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Robust analysis of future climate change impacts on water for agriculture and other sectors: a case study in the Sacramento Valley

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Abstract As part of the 2006 Climate Change Report to Governor Schwarzenegger and the California Legislature, an application of the Water Evaluation and Planning (WEAP) system in the Sacramento River Basin was deployed to look at the impact of climate change on agricultural water management and the potential for adaptation. The WEAP system includes a dynamically integrated rainfall runoff hydrology module that generates the components of the hydrologic cycle from input climate time series. This allows for direct simulation of water management responses to climate change without resorting to perturbations of historically observed hydrologic conditions. In the Sacramento River Basin, the four climate time series adopted for the 2006 Climate Change Report were used to simulate agricultural water management without any adaptation and with adaptation in terms of improvements in irrigation efficiency and shifts in cropping patterns during dry periods. These adaptations resulted in lower overall water demands in the agricultural

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sector, to levels observed during the recent past, and associated reductions in groundwater pumping and increases in surface water allocations to other water use sectors.

1 Introduction

Climate change impact assessments generally start from the assumption that the future climate will be significantly different than that experienced in the past, an assumption that is increasingly buttressed by the results of recent global climate monitoring and the results of general circulation models (GCM) used to simulate the global climate. By extension, altered future climatic conditions will produce hydrologic patterns that differ from those captured in the observed historic stream discharge record. Climate dependent deviations from historic hydrologic regimes may also change as a function of shifts in land cover brought about by changing temperature and precipitation patterns and as a function of changes in land use related to future population growth and development. The logical conclusion is that water resource systems models that are used to understand the impacts of future climate change and to explore potential adaptations should be run using hydrologic conditions derived from future climate scenarios and not from the perturbation of past hydrologic data.

This has been, however, the approach commonly used in California as researchers attempt to move the focus of analysis from regional scale changes in climate and natural hydrology (Dettinger and Cayan 1995) to assessments of the potential impact of these changes on the management of water resources (Brekke et al. 2004). This important early transitional work relied on the use of CalSim-II, the primary water-planning model used in California, which is a tool for water resources systems analysis that has been developed based on the characterization of the hydrologic regime in place between 1921 and 1994. In competing this analysis the authors attempted to perturb the assumed historic reservoir inflow time series in a manner that was consistent with anticipated shifts in snow accumulation and snowmelt patterns associated with different climate scenarios. The implication of this approach was that the temporal pattern of wet and dry periods in the historic record would repeat themselves sequentially with appropriate changes in magnitude, and that new extended wet and dry periods of longer duration or higher frequency would not occur. The approach also assumed that hydrologic conditions below the major reservoirs remained unchanged from the historic period, and that evaporatively driven irrigation water demand remained unchanged in the future in spite of potentially higher temperatures.

As the confidence in future global climate scenarios improves, along with the ability to downscale these scenarios to regional climate time series, there is a need to likewise increase the resolution of anticipated future hydrologic conditions. This paper describes the application of a dynamically integrated watershed hydrology/water resources systems modeling tool that uses as input data information on future climate time series and future land use/land cover patterns. From this information, associated natural patterns of stream discharge, evapotranspiration (ET), groundwater recharge and stream–aquifer interactions are simulated, upon which the simulated impact of reservoir operations, cropping decisions, surface water diversions and groundwater pumping can be superimposed. This framework, based on the Water Evaluation and Planning (WEAP) system, has been applied in the Sacramento Valley and demonstrates the utility of the integrated climate/hydrology/management approach as compared to the companion water management articles that rely on perturbation analysis.

Specifically this paper describes the application of the Sacramento Valley WEAP model to analysis conducted as part of the 2006 Climate Change Report to the Governor and the State Legislature. As part of this analysis, the analytical framework was refined from previous applications to include:

- The disaggregation of the regional mass-balance computational units into smaller units defined loosely on water district boundaries.
- The introduction of econometric expressions that dynamically link cropping patterns within water districts to climatic and water supply variables.
- The assumption that in the future changes in irrigation management technology will allow for similar levels of crop ET demand to be met with less applied water.

These refinements were designed to provide improved resolution of the potential impacts of climate change and to be able to investigate in some detail whether adaptations made in the agricultural water use sector could allow for broader satisfaction of a range of water management objectives. The refined model was run under four GCM/emission scenario combinations under different assumptions regarding adaptation in water use behavior.

