations also supported the effort. These include the Scripps Institute of Oceanography, USGS, DOD, National Center for Atmospheric Research, University of Washington, and Battelle Pacific Northwest National Laboratories.

This research was also supported by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement #NA17RJ1232, Contribution #923.

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(Received 17 July 2002; in revised form 13 August 2003)