CLIMATE CHANGE IMPACTS ON WATER SUPPLY AND AGRICULTURAL WATER MANAGEMENT IN CALIFORNIA'S WESTERN SAN JOAQUIN VALLEY, AND POTENTIAL ADAPTATION STRATEGIES

A Paper From:
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Arnold Schwarzenegger, *Governor*

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Table of Contents

Preface.. iii
Abstract ix
1.0 Introduction 1
1.1. California Water Resources 1
1.2. Background 3
1.3. Paper Organization 4
2.0 Project Approach 4
2.1. WEAP Model Description 4
2.1.1. Sacramento Valley WEAP Application 5
2.1.2. WEAP Hydrology 6
2.1.3. Agricultural Water Demands 7
2.2. Model Refinements 7
2.2.1. Expanding the Model into the San Joaquin Valley 7
Agricultural and Urban Water Demands 8
Delta Export Operations 11
San Luis Reservoir 12
Other Water Sources 12
2.2.2. Introducing Delta Water Quality Standards 13
2.2.3. Model Summary 13
2.3. Analytical Approach 14
2.3.1. Future Climate Scenarios 15
2.3.2. Adaptation Strategies 16
Improving Irrigation Efficiency 16
Shifting Cropping Patterns 17
3.0 Results 18
3.1. Climatic Analysis 19
3.2. Hydrologic Analysis 23
3.2.1. Reservoir inflows 23
3.2.2. Occurrence of Drought 24
3.3. Demand Analysis 25
3.4. Operations Analysis without Adaptation 29
3.5. Operations Analysis with Adaptation 33
3.5.1. Water Supply Requirements with Adaptation 34
Improved Irrigation Efficiency 34
Shifting Cropping Patterns 37
3.5.2. Water Supply and Delivery 41
Improved Irrigation Efficiency 41
Shifting Cropping Patterns 44

4.0 Conclusions ... 48
5.0 References ... 49
6.0 Glossary ... 50

List of Figures

Figure 1. California geography ... 1

Figure 2. Major state, federal, and local water projects in California ... 2

Figure 3. Interbasin Water Transfers ... 3

Figure 4. Simplified schematic of the water resources elements implemented in the Sacramento River WEAP model ... 6

Figure 5. WEAP schematic of Delta export zone ... 8

Figure 6. CVPM regions ... 18

Figure 7. Annual precipitation (2006–2099) ... 20

Figure 8. Annual average temperature (2006–2099) ... 21

Figure 9. Boxplots of precipitation across all projections for three periods (2006–2034, 2035–2064, and 2065–2099). The dotted horizontal line is historic (1961–1999) mean precipitation. (Units are in millimeters.) ... 22

Figure 10. Boxplots of average annual temperature (°C) for three periods (2006–2034, 2035–2064, and 2065–2099). ... 23

Figure 11. Average monthly inflow to Shasta, Folsom, and Oroville for A2 and B1 emission scenarios ... 24

Figure 12. Changes in drought conditions. Vertical dotted line delineates the historical period from the future climate projection period. ... 25

Figure 13. Projected water supply requirements for the Sacramento Valley ... 27

Figure 14. Projected supply requirements for the western San Joaquin Valley / Tulare Basin ... 28

Figure 15. Sacramento Valley agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values. ... 30

Figure 16. Western San Joaquin and Tulare Lake agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values. ... 30

Figure 17. Sacramento Valley annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values....31

Figure 18. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values. 31

Figure 19. Average groundwater depths in the western San Joaquin Valley for A2 and B1 emission scenarios 32

Figure 20. Carryover storage for A2 and B1 scenarios without adaptation 33

Figure 21. Changes in water supply requirement in Sacramento Valley associated with improvements in irrigation technology for A2 and B1 scenarios 35

Figure 22. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with improvements in irrigation technology for A2 and B1 scenarios....37

Figure 23. Changes in water supply requirement in Sacramento Valley associated with changes in cropping patterns for A2 and B1 scenarios 38

Figure 24. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with changes in cropping patterns for A2 and B1 scenarios....39

Figure 25. Simulated changes in cropping patterns in the Sacramento and San Joaquin Valleys for A2/GFDL-CM21 scenario 40

Figure 26. Sacramento Valley agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values. 42

Figure 27. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median and hash marks indicate minimum and maximum values. 42

Figure 28. Sacramento Valley annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values. 43

Figure 29. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values. 43

Figure 30. Carryover storage for A2 and B1 scenario with improved irrigation technology....44

Figure 31. Sacramento Valley agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values. 45

Figure 32. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values. 45

Figure 33. Sacramento Valley annual groundwater pumping for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values. 46

Figure 34. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios shifting cropping patterns. Circles indicate period median and hash marks indicate minimum and maximum values. 46

Figure 35. Carryover storage for A2 and B1 scenario with shifting cropping patterns 47

List of Tables

Table 1. Agricultural areas receiving Delta export water 9

Table 2. Irrigated crops 10

Table 3. Demand areas outside of the Sacramento and San Joaquin basins that receive Delta export water 11

Table 4. General circulation models used in study 15

Abstract

Climate change impacts and potential adaptation strategies were assessed using an application of the Water Evaluation and Planning (WEAP) system developed for the Sacramento River basin and Delta export region of the San Joaquin Valley. WEAP is an integrated rainfall / runoff, water resources systems modeling framework that can be forced directly from time series of climatic input to estimate water supplies (watershed runoff) and demands (crop evapotranspiration). We applied the model to evaluate the hydrologic implications of 12 climate change scenarios as well as the water management ramifications of the implied hydrologic changes. In addition to evaluating the impacts of climate change with current operations, the model also assessed the impacts of changing agricultural management strategies in response to a changing climate. These adaptation strategies included improvements in irrigation technology and shifts in cropping patterns towards higher valued crops. Model simulations suggested that increasing agricultural demand under climate change brought on by increasing temperature will place additional stress on the water system, such that some water users will experience a decrease in water supply reliability. The study indicated that adaptation strategies may ease the burden on the water management system. However, offsetting water demands through these approaches will not be enough to fully combat the impacts of climate change on water management. To adequately address the impacts of climate change, adaptation strategies will have to include fundamental changes in the ways in which the water management system in operated.

Keywords: climate change, water management, crop water demand, irrigation, water resources modeling

1.0 Introduction

1.1. California Water Resources

One of the defining features of the California landscape is the Sierra Nevada mountain range that runs along much of the eastern part of the state (Figure 1). The rivers that run out of the Sierra provide drinking water for the state's large urban areas and provide irrigation for the state's vast agricultural land in the Central Valley. Precipitation, however, falls mainly in the fall and winter, so flows in these rivers are sustained throughout the year by melting snow. In fact, Sierra snowpack accounts for approximately half of the surface water storage in the state. Current projections forecast that this snowpack may decline by 70% to as much as 90% over the next 100 years, threatening California's water supply (California Climate Change Center 2006).

Figure 1. California geography

In addition to having to manage water supplies that are unequally distributed throughout the year and, indeed, vary considerably from year to year, the state also faces the challenge of moving water from the water-rich northern part of the state to support cities and agriculture in drier areas in the south. Left to flow naturally through the state's rivers, most of the precipitation that falls in the state would flow out to the Pacific Ocean either directly through the rivers of the North Coast or through the San Francisco Bay via the Sacramento and San Joaquin rivers. This would leave the southern part of the state—which contains roughly two-thirds of the state's population—with little of the state's available fresh water supplies. To address this imbalance, several local, state, and federal water projects have been built to deliver water from the water-rich parts of the state to the arid south (Figure 2).

Figure 2. Major state, federal, and local water projects in California
Courtesy of the California Department of Water Resources

Indeed, the state has made a fairly Herculean effort to transfer water between watersheds through a complex of canals and tunnels that have been built over the last century. Figure 3 shows average annual volumes of water that are transferred between the state's ten hydrologic regions. It is clear from this graphic that many parts of the state rely heavily upon water exports from the Sacramento River Basin. It is critical then for the viability of water management in California to understand how climate change may affect the sustainability of operating the water management system to deliver water throughout the state.

The importance of the Sacramento River as a source of water for the entire state led the research team, as part of the 2006 Scenarios Project reporting, to focus on that region when investigating the potential impacts of climate change on water management. In that work, possible changes in hydrology and water demand in the regions south of the Delta was not explicitly considered in the analysis. As part of the 2009 Scenarios Project reporting, an effort was made to extend the scope of the analysis to include the impact of climate change on water demand in the western San Joaquin Valley. This incremental expansion will allow for a more comprehensive assessment of climate change impacts, and possible management adaptations, in the California Water System, particularly since this area constitutes a major portion of the water demand that drives water exports from the Delta. While future work would logically include bringing the rest of system in to the model, the current expansion represents an important step in developing a tool for climate change assessment in California water management.

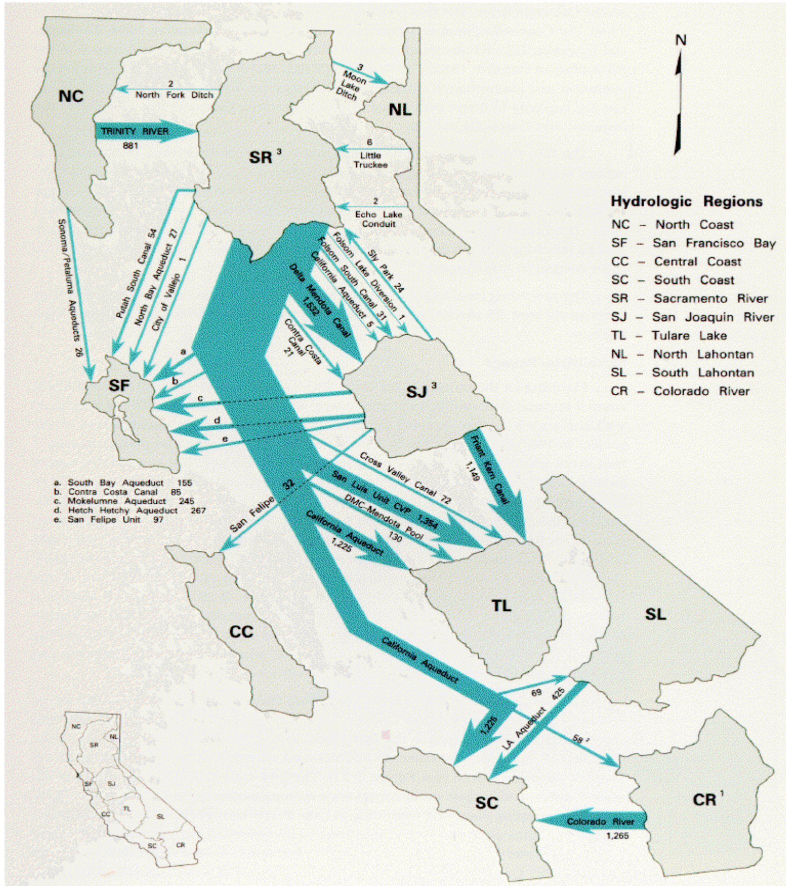


Figure 3. Interbasin Water Transfers
Courtesy of the California Department of Water Resources

1.2. Background

The 2006 edition of the report to the California governor and legislature on potential climate change impacts and adaptations (California Environmental Protection Agency 2006) included an annex report on potential impacts to Sacramento Valley agriculture (Joyce et al. 2006). This analysis was conducted using the Water Evaluation and Planning (WEAP) modeling system (Yates et al. 2005a; Yates et al. 2005b) developed by the Stockholm Environment Institute. While the technical aspects of the WEAP model and the Sacramento Valley application are presented later in this paper, it is worth mentioning that WEAP is an integrated rainfall / runoff, water resources systems modeling framework that can be forced directly from time series of climatic input. Within a single software package, the hydrologic implications of a climate change scenario as well as the water management ramifications of this hydrologic change can be assessed.