2 WEAP model and application

A series of recent papers (Yates et al. 2005a, b) describe the manner in which the watershed hydrology module was integrated into WEAP and how the framework was applied to the Sacramento River system (see Fig. 1). Readers are referred to these papers for details about

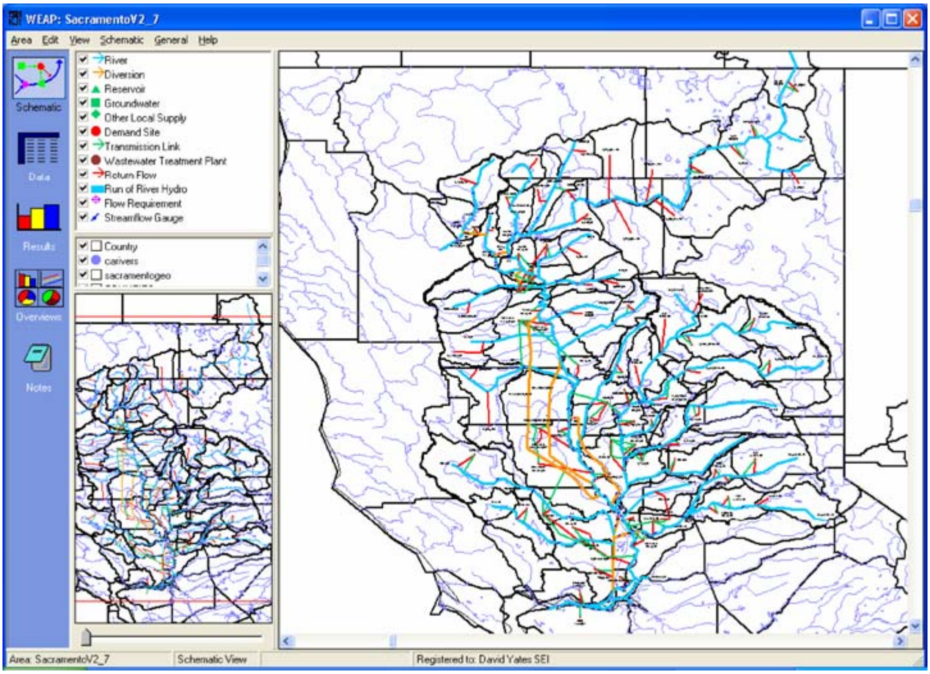


Fig. 1 Schematic of the Sacramento River Basin WEAP application. Includes representations of California Counties, simulated sub-catchments, river with installed hydraulic infrastructure and flow requirements, and centers of non-evaporative demand

the specific formulation of the integrated hydrologic/water systems WEAP model. One important feature is that WEAP allows the user to set priorities among different users, such as municipal and industrial (M&I) users and agriculture, define the preference of a particular user for a particular source, such as surface water or groundwater, and to constrain the transmission of water between sources and users based on physical and or regulatory constraints. The WEAP application of the Sacramento River system included the possibility of allowing agricultural water users to tap groundwater in times of surface water scarcity so that water could be allocated to M&I uses. Further the formulation allowed for agricultural areas to change as a function of the amount of water in system, avoiding the assumption that these areas are held constant as some level of development. Finally, the model included assumption as such the system can be used to explore the management tradeoffs intrinsic to the California water system that may accompany future climate change in the State. The following sections briefly describe how the Sacramento River WEAP application functions.

2.1 Hydrology

The hydrology module in WEAP is spatially continuous, with a study area configured as a contiguous set of sub-catchments that cover the entire extent of the Sacramento River basin. The spatial continuity of the WEAP application across a catchment allows for simulation of all terrestrial components of the hydrologic cycle. The Sacramento Valley application includes 54 sub-catchments. A unique climate forcing data set of precipitation, temperature, relative humidity and wind speed is uniformly applied across each sub-catchment that is fractionally divided into land use/land cover classes. A one-dimensional, two-store, quasi-physical water balance model for each land use/land cover class partitions water into, surface runoff, infiltration, evapotranspiration, interflow, percolation and baseflow components. Values from each fractional area within a sub-catchment are summed to represent the lumped hydrologic response. Details of the WEAP hydrologic module are found in Yates et al. (2005a, b) and more general justification for this sort of simulation approach is found in Beven (2001, 2002). The approach entails describing hydrologic processes in a representative or characteristic fashion rather than using physical first principles to describe the actual movement of water through a watershed. As the physical hydrology routine is representative and not physical it is possible image a system where the parameters are scaled to the time step in question. Thus the representative soil depth, for example, can be scaled to accommodate the amount of precipitation that would come in a month even though that amount would overwhelm the physical soil system if it were to come in 1 day.

2.2 Management

At each time step, WEAP first computes the hydrologic fluxes, which are passed to each associated river and groundwater object. These include surface inflows for the portions of the catchment associated with a stream reach, groundwater recharge to the aquifer, and stream–aquifer interactions along each stream reach. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs (operating rules designed to mimic the balance between flood control, water delivery and water storage objective) and the distribution network, environmental regulations, as well as the priorities and preferences assigned to points of demands are use to condition a linear programming (LP) routine that maximizes the demand “satisfaction” to the greatest extent possible. By defining the preference landscape that is fed to the LP the user avoids the need to build a rule-based simulation, which is complicated in a system like California. This preference landscape can be adjusted so that the model approximates the way the system is operated. All flows are assumed to occur instantaneously, thus a demand site can withdraw water from the river, consume some, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate water to meet any specific demand in the system, without regards to travel time. Thus, the model time step should be at least as long as the residence time of the study area. For this reason, a monthly time step was adopted for this Sacramento Basin analysis.

3 Future climatic and hydrologic conditions

For the purposes of this study, outputs from two general circulation models, the Parallel Climate Model (PCM) developed at the National Center for Atmospheric Research and the Coupled Model 2 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL), were used to estimate future climate conditions under the A2 and B1 emissions scenarios. These models are well established climate model used by the climate research community and they have been run for this study under the assumptions that greenhouse gas emissions will increase dramatically (A2) or more moderately (B1) over the course of the 21st century. Outputs from these models were downscaled by based on Maurer et al. (2002) to create a 1/8th degree gridded data set for daily climate variables. The statistical downscaling technique is based on the method developed by Wood et al. (2002), which is an empirical statistical technique that maps precipitation and temperature during a historical period (1950–1999 for our study) from the global climate model to the concurrent historical record. The method also attempts to statistically correct some of bias present in the global climate models. The probability distributions of the observations are reproduced by the bias corrected model data for the overlapping historical period, while both the mean and variability of future climate can evolve according to the global climate projections. The combined bias correction/spatial downscaling method has been shown to compare favorably to different statistical and dynamic downscaling techniques (Wood et al. 2004). This downscaled daily data was used to derive average monthly time series of precipitation, temperature, relative humidity and wind speed for each of the 54 sub-catchments in the WEAP model. Analysis of the averages of the 54 climate locations used as inputs to WEAP were conducted for four distinct periods: 1960–1999, 2005–2034, 2035–2064, and 2070–2099. Gaps between 2000–2004 and 2065–2069 exist because the downscaling routines were set up to generate 30-year time series of climatic data.

3.1 Temperature

Each of the four GCM/scenario combinations predicted higher average winter and summer temperatures over the next century. GFDL A2 showed the highest increases in temperature: 3.0°C for winter and 5.0°C in summer. PCM B1 showed the smallest change in temperature: 1.5°C for winter and 1.4°C in summer. The GFDL B1 and PCM A2 scenarios predicted intermediate changes in temperature. GFDL B1 predicted changes of 1.9°C in winter temperature and 2.8°C in summer temperature. PCM A2 predicted changes of 2.2°C in winter temperature and 2.5°C in summer temperature.

3.2 Precipitation

The two GFDL scenarios predict a decreasing trend in precipitation over the next century, with wet years showing the largest downward shift in annual rainfall. The two PCM scenarios show less pronounced changes in annual precipitation. PCM B1 predicts slightly wetter conditions at the end of the century, while the PCM A2 shows a decrease in precipitation in normal-dry years and an increase in precipitation in normal-wet years.

3.3 Hydrology

The simulated impacts of the climate change scenarios on the Sacramento Basin hydrology are characterized by considering inflows to the three major reservoirs in the basin: Lake Shasta, Lake Oroville and Folsom Lake. Two aspects of the hydrologic system that could be affected by the climate change scenarios: changes to inflow timing, magnitude and duration and changes to drought persistence.