Using this WEAP application as part of CalEPA's 2006 report to the governor, it was possible to assess the implications of a limited set of future climatic sequences on water demand in the various sectors and to evaluate the availability of supplies to meet these demands. These future climate scenarios were developed based on downscaling of two general circulation models (GCMs)—the Geophysical Fluid Dynamic Laboratory model (GFDL) and the Parallel Climate

Model (PCM)—run under two emissions scenarios (A2 and B1). The results suggested that increasing agricultural demand under climate change due to increased evapotranspiration (ET) would place additional stress on the water system in the Sacramento Valley. The model was also used to assess the effectiveness of two agricultural adaptations, increasing on-farm efficiency and crop shifts toward lower consumption / higher value crops in times of shortage. These were found to be effective at reducing supply shortfalls in agriculture and other sectors.

The completeness of this analysis was limited somewhat, however, because the water demand within the region that depends upon water deliveries from the Sacramento-San Joaquin Delta was not adjusted according to the assumed climatic sequences, and was instead a composite of historic export demands. This demand is a critical driver of water operations in the Sacramento Valley and a major factor in characterizing the status of the Delta itself, a topic of increasing urgency. The current work attempts to resolve this issue by bring agricultural demand and water management in the western San Joaquin Valley into the WEAP application. This will include representing climatically driven water demand in the agricultural sector in this region along with the operations of state and federal conveyance and storage infrastructure. This expanded WEAP application, run under 12 climatic sequences using the same two adaptation strategies, will provide a much more complete assessment of the potential impact of climate change on agriculture in the Central Valley and the other users that depend on the waters of the Sacramento River Basin.

1.3. Paper Organization

This paper presents an analysis of climate change impacts on agricultural water management in California's Central Valley and is an extension of research conducted by Joyce et al. (2006) as part of the first report to the governor on climate change (California Environmental Protection Agency 2006). We begin the paper by briefly describing the main features of the water planning model that was used in our previous research and used here as a point of departure for the current effort. We then describe the modifications made to this model that were required to make it suitable for considering climate change impacts on a broader scale than was considered under the previous research effort. This is followed by a section describing the scope of the analyses conducted in the current effort. Specifically, it outlines how we used downscaled climate projections to estimate impacts on water management and then how we constructed hypothetical adaptation strategies that were geared toward offsetting anticipated water shortages. This is followed by a results section wherein we present the estimated impacts of the climate projections on water management and discuss the capacity of combating these impacts through demand reduction adaptation strategies. We end with some conclusions about our findings.

2.0 Project Approach

2.1. WEAP Model Description

The Water Evaluation and Planning (WEAP) system is a comprehensive, fully integrated water basin analysis tool. It is a simulation model that includes a robust and flexible representation of water demands from all sectors and flexible, programmable operating rules for infrastructure elements such as reservoirs, canals, and hydropower projects. Additionally, it has watershed rainfall-runoff modeling capabilities that allow all portions of the water infrastructure and demand to be dynamically nested within the underlying hydrological processes. In effect, it allows the modeler to analyze how specific configurations of infrastructure, operating rules, and priorities will affect water uses as diverse as in-stream flows, agricultural irrigation, and municipal water supply under the umbrella of input weather data and physical watershed conditions. This integration of watershed hydrology with a water systems planning model makes it ideally suited to studies of the impacts of climate change internal to watersheds.

2.1.1. Sacramento Valley WEAP Application

For a complete description of the Sacramento Valley WEAP application, the reader is strongly encouraged to refer to Yates et al. (2008). In summary, however, the WEAP application for the Sacramento Valley water system includes the major rivers; the major alluvial aquifers; the major trans-basin diversion from the Trinity River; the main reservoirs (Clair Engle, Shasta, Whiskeytown, Black Butte, Oroville, Almanor, Bullard's Bar, and Folsom); the major irrigation canals and their associated demand centers (e.g., Tehama-Colusa canal, the Glen-Colusa canal, and others); aggregated irrigation districts that draw water directly from rivers; and the principal urban water demand centers. Three flood conveyance systems included in the model are the Sacramento Weir and the Yolo and Sutter bypasses. A simplified schematic is presented in Figure 4.

The WEAP system allows the user to set priorities among different users, such as urban users and agriculture, to 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. In formulating a WEAP application, the user describes the multi-objective nature of most engineered water systems.

This last point merits additional comment. The original EPA call for research proposals sought to develop a framework for climate change impact and adaptation analysis for water resources and aquatic ecosystems that could be used to investigate potential large-scale tradeoffs between various water management objectives. The goal was not to investigate future water supply reliability to individual water users but rather to assess whether the broad range of water uses might remain compatible under what are uncertain future climate scenarios, and if not, whether adaptations would be available to reduce potential conflicts.

The critical point to state here is that the WEAP application of the Sacramento River system includes the possibility of allowing users to tap groundwater in times of surface water scarcity and for allocation of water to urban uses in times of shortage. 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.

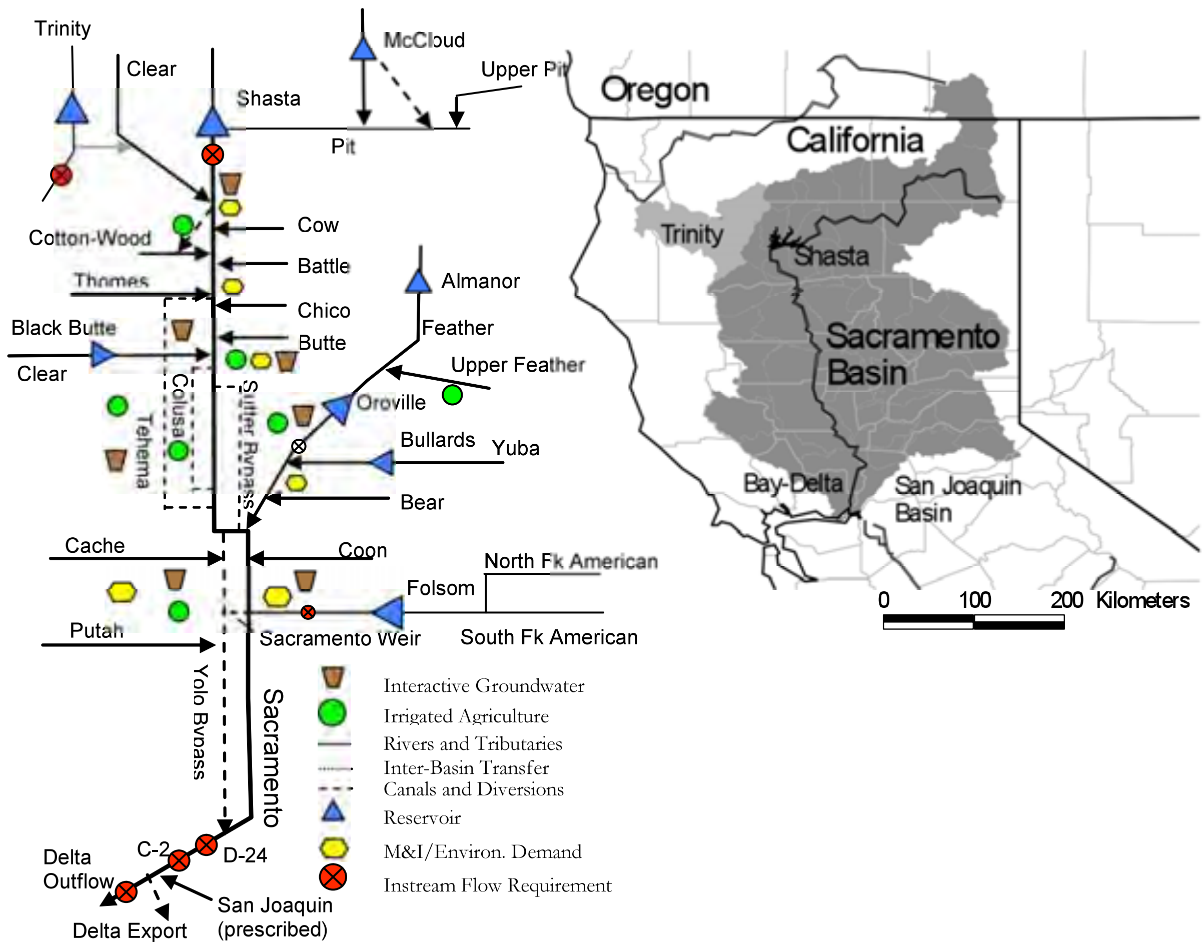


Figure 4. Simplified schematic of the water resources elements implemented in the Sacramento River WEAP model

2.1.2. WEAP 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 river basin in question. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centers, aquifers and other features (see Yates et al. 2005a and Yates et al. 2005b for details). Within each sub-catchment (SC), the entire area is fractionally subdivided into a unique set of independent land use/land cover classes that lack detail regarding their exact location within the SC, but which sum to 100% of the SC's area. A unique climate-forcing data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each sub-catchment.