Figure 2 shows monthly pattern of inflows to major reservoirs in the Sacramento Basin for two time periods: 2035–2064 and 2070–2099. As can be seen in the figure all the scenarios show an earlier timing of inflow as against historic conditions. The impacts are higher for the Feather and American watersheds, which have more dependence on snowmelt runoff than for the Sacramento watershed, much of which already lies below the snowline. The impacts are also higher for those scenarios with larger increases in temperature (e.g. GFDL A2). Warmer temperatures lead to earlier loss of the snow pack. The results also are consistent with the changes in annual precipitation, i.e. PCM B1 is a wet scenario and therefore has higher annual inflows, and GFDL A2 is a dry scenario and therefore has lower annual inflows. The other two models are intermediary. A drier climate would reduce the overall water supply.

A major advantage of WEAP's integrated hydrology is that it can be used to examine scenarios that don't preserve the historic sequence of wet and dry years. Thus, WEAP can simulate conditions under different levels of drought persistence that might occur with climate change. Drought conditions in the Sacramento basin are described using an index composed of inflows to Shasta, Oroville and Folsom reservoirs plus streamflow in the smaller Yuba River. Based on the value of this index a water year is classified as wet, above normal, below normal, dry and critical. Assuming that a drought will be indicated by a year below the dry threshold, an accumulated deficit representing the positive difference between the "dry" threshold and the index was calculated. Deficits are accumulated in consecutive dry years and whenever the index is above the "dry" threshold, the deficit is reset to 0. Figure 3 show the accumulated deficits for the historic period (the 1976–1977 and early 1990's droughts are apparent), the four climate change conditions included in this analysis, and one climate change scenario corresponding to the PCM model run under the A1fi emission scenario. This emissions scenarios, which assumes extreme increases in greenhouse gas emissions over the course of the 21st century, was not included in the current study but was used by some of the authors on earlier studies (Hayhoe et al. 2004). It has been included in this figure for the sake of comparison.

The results show that drought persistence will be smaller for the two PCM scenarios considered in this analysis but not under the A1fi emission scenario. In this case droughts comparable in magnitude to the early 1990's drought will occur with regularity. On the other hand the GFDL B1 scenario anticipated weaker drought persistence relative to the historic conditions. This is clearly not the case under GFDL A2 scenario that includes a very severe drought ("mega-drought") during the last 15 years of the century. The future