A one-dimensional, quasi-physical water balance model depicts the hydrologic response of each fractional area within an SC and partitions water into surface runoff, infiltration, evapotranspiration, interflow, percolation, and baseflow components. Values from each fractional area within the SC are then summed to represent the lumped hydrologic response, with the surface runoff, interflow and baseflow being linked to a river element; deep percolation being linked to a groundwater element where prescribed; and evapotranspiration being lost from the system. Where stream-aquifer interactions are significant, the two-store water balance representation within select SCs can be reformulated by recasting the lower store as a simplified groundwater element that has hydraulic connection to associated river reaches. The hydrology module also includes a snow accumulation / melt routine based on the use of an index temperature approach.

At each time step, WEAP first computes the hydrologic flux, which it passes to each river and groundwater object. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to points of demands are used to condition a linear programming optimization routine that maximizes the demand "satisfaction" to the greatest extent possible (see Yates et al. 2005a for details). 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 regard 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.

2.1.3. Agricultural Water Demands

Irrigated crops can be one of many fractional areas within an SC and thus share the same surface hydrologic model as the natural and non-irrigated land covers. Irrigated land covers differ, however, in that the user can assign unique irrigation schedules and upper and lower thresholds for soil water storage, which together dictate the quantity, timing, and efficiency of applied irrigation. Irrigated areas require water sources to meet that demand and in WEAP the user associates surface and / or groundwater supplies to the appropriate catchments that contain irrigated land covers.

Meteorological drivers and crop coverage combine to uniquely define water demands for each sub-catchment. WEAP reads in monthly climate data—precipitation, temperature, relative humidity, and wind speed—to calculate reference evapotranspiration using a modified Penman-Montieth approach. Crop coefficients, characterized for six generalized crop types (row crops, oil crops, cereals, rice, orchards, and pasture), are applied to the reference evapotranspiration to determine crop water requirements, which are met from the soil water stores assigned to each crop type. Water deliveries for irrigation then are requested when soil water is drawn below a lower threshold. The volume of water requested depends upon the depth of the water needed to fill the soil to the upper threshold and the total acreage assigned to each crop type.

2.2. Model Refinements

2.2.1. Expanding the Model into the San Joaquin Valley

The Sacramento Valley WEAP application considered water demands outside of the Sacramento Basin that rely upon water transfers through the Delta (herein referred to as the *export zone*) to be unchanged from historical patterns. This assumption limited the scope of the analysis conducted, because it did not consider how shifting Delta exports could potentially affect the operations of the water system in the Sacramento Valley. The current effort addresses this issue by expanding the model domain such that it includes the agricultural areas in the western San Joaquin and Tulare Lake Basins.

Expanding WEAP to include the demands within the export zone requires the consideration of different demands types (agricultural, urban) and the major management authorities that serve them: the Central Valley Project (CVP), State Water Project (SWP), and the Contra Costa Water District (CCWD). Whereas the Sacramento Valley model lumped all exports from the Delta and did not follow them to their point of use, the revised model tracks exports from the main points of diversion—Jones Pumping Plant, Banks Pumping Plant, and the Contra Costa Canal—to the main areas of use: CVP agricultural contractors in the western San Joaquin and Tulare Lake Basin, SWP users south of the Delta, CCWD, and CVP water contractors in the Santa Clara Valley (herein referred to as *the San Felipe unit*). Additionally, because the demand for water in the export zone is out of phase with the available water supplies from the Delta, the revised model includes a representation of San Luis reservoir and its operations. The modified WEAP schematic of the area serviced by Delta exports is shown in Figure 5.

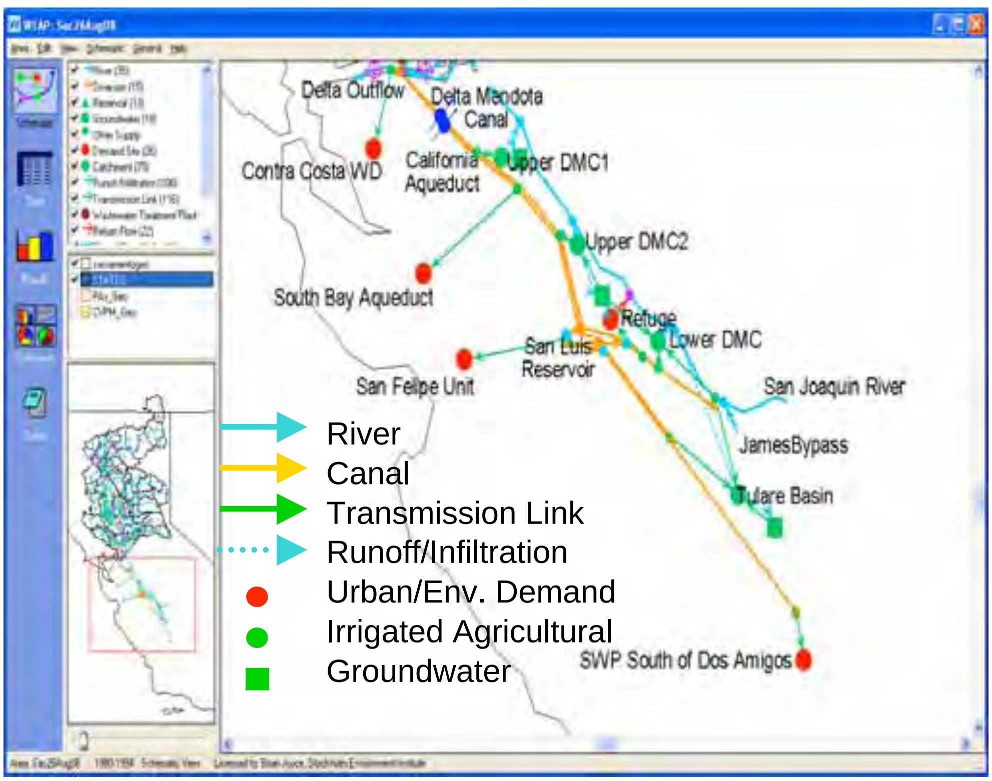


Figure 5. WEAP schematic of Delta export zone

The details of the model changes required to include the west side of the San Joaquin Valley and export zone are presented below. A description of the model recalibration to historical data is given in Appendix A: Model Calibration.

Agricultural and Urban Water Demands

The model was expanded to include agricultural areas in the western San Joaquin and Tulare Lake Basins that receive water pumped from the Delta. These irrigators contract water primarily with the CVP and are serviced by the Delta Mendota Canal (DMC) and San Luis Reservoir. These demand areas were divided into four general regions based upon water sources and, because this study linked with an economic model of changing cropping patterns, overlap with regions defined within the Central Valley Production Model, CVPM (U.S. Department of the Interior 1997). The demand areas are summarized in Table 1.

Table 1. Agricultural areas receiving Delta export water

WEAP demand	Water Users	Surface Water Source	CVPM Region
Upper DMC1	CVP contractors	DMC	Region 9
Upper DMC2	CVP contractors	DMC	Region 10
Lower DMC	CVP contractors, Exchange contractors	DMC, San Luis Reservoir, Mendota Pool	Region 10
Tulare Basin	CVP contractors	San Luis Canal, Mendota Pool	Region 14

For each of the four agricultural areas in the western San Joaquin and Tulare Lake Basins, irrigation schedules and cropped acreages were defined for thirteen irrigated and one non-irrigated land classes (Table 2). Unique irrigation schedules were defined for each commodity, while rice included an explicit representation of ponding to mimic its flood irrigation strategy and to represent the capture and storage of water by rice fields. Cropping patterns were fixed over the calibration period, 1993–2001 (see Appendix A: Model Calibration) and for base scenario runs, but they were allowed to change from year to year for other analyses (see Section 3.3 Demand Analysis) by linking WEAP to CVPM outputs (see Shifting Cropping Patterns in Section 2.3.2).

Table 2. Irrigated crops

Crop Type	Irrigation Schedule
Alfalfa	February–October
Cotton	May–October
Grain	November–May
Pasture	February–October
Rice	May–September
Sugar Beet	April–September
Tomato – Process	March–August
Tomato – Market	April–August
Vineyard	March–November
Orchard	March–October
Subtropical	March–October
Field crops	April–September
Truck crops	April–September
Fallow	N / A

The agricultural areas in the western San Joaquin and Tulare Lake Basins represent only part of the total demands within the export zone. Delta export water is delivered also to demand areas in the San Francisco Bay, the Central Coast, and the South Coast. These demand areas that lie outside of the geographic area covered by the WEAP model are summarized in Table 3. These demands are treated as boundary conditions to the current model. Two of these areas—the South Bay Aqueduct and the State Water Project south of Dos Amigos—receive surface water deliveries directly from the California Aqueduct; whereas, the Contra Costa Water District pumps from the Delta and the San Felipe Unit takes water from San Luis Reservoir.

For each of these areas, we used average historical monthly deliveries (1993–2001) to estimate their total annual demands and their monthly variation. For the calibration period, we applied a multiplier to adjust the annual demands to the observed historical record. For future scenarios, we assumed that these demands could be approximated by their observed 1993–2001 averages.

While it is reasonable to assume that water demands in these areas may increases in the future, we chose not to adjust these demands such that we could limit our analyses to evaluating the changes in demand and management that were driven by climate inputs to the model. Thus, our assessment focused on conducting a differential analysis of climate change impacts on agricultural water demand and the subsequent impacts on water management.

Table 3. Demand areas outside of the Sacramento and San Joaquin basins that receive Delta export water

WEAP Demand	Average Annual Demand (1993–2001)
Contra Costa Water District	0.109 million acre-feet
South Bay Aqueduct	0.102 million acre-feet
San Felipe Unit	0.128 million acre-feet
State Water Project south of Dos Amigos	2.245 million acre-feet

Delta Export Operations

Exports from the Delta at the Banks (SWP) and Jones (CVP) pumping plants are controlled by many regulatory rules and operational objectives. The regulatory rules include export restrictions during critical migration periods for anadromous fish called for under Section 3406b(2) of the Central Valley Project Improvement Act (CVPIA), flow objectives for the Bay-Delta estuary in accordance with SWRCB Decision 1641, and discretionary use of the environmental water account (EWA) to set limits on Delta exports. The operational objectives include delivery allocations to SWP and CVP contractors and sharing surplus and deficit flows within the Delta by the two projects under the Coordinated Operations Agreement (COA). The WEAP application was modified to include representations of regulatory guidelines that restrict Delta exports during periods deemed critical for supporting aquatic ecosystems and operational objectives that limit exports during dry periods when water supplies are insufficient to satisfy all consumptive water demands within the system.

The regulatory guidelines restricting Delta exports include aspects of the standards mentioned above. While the model does not perform a full accounting of b(2) or EWA operations, rules were added that curtail Delta exports during and following the critical April–May pulse period, during which extra releases are made on the San Joaquin River to facilitate juvenile salmon out-migration. Further, whereas b(2) and EWA restrictions are discretionary actions that vary in degree from year to year, we have added rules that are applied in each year, which capture average Delta operations over the calibration period, 1993–2001. First, between April 15 and May 15 the combined CVP and SWP Delta exports were limited to 1500 cubic feet per second (cfs). Following this period, separate restrictions were applied to Banks and Jones exports. For CVP Delta exports, the b(2) pulse period restrictions were extended to the end of May and ramped up to 3000 cfs for the month of June. For SWP, assumed EWA actions limited Delta pumping at Banks to 3000 cfs for the period May 16–June 30.

Inter-annual variability in water supply motivates many of the reservoir operating rules. These rules are intended to secure water for dry years by balancing current water demands against carryover storage for delivery in subsequent years. Currently, the WEAP model contains routines for tracking water year-types using the Sacramento Valley Index, the Eight River Index, and the Shasta Index. These routines are used within the model to adjust environmental flow requirements, but are not implemented to guide curtailment of deliveries to CVP and SWP water contractors. That is, the model does not calculate annual allocations for the two projects. Instead, the WEAP model imposes limits on the amount of water that can be released from reservoirs. When storage drops below certain thresholds (i.e., into the buffer storage zone) reservoir releases are limited to a fraction (or buffer coefficient) of remaining active storage. This limits the amount of surface water available that can be diverted from rivers and, ultimately, pumped from the Delta.

The Sacramento-western San Joaquin WEAP application has been developed to evaluate regional water supply and demand conditions. Therefore, analyses focus on water deliveries to different water use sectors (i.e., domestic, agriculture, and environment), but do not distinguish between all of the various users within a sector. The model, however, represents the major infrastructural components that influence the distribution of water through the system. Therefore, many of the principal water users are explicitly represented. For example, the main service areas of the Delta-Mendota Canal and the California Aqueduct are modeled as distinct demand areas because the magnitude and seasonal pattern of their demands affect Delta export and San Luis reservoir operations. However, for reporting purposes, we consider the aggregate of deliveries to water use sectors, and not to each project. This obviates the need to consider sharing of surplus Delta flows between the projects under COA. For sharing responsibility to satisfy Delta standards, reservoir storage priorities and buffer coefficients were used to train the model.

San Luis Reservoir

The San Luis Reservoir is an off-stream (or pump-storage) reservoir located in the eastern part of the Diablo Range, west of the San Joaquin Valley. Water from California's Sacramento-San Joaquin Delta is delivered to San Luis Reservoir via the California Aqueduct and Delta-Mendota Canal for temporary storage during the rainy season. During the dry season, this stored water is released for use by SWP and CVP water contractors located south of the Sacramento-San Joaquin Delta. San Luis Reservoir also provides water to the Santa Clara Valley Water District (SCVWD) and the San Benito County Water District (SBCWD). Water is delivered to these users through the CVP's San Felipe Division on the west side of the reservoir.

The San Luis Reservoir is set up within the WEAP model to fill in the fall and winter (Oct–Mar) and release in the spring and summer (Apr–Sep). This is accomplished by using a combination of priorities, target storages, and pumping limits. The priority for San Luis storage is set such that water is pumped into the reservoir only after all other demands (agricultural, urban, environmental) have been met, including meeting target storages for Sacramento Valley reservoirs. The target storage for San Luis is set to fill the reservoir from its low point – generally at the end of August—to its maximum capacity (2.04 million acre feet, or MAF) by the end of March. For the period April–September, pumping into the reservoir is turned off and releases are limited to a fraction of the available storage. This fraction increases as the irrigation season proceeds, such that all of the available storage in San Luis can be utilized (i.e., April = 1/6, May = 1/5, June = 1/4, July = 1/3, August = 1/2, and September = 1).

Other Water Sources

Many of the water users in the San Joaquin Valley receive their surface water deliveries out of the Mendota Pool, which lies at the confluence of the San Joaquin River with the Delta Mendota Canal (DMC) and Fresno Slough/James Bypass. Much of the water that flows into the Mendota Pool comes from the Delta Mendota Canal. In exceptionally wet years, however, a large fraction of the water that is delivered from the Mendota Pool may originate from the San Joaquin River and / or the Fresno Slough / James Bypass.

For the purposes of model calibration and baseline historical runs, we used observed (1922–2003) San Joaquin River and Fresno Slough / James Bypass inflows to Mendota Pool. While the San Joaquin River record showed a consistent seasonal pattern of flow, the Fresno Slough / James Bypass record demonstrated no such pattern. For future scenarios, we used average monthly inflows (omitting outlying peak events) from the San Joaquin River into the Mendota Pool, but did not construct a similar boundary condition for the Fresno Slough / James Bypass, because of the irregularity of flows. Thus, it should be noted that in the scenarios unmet demands and / or deliveries from other sources may be overestimated in wet years for Mendota Pool water users.

2.2.2. Introducing Delta Water Quality Standards

The previous version of the Sacramento Valley WEAP model included a schedule of minimum Delta outflow requirements, which were intended to support and protect estuarine habitat for anadromous fish and other estuarine-dependent species. Expanding the WEAP application to include a model of the western San Joaquin Valley and export zone decoupled a boundary condition of the model, which had included elements of both consumptive and non-consumptive water demands. This then necessitated the consideration of Delta water quality standards as a means of bounding Delta export operations. For this study, we included two Delta water quality standards—salinity and X2—that together with the Delta outflow requirement combine to determine the minimum required Delta outflow.

Outflow requirements to meet Delta salinity standards were determined by linking WEAP to the Contra Costa Water District's salinity-outflow model, commonly referred to as the "G-model" (Denton and Sullivan 1993). The G-model is based on a set of empirical equations, developed from the one-dimensional advection-dispersion equation. The model predicts the salinity caused by seawater intrusion at a number of key locations in Suisun Bay and the western Sacramento-San Joaquin Delta as a function of antecedent Delta outflow. This antecedent or effective Delta outflow incorporates the combined effect of all the previous Delta outflows. That is, the model acknowledges that today's salinity is not just a function of today's outflow but also the outflows going back at least three to six months. Because this salinity-outflow model was developed from the one-dimensional advection-dispersion equation, it accounts for the transport of salt by both mean flow (advection) and tidal mixing (dispersion).

In addition to setting flow requirements to meet Delta salinity standards, WEAP sets a Delta outflow standard to maintain the position of the two parts per thousand bottom isohaline, X2, which is applied as a habitat indicator for the Delta. For this, WEAP uses the Kimmerer-Monismith equation to compute the required net Delta outflow, based upon the position of X2 in the previous month (Kimmerer and Monismith 1992).

2.2.3. Model Summary

The WEAP application developed for this study covers much of the same area and water management features that are represented in other models used in water planning in California: mainly, CalSim-II and CALVIN. The WEAP model, however, differs from these tools in a couple of important respects. First, unlike standard water resource planning tools that rely on exogenous information on water supply and demand to simulate how available water should be allocated, WEAP has embedded a watershed hydrology module into a water resources modeling framework, such that climatic inputs can be used directly to drive the model. This integration of hydrologic processes into a water resources modeling framework allows for analysis of the future climate scenarios that are unbounded by a reliance on historical hydrologic patterns. That is, analysis in the WEAP framework flows directly from the future climate scenarios and not from a perturbation of the historic hydrology as is necessary in applying standard tools to the question of potential climate change impacts in the water sector.

The other important distinction to make about the WEAP application is that it contains a rather simplified representation of the rules that guide the operations of the CVP and SWP systems. As such, we have not entered all of the sharing agreements (e.g., Coordinated Operations Agreement), regulatory guidelines (e.g., CVPIA b(2) accounting), and other rules (e.g., project allocations) that are explicitly represented in other planning models. Rather, we have attempted to capture the main features that govern the operation of the system as a whole. This choice was made in response to the main research objective which was to develop a tool that could illuminate high level implication of climate change and potential adaptive responses. This is as against an objective which would focus on impacts that may be felt by individual water right and water contract holders in California.

Even though we have not focused on these individual water right and water contract impacts, we have captured enough of the details of the system to allow us, through this and other studies (Joyce et al. 2006; Yates et al. 2005b; Yates et al. 2008), to refine the representation of model features such that model simulations reliably recreate observed patterns in water supply (i.e., reservoir storage, unimpaired streamflow, groundwater elevation, snow pack), water demand (i.e., crop evapotranspiration of applied water, urban demand), and system operations (i.e., surface water deliveries, delta inflows, delta exports, delta outflows). This same type of calibration, it is argued by some, is impossible for other models that possess detailed regulations that have changed through time.

The successful calibration and validation of the model gives us confidence that WEAP can reliably simulate the water management system and, so, can be used to evaluate the impacts of changes in water management in response to changing water supply conditions. It should be understood, though, that the WEAP model is intended to complement the standard set of water planning tools. Given the simplifications made in describing project-specific operations, the WEAP model is directed towards evaluating broader-scale issues of water management. Its utility is mainly in evaluating high-level water management objectives and identifying the most promising set of strategies that may be used to optimally operate the system. Once identified, such strategies may require further investigation using standard tools, which can address management issues at a finer scale. Lastly, the integration of hydrological processes into the WEAP planning model make the tool particularly strong in evaluating proposed management alternatives in the context of climate change.

2.3. Analytical Approach

The WEAP model was used to evaluate the impact of twelve future climate scenarios on agricultural water management in the region, and to investigate whether water management adaptation could reduce potential impacts. Each of the twelve climate sequences was run for three management scenarios: one in which no changes in agricultural practices occurred (No Adaptation); a second in which improvements in irrigation efficiency occurred gradually until 2050 (Increased Irrigation Efficiency); and a third in which annual cropping patterns changed in response to water supply conditions (Shifting Cropping Patterns). All scenarios were run for an analysis period 2006–2099.

2.3.1. Future Climate Scenarios

The Intergovernmental Panel on Climate Change (IPCC) released a *Special Report on Emissions Scenarios* (SRES) that grouped future greenhouse gas emission scenarios into four separate "families" that depend upon the future developments in demography, economic development, and technological change (Nakicenovic and Swart 2000). Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving force behind global climate change. These scenario families are summarized in Box 1. For the purposes of this study, outputs from six general circulation models (GCMs) were used to estimate future climate conditions under two SRES scenarios: A2 and B1. By choosing six GCM and two emission scenarios that would be applied to all investigations in response to the governor's executive order (S-3-05), the Climate Action Team hoped to create a consistent set of output that would represent the range of future climate conditions.