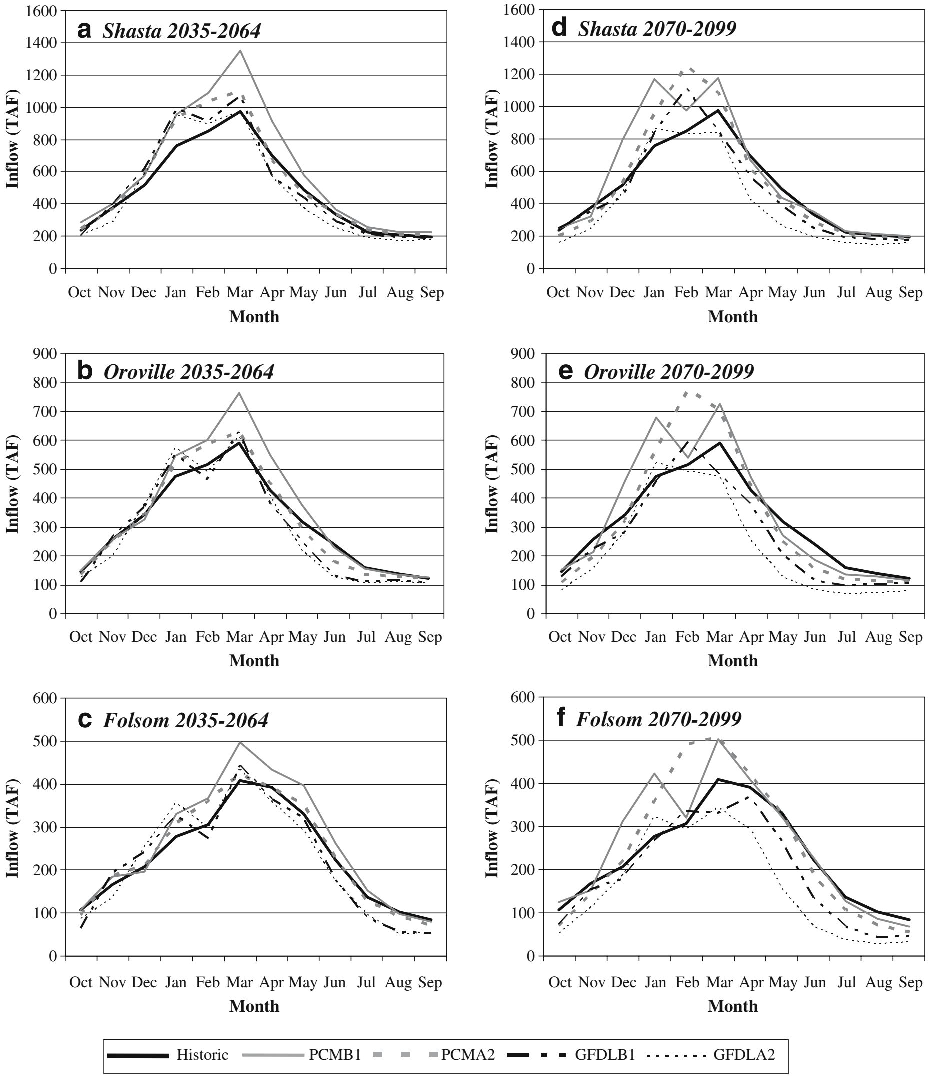


Fig. 2 Monthly distribution of average reservoir inflows during the mid century and late century periods to Shasta (**a**, **d**), Oroville (**b**, **e**) and Folsom (**c**, **f**) reservoirs

pattern of drought persistence associated with each of the GCM/emission scenario combination is directly related to the sequence of climate data associated with each combination. Less precipitation means more droughts. Dry scenarios such as PCM/A1fi and GFDL/A2 are associated with drought conditions that are more numerous or more severe than recent history. Again, here is a major advantage of using climate as model input rather than some perturbation of some historic pattern of streamflow, the effect of drought patterns not captured in the historic record but possible in the future can be explicitly evaluated.

One important thing to keep in mind when considering this information on climate and hydrology is that the climate time series associated with each GCM/emission scenario combination represents a single realization of the future climate. It would be possible to develop ensembles of future climate time series, which would allow for a more robust

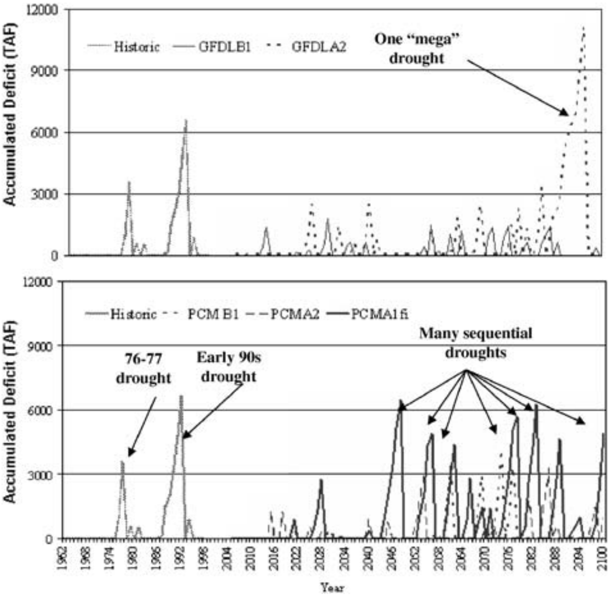


Fig. 3 Structure of drought persistence under discrete climate scenarios associated with four GCM/emission scenario combinations

depiction of potential future conditions, including a representation of climate variability and uncertainty. The WEAP platform, with it integrated hydrology module is ideally suited to be run under an ensemble of future climate scenarios.

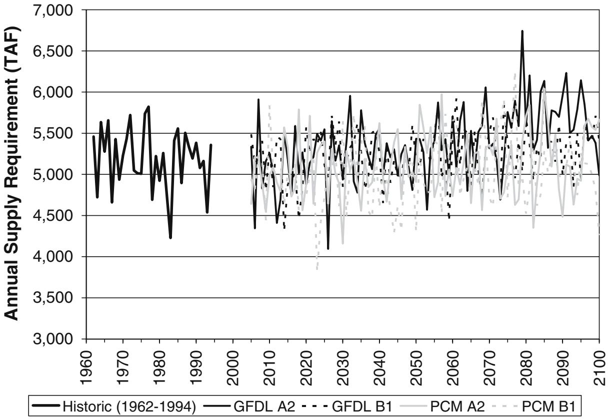
4 Water management and adaptation

It is at this point that progress must be demonstrated in response to the earlier assertion that in order for climate change research to be relevant in a setting such as California, analysis must move from anticipating hydrologic change to understanding management implications. Specifically, what management decisions should be made to accommodate the changes in available supply? Any meaningful answer to that question must also consider the demands such decisions must satisfy. In California, this means accounting for changes in the largest water use sector, irrigated agriculture.