The six GCMs used to generate the future climate conditions for the current investigation are summarized in Table 4. Outputs from these models were downscaled by applying the methodology developed by Maurer et al. (2002) to create a 1/8 degree gridded data set for daily climate variables. These downscaled daily data were used to derive average monthly time-series of precipitation, temperature, wind speed, and relative humidity for each of the 75 sub-catchments in the WEAP model.

Table 4. General circulation models used in study

Developer	GCM	Study Code
Center for National Weather Research, CNRM (France)	CM3	GCM1
Geophysical Fluid Dynamics Laboratory, GFDL (US)	CM2.1	GCM2
Center for Climate System Research, CCSR (Japan)	MIROC 3.2	GCM3
Max Planck Institute, MPI (Germany)	ECHAM5	GCM4
National Center for Atmospheric Research, NCAR (US)	CCSM3.0	GCM5
National Center for Atmospheric Research, NCAR (US)	PCM1	GCM6

Box 1. Main Characteristics of the Four SRES Storylines
from Nakic´enovic and Swart (2000), *Special Report on Emissions Scenarios*, published by the Intergovernmental Panel on Climate Change.

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive sources (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

2.3.2. Adaptation Strategies

Adaptation to climate change within the agricultural sector is likely to occur naturally in response to economic signals that are driven by public policy, market conditions, and, in a setting like California, the availability of irrigation water supply. Understanding the evolution of this last factor under future climate conditions requires the application of a water resources systems model that tracks the management of the available hydraulic infrastructure.

In the context of adaptations, WEAP allows the model user to represent dynamic changes in water management by programming in model parameters that vary over the course of a simulation. These parameter changes can be imposed as exogenous forces upon the model (e.g., as functions of the passage of time) or they can be expressed within the model as a function of the state of the system (e.g., water supply, crop yields, depth to groundwater). Both methods are used here separately to represent the adaptation strategies considered in this study.

Improving Irrigation Efficiency

With regard to improvements in irrigation efficiency, the research team believes that existing and anticipated future regulatory pressures for improved agricultural water use efficiency are likely to lead to increased efficiency such that most crops other than rice will employ drip irrigation by the middle of the century. For this study, it is assumed that these changes occur gradually over the first half of the century and reach a maximum level by 2050.

To represent these improvements in the WEAP model the parameters that determine the irrigation process in the model were modified. The first of these parameters called the lower irrigation threshold represents the soil moisture level at which irrigation will be required to increase the soil moisture up until it reaches an upper irrigation threshold. Considering that these two parameters were directly related to irrigation procedures they were chosen as parameters to be modified to represent improvements in irrigation efficiency.

Improvements in irrigation efficiency will generally be achieved through reductions in both the lower and upper irrigation thresholds. In practice, this means allowing soils to become dryer when managing irrigation scheduling. Reducing the lower threshold lowers supply requirements, because irrigation is called less frequently, so the level of soil moisture tolerance before external supplies of water are needed are increased. Similar reductions in the upper threshold imply that the same depth of water will be applied at each irrigation. However, as the soil moisture is reduced, irrigation losses to surface runoff and percolation are also reduced, thus improving the overall irrigation efficiency.

Shifting Cropping Patterns

Each agricultural demand unit in WEAP possesses a characterization of how crops are distributed across the land available for irrigation. These cropping patterns were initially estimated using historical land use surveys, which show only a snapshot in time of how crops are distributed. In actuality, cropping patterns change from year to year as farmers react to water supply conditions and economic and social factors. To capture this dynamic, we have included in WEAP cropping relationships, developed by the Lawrence Berkeley National Laboratory (L. Dale, personal communication), that relate the share of various crops within a command area to water supply conditions at the time of planting.

The share of crop acreage in each demand area varies as a function of changes in the supply of surface water and depth to groundwater. The function is derived from a multinomial logit regression analysis of synthetic data of crop shares generated by the Central Valley Production Model (CVPM) for 21 regions in the Central Valley (Figure 6). The data were generated from CVPM model runs assuming the base water supply and groundwater depth and perturbations from these base levels. These model runs provided a suite of synthetic estimates of crop shares across a range of different regional water supply and groundwater depth assumptions. These crop share equations were then used by WEAP to show changes in crop acreage and water use over time.

Figure 6. CVPM regions

3.0 Results

This section shows some results of the WEAP model simulations for each of the 12 climate change scenarios. We begin by evaluating the projected climate data for each of the scenarios used as input to the WEAP model. We then discuss the implication of these projected climate sequences by following their impacts downward through the watershed. First, we evaluate the projected changes in reservoir inflows. This includes an assessment of the changes in timing and magnitude of inflows, as well as a look at the relative magnitude and duration of future droughts. In addition to evaluating the impacts of changing climate on water supply, we also look at how climate change may affect crop water demands. We then evaluate the combined impact of these changes on water management in the Sacramento Valley and Delta export zone. Here we consider the ability of the water resources system to deliver water to satisfy future demands and evaluate the impact of water management on resources protection. This is followed by an evaluation of water management strategies that are expected to offset some of the anticipated consequences of climate change by reducing stressors on California's water resources. We considered separately two "adaptation" strategies: improvements in irrigation efficiency through investments in technology and a shift toward less water-intensive crops as farmers react to changes in water supply conditions.

3.1. Climatic Analysis

In the following analysis, precipitation and temperature data are presented for 12 climate projections. Precipitation and temperature data are presented as averages of 56 climate locations used as inputs to WEAP, aggregated into three regions—Central Valley, Coastal Range and Sierra. Figure 7 and Figure 8 respectively plot the annual precipitation and average annual temperature time series from 2006–2099 for all climate projections. While the data exhibits considerable inter-annual and inter-model variability, there is no apparent change in annual precipitation for either emission scenario (Figure 7). By contrast, a warming trend is discernible in all climate projections across models and emissions scenarios, in all three regions. Further, Figure 8 also shows that, as expected, the rate of warming is higher in the medium-high emissions scenario A2 than in the low emissions scenario B1.

A clearer picture of precipitation changes emerges when comparing across three distinct periods: 2006–2034, 2035–2064, and 2065–2099. Figure 9 shows boxplots of period-averaged annual precipitation across all climate projections. These plots suggest that there is generally a decreasing trend in precipitation from the first third of the century to the latter part of the century, when considering all 12 scenarios. Comparing between emission scenarios, precipitation projections tend to be lower in the A2 scenarios compared to the B1 scenarios, with CNRM-CM3 A2 for 2006–2034 being the exception.

Temperature projections suggested a much stronger trend than that seen with the precipitation data. Figure 10 shows a boxplot for temperature that consistently indicates warming across all projections.

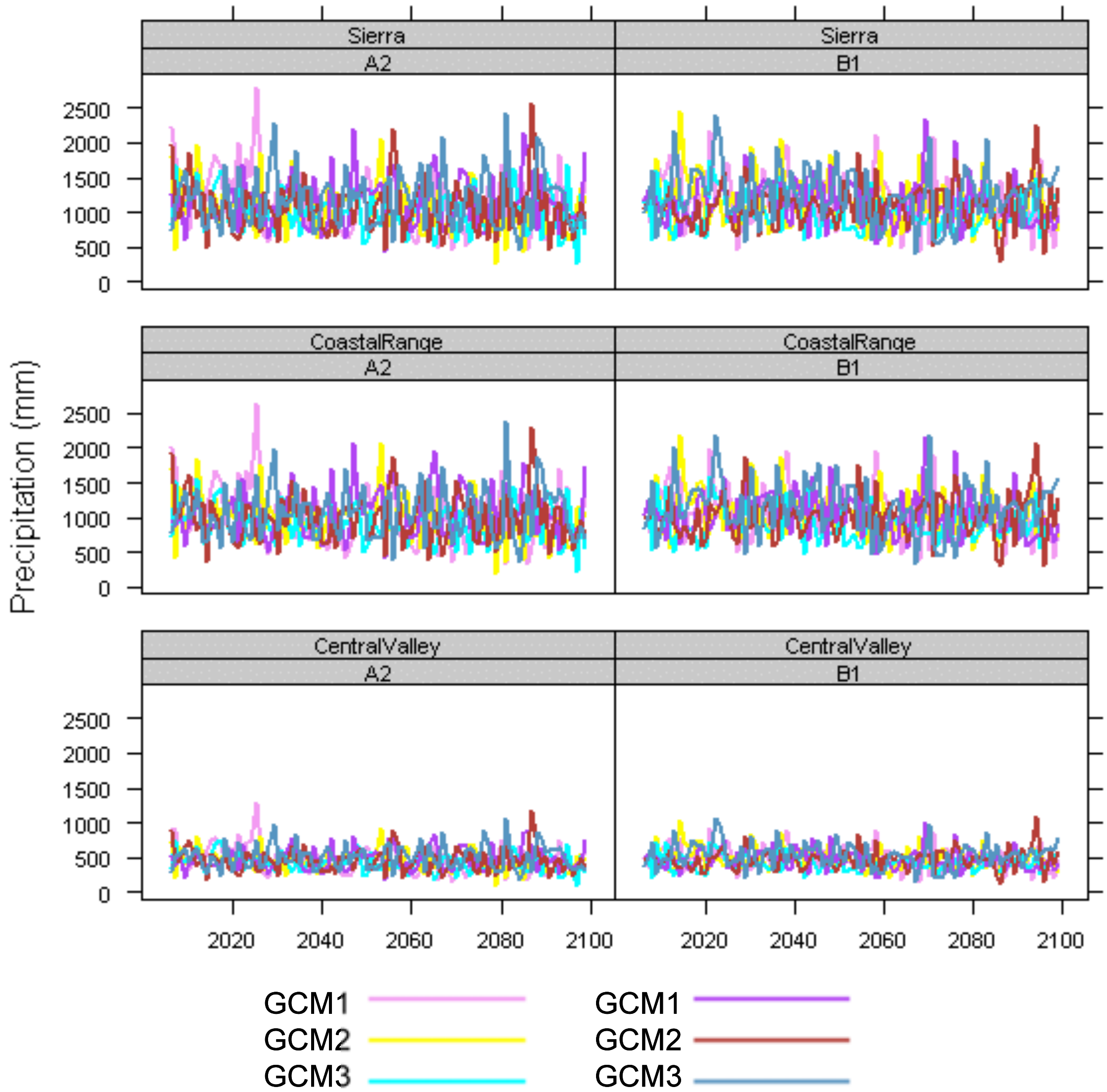


Figure 7. Annual precipitation (2006–2099)