Annual water requirements for Sacramento Valley agricultural under the four GCM/emission scenario combinations are summarized in Fig. 4. These are the sum of the crop water requirements calculated from the future climate time series using WEAP's internal evapotranspiration routine and its representation of losses incurred in delivering water to meet evaporative demand. All four scenarios showed an increasing trend in water requirements with time, with the GFDL A2 scenario exhibiting the most pronounced increase. These increasing supply requirements are due primarily to increasing summer temperatures for each of the four scenarios. These projections of water supply requirements of irrigated agriculture are based on the assumption that both irrigation water management efficiency and cropping patterns remain unchanged in the face of a century of steady climate change.

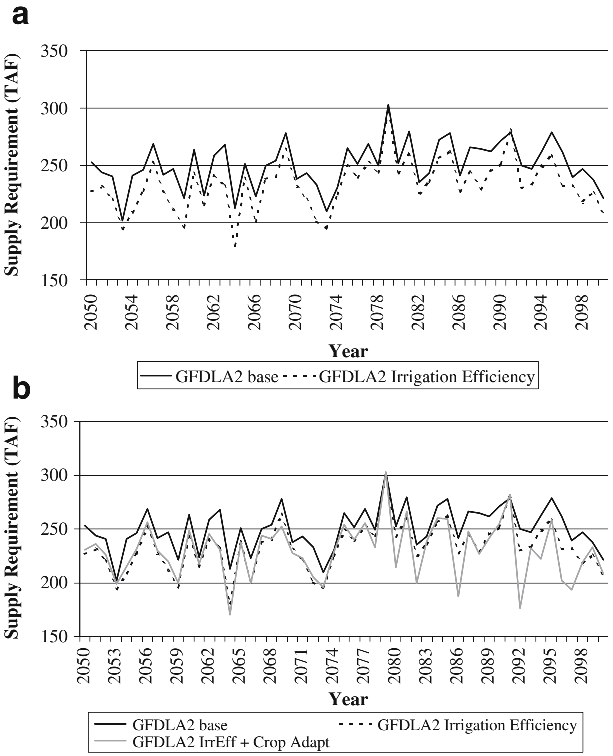
Obviously, adaptation strategies may mitigate the impacts of climate change. Therefore, improved irrigation efficiency and changes in cropping patterns in response to water supply conditions were implemented in the model. In investigating the impact of adaptation

Fig. 4 Evolution of the total water supply requirement of irrigated agriculture in the Sacramento Valley



strategies, the supply requirement for regions within a single sub-catchment of the Sacramento Valley application were considered, first in the case where irrigation efficiency improvements were the sole adaptation. For the southern region of the Tehama–Colusa Canal Authority, which is representative of irrigated agriculture in the Sacramento Valley, Fig. 5a shows the 2050–2100 base supply requirement without changes in irrigation efficiency under the GFDLA2 scenario and the 2050–2100 supply requirement with improvements in irrigation efficiency. The results show a decline in supply requirements as

Fig. 5 Representative evolution of water supply requirement without (**a**) and with (**b**) adaptation



improvements in irrigation efficiency are implemented. It is interesting to note, however, that even with these improvements, the supply requirement in the face of climate change will increase relative to that observed under the historic climate.

As a further potential adaptation scenario, the improvement in irrigation efficiency was combined with shifts in cropping patterns. The simulated shifts in cropping were based on econometric analysis of observed shifts in cropping pattern associated with periods of limited surface water availability and depleted groundwater levels. The econometric relationship used in the model produced an increase in land fallowing as the climate becomes progressively warmer and drier and also a slight increase in the amount of water used to irrigate orchards. Figure 5b shows the evolution of water supply requirements for the region when crop shifts occur during times of shortage. When coupled, the effect of improved irrigation efficiency and a dynamic crop pattern based on simulated water supply and groundwater conditions is a decline in water supply requirements during the period of analysis, particularly at the end of the period when large and frequent droughts are assumed to occur. The effect of changing cropping patterns is reflected in the difference between these two sets of graphs. Early in the 2050–2100 period shifts in cropping actually result in sight increases in water demand as against the assumption of improved irrigation efficiency alone. This is due to the fact that this was assumed to be a relatively wet period during which simulated cropping was more extensive. It is interesting to note that the combined effect of these adaptations is to bring the simulated supply requirement in the face of climate change nearly back to the levels observed in the recent past. This will likely provide useful water management flexibility as the climate evolves.