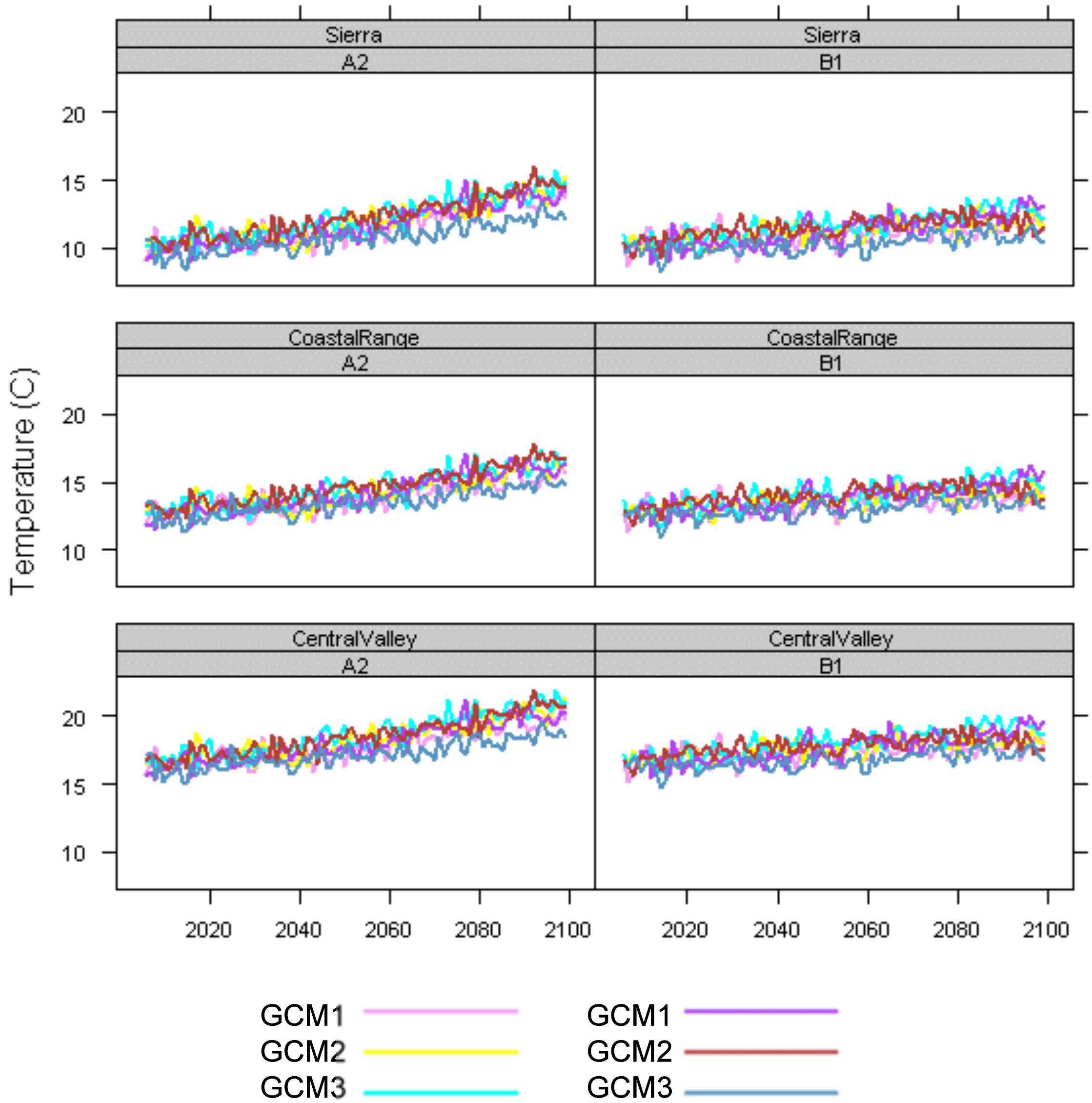


Figure 8. Annual average temperature (2006–2099)

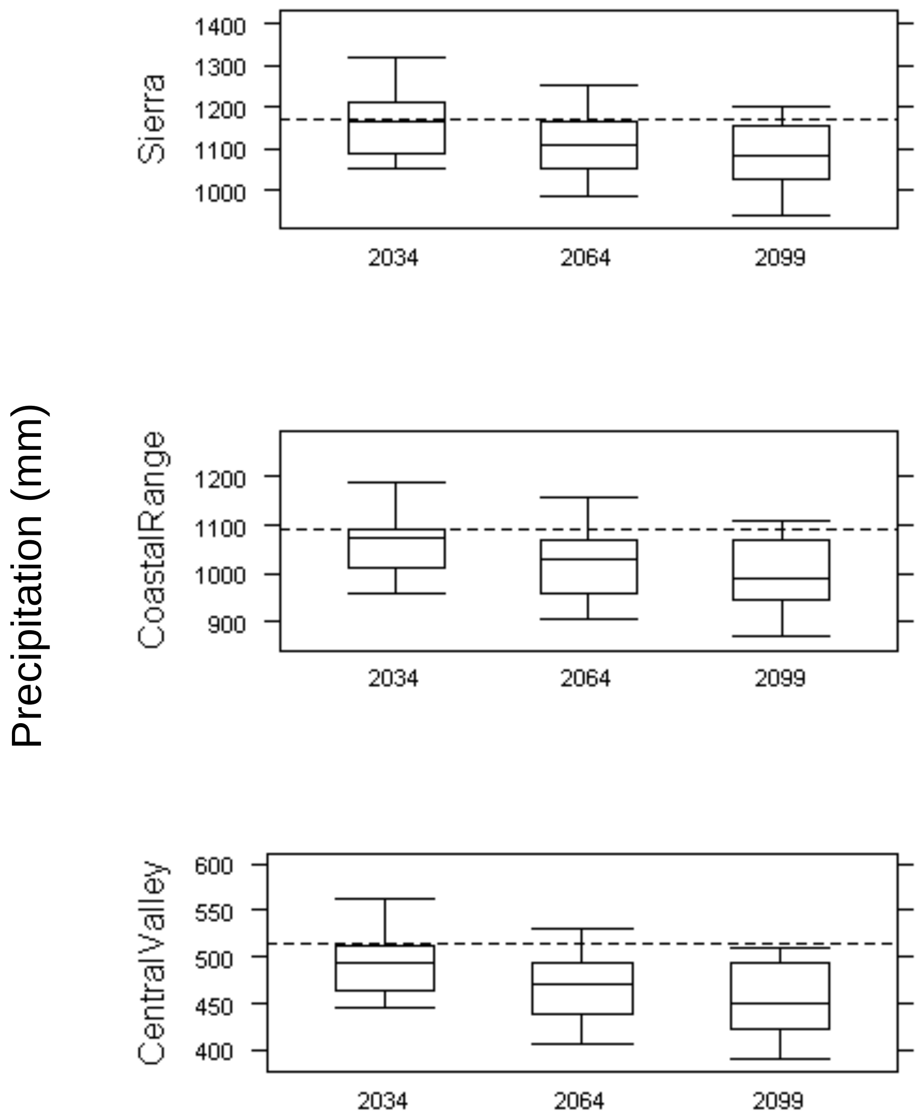


Figure 9. Boxplots[1] of precipitation across all projections for three periods (2006–2034, 2035–2064, and 2065–2099). The dotted horizontal line is historic (1961–1999) mean precipitation.

[1] Box covers middle 50% of data, from 25th to 75th percentile. Whiskers are the 1.5*interquartile range. Outliers are not shown.

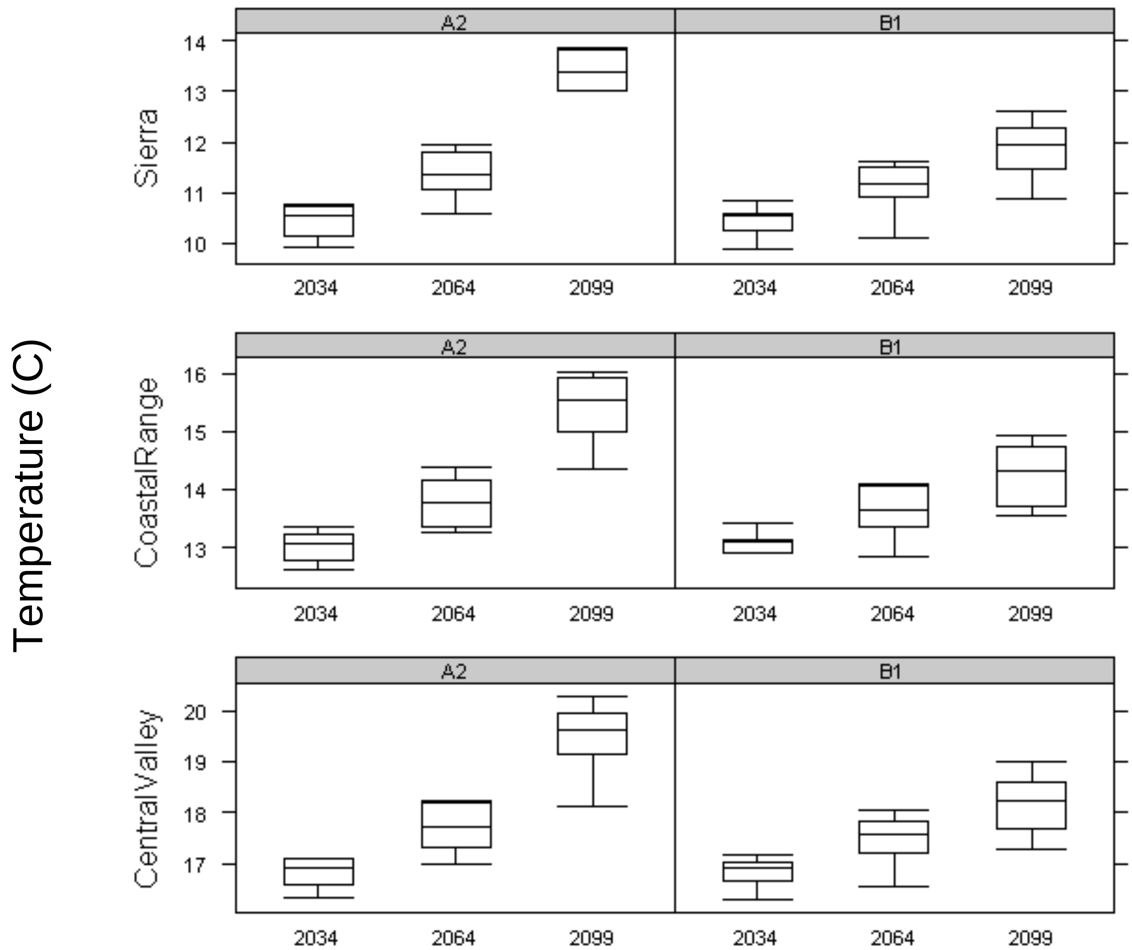


Figure 10. Boxplots[2] of average annual temperature (°C) for three periods (2006–2034, 2035–2064, and 2065–2099)

3.2. Hydrologic Analysis

3.2.1. Reservoir inflows

Figure 11 shows changes in monthly average inflows to the major reservoirs in the Sacramento Basin (Shasta, Folsom, and Oroville) for the end-of-century period 2065–2099. While neither emission scenario showed a statistically significant difference in annual volume of inflow to the three reservoirs as compared to the historic (1950–2005) WEAP baseline, all GCM / emission scenario combinations showed an earlier timing of streamflow. This shift in runoff timing appeared consistent for all reservoirs across models and emission scenarios. These results are consistent with the supposition that warmer temperatures lead to earlier loss of snowpack.

[2] Box covers middle 50% of data, from 25th to 75th percentile. Whiskers are the 1.5*interquartile range. Outliers are not shown. In some plots, whiskers are so close to the box as to appear missing.

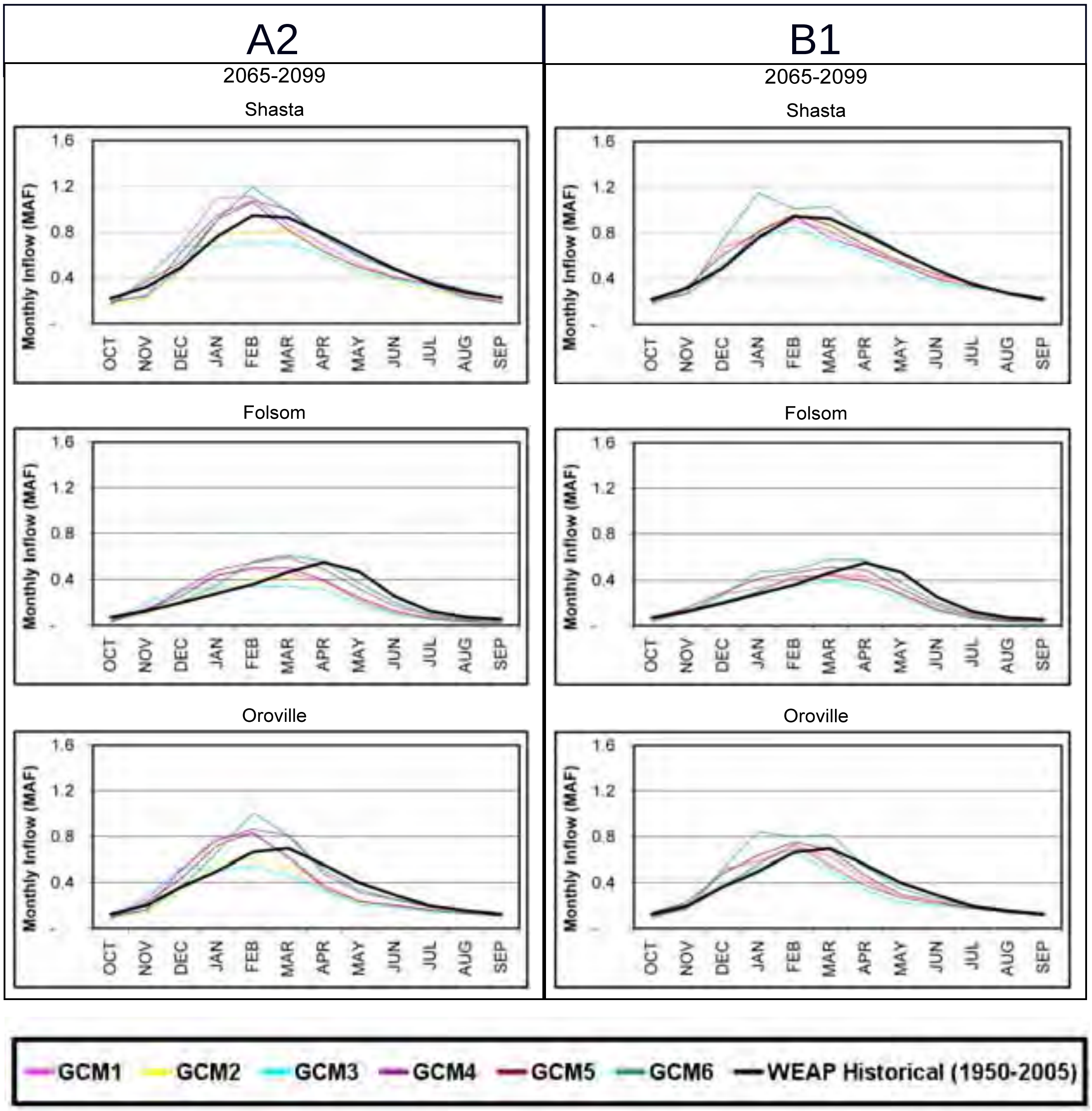


Figure 11. Average monthly inflow to Shasta, Folsom, and Oroville for A2 and B1 emission scenarios

3.2.2. Occurrence of Drought

Whereas some analysis approaches use historic sequences of wet and dry years for future analyses, a major advantage of the WEAP model is that it can examine evolving sequences of wet and dry years for GCM based future climate projections. Thus, WEAP can simulate conditions under different levels of drought persistence that might occur with climate change. This paper includes an estimate of possible changes in future hydrologic conditions in terms of drought persistence. Drought conditions in the Sacramento Basin were described using a construction of the Sacramento Valley 40-30-30 Water Year Hydrological Classification Index

(State Water Resources Control Board 1995).[3] This index is measured in million acre-feet and is composed of unimpaired runoff into Shasta, Oroville, and Folsom Reservoirs plus streamflow at the Yuba River. Based on the value of this index, a water year is classified as wet, above normal, below normal, dry, or critical. Droughts were assumed to occur during years designated as critically dry. The severity of the drought was indicated by a value called the accumulated deficit, which is calculated by subtracting the value of the 40-30-30 index for a given year for a given climate change scenario from the threshold value for the critical year designation (5.4 MAF). These deficits were accumulated in consecutive dry years and were reset to zero whenever the index exceeded the threshold for the critical year designation,.

Figure 12 shows the accumulated deficits for the historic period (the 1976–1977 and early 1990s droughts are apparent) and each of the twelve climate change conditions included in this analysis. The results show much variability in drought persistence between the various climate change projections—with some GCM / emission scenario combinations replicating historic drought conditions, some showing more moderate droughts than observed, and others suggesting more severe droughts. In general, the A2 emission scenario predicted more severe droughts than the B2 scenarios, which agrees with the lower precipitation seen with these scenarios.

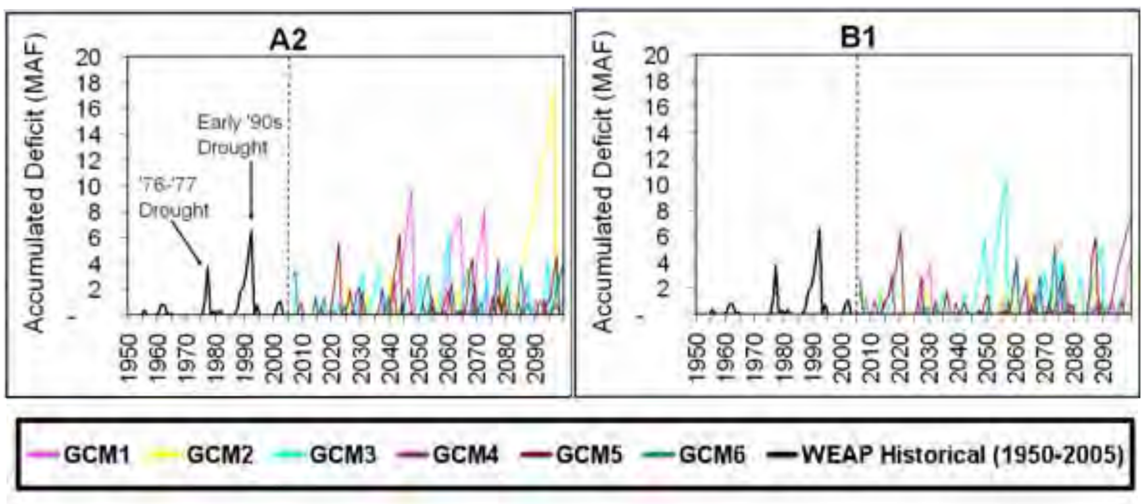


Figure 12. Changes in drought conditions. Vertical dotted line delineates the historical period from the future climate projection period.

3.3. Demand Analysis

Annual supply requirements for agricultural areas in the Sacramento and western San Joaquin valleys are summarized in Figure 13 and Figure 14, respectively. These are the sums of the crop water requirements for all irrigated areas calculated from the future climate time series using WEAP's internal Penman-Montieth routine, adjusted based on assumed losses in delivering water to meet these requirements. Following a trend consistent with the predicted changes in

[3] The Sacramento Valley 40-30-30 Water Year Hydrological Index is equal to 0.4 x current April to July unimpaired runoff + 0.3 x current October to March unimpaired runoff + 0.3 x previous year's index (if the previous year's index exceeds 10.0, then 10.0 is used).