While the southern region of the Tehama–Colusa Canal Authority is representative of irrigated agriculture in the Sacramento Valley, adaptation strategies have varying impacts on water supply requirements at the irrigation district level depending upon water rights and the type of crops grown within districts. In general, improvements in irrigation efficiency were most effective in reducing crop water demands in districts that did not plant a large portion of their land in rice, which was not a targeted crop for irrigation technology advancement due to its need for ponded water over extended periods of the growing season. Fallowing agricultural land in dry years also achieved substantial water savings, but had the biggest impact in districts that had the weakest surface water rights. The combined effect of both adaptation strategies showed that in the driest years some districts could reduce

Table 1 Changes in water supply requirements for irrigated agriculture in different regions of the Sacramento Valley

Scenario	Period	User		
		TCCA south	GCID	Non-district north
Hist	1962–1998	230	580	121
Base (no adaptation)	2050–2074	242	606	126
	2075–2099	259	639	135
Irrigation efficiency	2050–2074	222	597	113
	2075–2099	243	631	123
Irrigation efficiency and dynamic crop	2050–2074	224	587	114
	2075–2099	235	616	124

Tehama–Colusa Canal Authority includes less rice and has relatively weak water rights, Glenn–Colusa Irrigation District includes a great deal of rice and has strong water rights

CGID Glenn–Colusa Irrigation District

irrigation requirements by 20% to 30%. These differences are summarized in Table 1, which also has results for the Glenn–Colusa Irrigation District which grows a lot or rice and has very senior water rights.

5 Results

WEAP simulations were run for each of the climate change scenarios with both adaptation strategies implemented across all agricultural areas of the Sacramento Valley. These simulations suggested that increasing temperatures and declining precipitation resulted in similar spatial and temporal patterns of agricultural water supply and delivery whether or not adaptation occurs. However, adaptation strategies reduced the absolute effect. Table 2 compares the impacts of simulations run with and without adaptation for the driest and warmest future period (2070 to 2099). Improved irrigation efficiency and increased land fallowing in dry years resulted in substantial reductions in agricultural water supply requirements for all climate change scenarios. This, in turn, reduced the average annual surface water deliveries and groundwater pumping to agriculture. For the GFDL A2 scenario, however, which included a prolonged drought from 2085 through 2095, total water table drawdown was much greater than that simulated in each of the other scenarios (see Fig. 6). For all scenarios, the reductions in crop water demands meant that irrigation districts were able to satisfy a higher proportion of their irrigation requirements.

Despite the large decrease in agricultural demands, Central Valley Project and State Water Project reservoirs showed little change in their operation as a result of implementing adaptation strategies. Carryover storage levels in both Lake Shasta and Lake Oroville were only 0% to 1% higher than they were when no adaptation was in place. This suggests that other water users in the basin captured the water savings realized as a consequence of reducing consumptive demands in agricultural areas. Table 2 shows that some of the additional water was shifted to Sacramento Valley urban areas and delta exporters. The remaining water was used to satisfy various environmental requirements. The case of the GFDL A2 scenarios reveals, however, just how much storage levels will be impacted in the case of a severe and prolonged drought such a the one include in this climate time series. Both with and without adaptations, these levels are dramatically lower than was observed in the recent past.

Fig. 6 Changes in groundwater depth for the Colusa Basin

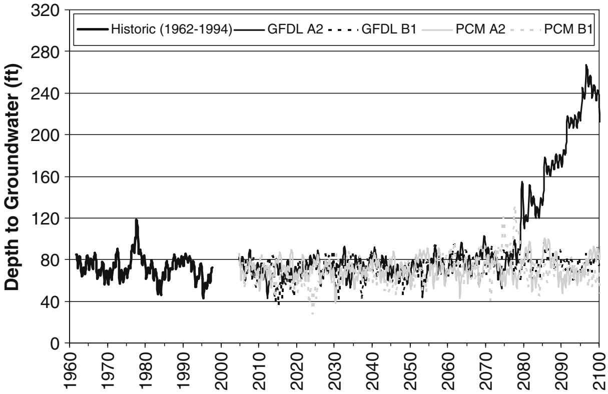


Table 2 Results of WEAP Simulations of Critical Water Management Variables under Four GCM/Emission Scenario Combinations

	Historic (1962–1994)	GFDL A2		GFDL B1		PCM A2		PCM B1	
	Baseline	Without adaptation	With adaptation	Without adaptation	With adaptation	Without adaptation	With adaptation	Without adaptation	With adaptation
Average annual agricultural water requirement (TAF)	5,189	5,658	4,856	5,348	4,612	5,188	4,502	5,107	4,339
Average annual agricultural deliveries (TAF)	3,593	3,672	3,279	3,719	3,301	3,624	3,230	3,533	3,124
Average annual groundwater pumping to agriculture (TAF)	1,496	1,831	1,550	1,545	1,328	1,473	1,262	1,477	1,230
Average carryover storage in Lake Shasta (TAF)	2,660	1,728	1,734	2,324	2,331	2,621	2,646	2,925	2,953
Average carryover storage in Lake Oroville (TAF)	2,287	1,641	1,647	2,032	2,044	2,275	2,296	2,475	2,503
Maximum groundwater drawdown in Stone-Corral (ft)	119	267	225	98	99	100	100	132	124
Average annual urban deliveries (TAF)	99	381	499	393	507	391	506	389	505
Average annual delta exports (TAF)	5,526	5,072	5,179	5,610	5,622	5,533	5,564	5,469	5,495

In general, modification of agricultural demands as a result of implementing adaptation strategies to climate change improved the reliability of surface water deliveries for all water users in the basin. The volumes of the water savings and increased deliveries, however, varied considerably across the four climate change scenarios. The drier scenarios generally showed greater differences from simulations run without adaptation, because land fallowing occurred more frequently in these scenarios. The relative effect of adaptation (i.e. the percent difference), on the other hand, was consistent for all scenarios. Thus, while there is still considerable uncertainty associated with evaluating the absolute impacts of a forecasted climate, it is clear that mitigation measures undertaken in times of water scarcity will have similar impacts on the water supply condition, independent of climatic variability.

6 Conclusions

This report illuminates two very important conclusions. The first is that an integrated hydrology/water resource systems tool offers profound advantages when it comes to investigating climate change impact and adaptations in the water sector. The WEAP framework is able to directly evaluate future climate scenarios without relying on a perturbation of the historic patterns of hydrology that were observed in the past. In addition, potential increases in water demand associated with higher temperatures and lower rainfall are included in the analysis in a more robust manner than with the other tools.

Second, water management adaptation in the water resources sector has the potential to mitigate the impacts of climate change. Improvements in irrigation efficiency and shifts in cropping patterns can reduce the demand in the agricultural sector and free up water for other purposes. This adaptation may prevent exceeding the safe-yield of the groundwater in the system in the coming decades.

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References

Beven K (2001) How far can we go in distributed hydrological modelling. Hydrol Earth Syst Sci 5(1):1–12

Beven K (2002) Towards an alternative blueprint for a physically-based digitally simulated hydrologic response modelling system. Hydrol Process 16:189–206

Brekke L, Miller N, Bashford K, Quinn N, Dracup J (2004) Climate change impacts uncertainly for water resources in the San Joaquin River Basin, California. J Am Water Resour Assoc 40(1):149–164

Dettinger MD, Cayan DR (1995) Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. J Climate 8(3):606–623

Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Nicholas , K, Cleland EE, Dale L, Drapek R, Hanemann RM, Kalkstein LS, Lenihan J, Lunch CK, Neilson RP, Sheridan SC, Verville JH (2004) Emissions pathways, climate change, and impacts on California. Proc Nat Acad Sci 101(34):12422–12427

Maurer EP, Wood AW, Adam JC, Lettenmaier DP, Nijssen B (2002) A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. J Climate 15:3237–3251

Wood AW, Maurer EP, Kumar A, Lettenmaier DP (2002) Long-range experimental hydrologic forecasting for the eastern United States. J Geophys Res Atmos 107(d20):4429

Wood AW, Leung LR, Sridhar V, Lettenmaier DP (2004) Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim Change 62:189–216

Yates D, Sieber J, Purkey D, Huber Lee A, Galbraith H (2005a) WEAP21: a demand, priority, and preference driven water planning model: part 2, aiding freshwater ecosystem service evaluation. Water Int 30 (4):487–500

Yates D, Sieber J, Purkey D, Huber Lee A (2005b) WEAP21: a demand, priority, and preference driven water planning model: part 1, model characteristics. Water Int 30(4):501–512