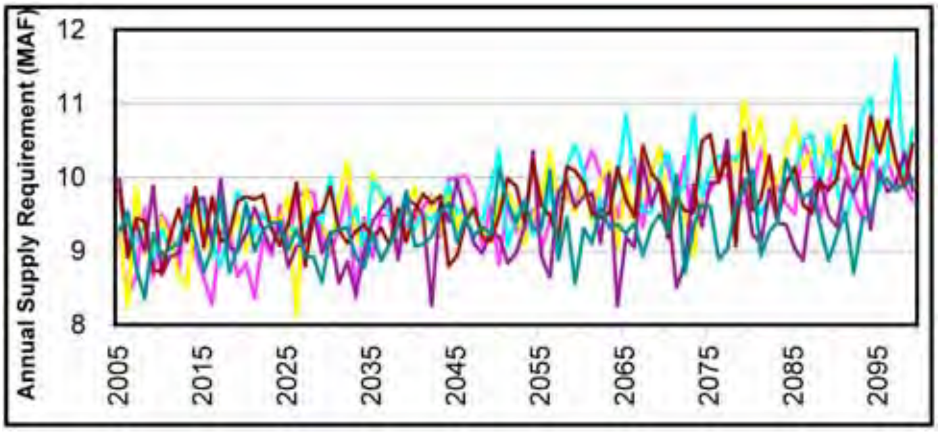
temperature (Figure 8), both emission scenarios showed an increasing trend in water requirements with time, with the A2 scenario exhibiting a more pronounced increase than the B1 scenario.

The model also suggested that crop water requirements would experience a greater increase in the Sacramento Valley (9% under A2, 6% under B1) than in the western San Joaquin Valley and Tulare Basin (6% under A2, 4% under B1) by the end of the century. This trend was driven by differences in the mix of crops in the two regions. In particular, there is almost a 100-fold difference in the amount of rice grown—with the Sacramento Valley having just over 600,000 acres in production and the western San Joaquin Valley and Tulare Basin having only 6,600 acres in production.

It should be noted again that these simulations reflect possible changes under future climate scenarios where the total cropped acreages remained fixed, irrigation technology and scheduling remain unchanged, and the development of crops is unaffected by changes in climate. It may be argued that agricultural water usage will adapt to changing climate through a combination of changes in management strategies and changes in crop physiology. These changes could maintain, or even reduce, the current level of annual crop water demand. Alternatively, annual crop water demands could increase if the length of time to crop maturation shortened to a point where additional crops could be planted within a single growing season. As such, the projections presented here should be interpreted as a first-order estimate of changes in crop water demand.

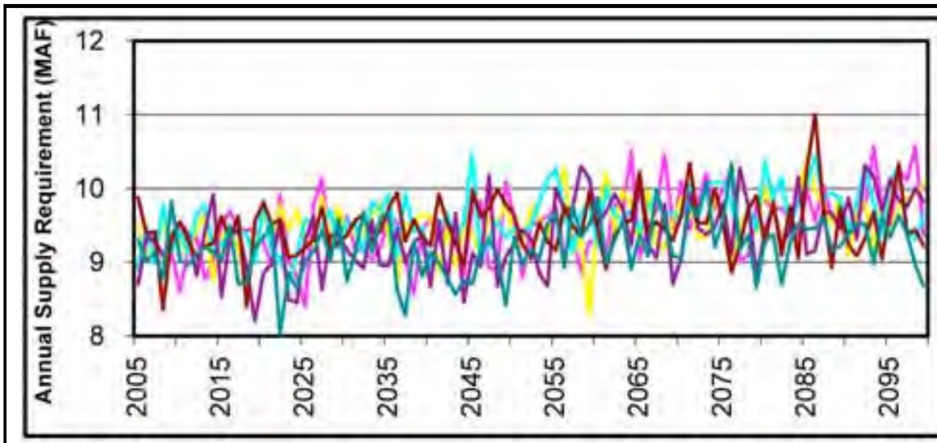
Sacramento Valley

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	8.98	9.10	1%	9.55	6%	9.90	10%
GCM2	9.09	9.27	2%	9.61	6%	10.13	11%
GCM3	9.08	9.34	3%	9.65	6%	10.16	12%
GCM4	9.10	9.17	1%	9.37	3%	9.61	6%
GCM5	9.09	9.36	3%	9.53	5%	9.99	10%
GCM6	9.10	9.10	0%	9.34	3%	9.48	4%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	9.08	9.27	2%	9.41	4%	9.75	7%
GCM2	9.09	9.38	3%	9.46	4%	9.63	6%
GCM3	9.08	9.38	3%	9.58	5%	9.81	8%
GCM4	9.07	9.13	1%	9.35	3%	9.60	6%
GCM5	9.06	9.33	3%	9.50	5%	9.58	6%
GCM6	9.07	9.11	0%	9.12	1%	9.37	3%

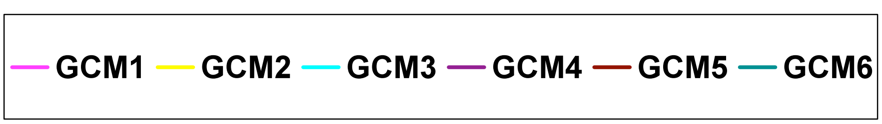
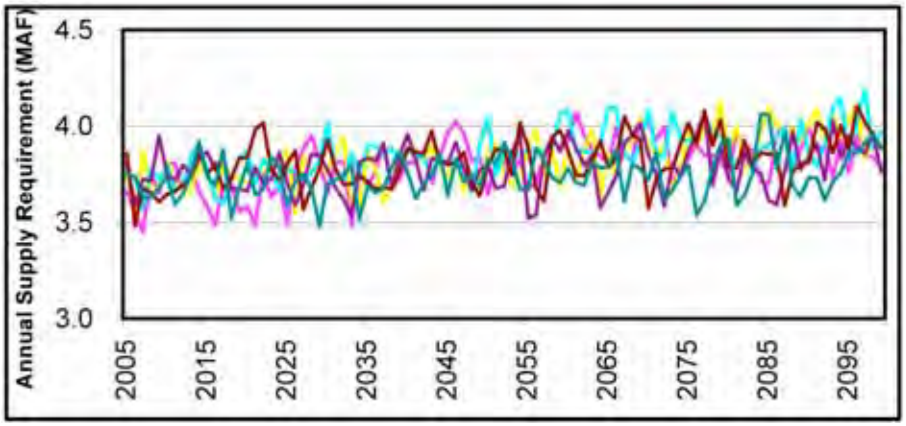


Figure 13. Projected water supply requirements for the Sacramento Valley

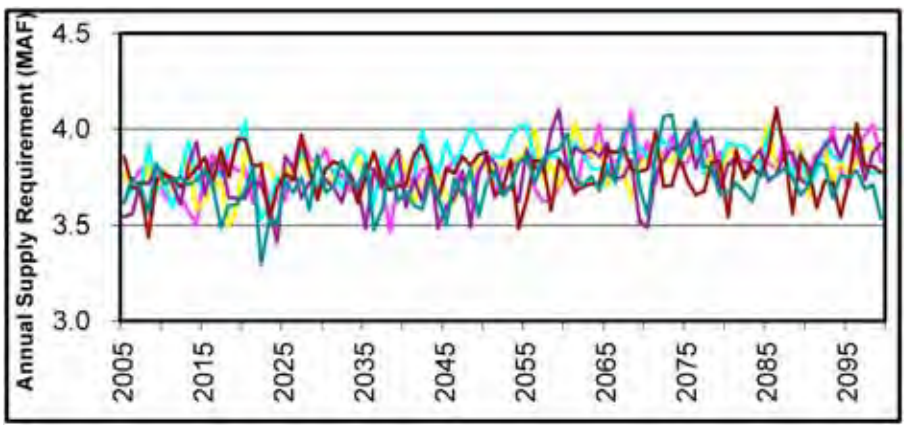
Western San Joaquin and Tulare Lake

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.67	3.68	0%	3.83	4%	3.86	5%
GCM2	3.68	3.74	2%	3.80	3%	3.93	7%
GCM3	3.68	3.76	2%	3.86	5%	3.94	7%
GCM4	3.68	3.74	2%	3.79	3%	3.82	4%
GCM5	3.67	3.75	2%	3.81	4%	3.88	6%
GCM6	3.67	3.70	1%	3.75	2%	3.78	3%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.68	3.73	2%	3.75	2%	3.86	5%
GCM2	3.68	3.74	2%	3.79	3%	3.83	4%
GCM3	3.67	3.76	2%	3.85	5%	3.86	5%
GCM4	3.67	3.71	1%	3.76	3%	3.82	4%
GCM5	3.66	3.75	3%	3.75	2%	3.79	3%
GCM6	3.67	3.68	0%	3.71	1%	3.78	3%

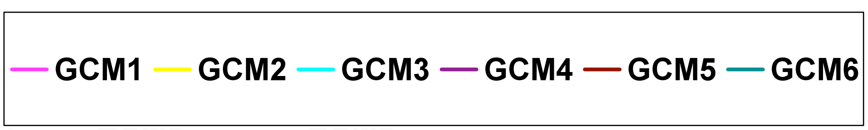


Figure 14. Projected supply requirements for the western San Joaquin Valley/Tulare Basin

3.4. Operations Analysis without Adaptation

The WEAP system attempts to satisfy crop water requirements by delivering water through canals and by pumping groundwater. The extent to which it is able to meet the full crop requirements depends upon surface water supplies and capacity constraints on canals and groundwater pumping. As a surrogate for contract allocations, WEAP imposes limits on the amount of water that can be released from reservoirs by restricting releases to a fraction of remaining active storage. This limits the amount of surface water available that can be diverted from rivers and, ultimately, pumped from the Delta.

Each of the twelve climate change scenarios was run continuously over a historical period (1950–2005) and a future period (2006–2099) using downscaled GCM climate data and current operational rules. The results of these scenarios are summarized in the following graphs, where climate change scenarios are compared against a historic baseline, which was generated by running the WEAP model over the period 1950–2005 using historical gridded climate data (Maurer et al. 2002).

Figure 15 and Figure 16 present the volume of surface water pumped annually from the rivers and streams of the Sacramento Valley and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. The graph suggests that under both emission scenarios higher crop water requirements (Figure 13) resulted in increasing diversions from rivers in the Sacramento Valley as the simulation progressed into a warmer era at the end of the century. This resulted in less water flowing into the Delta and, thus, less water available to be exported to San Joaquin Valley and Tulare Basin irrigators.

This pattern of higher water deliveries within the Sacramento Valley at the expense of Delta exports underlines an important distinction in the way in which WEAP allocates water among different users. As previously mentioned, demands are given priorities, such that WEAP delivers water according to a hierarchical ordering of water users. In this scheme, lower priority water users receive surface water deliveries only after the higher priority users have received their full request for water (subject to constraints on delivery capacities). In the Sacramento-San Joaquin application, agricultural water users share the highest priority for water with environmental (i.e., in-stream flows) and indoor urban demands.

Under this configuration, Delta exports are only permissible after the environmental requirements for Delta outflow (see Section 2.2.2) are satisfied. Because the outflow requirements are given equal priority to Sacramento Valley agricultural deliveries, it also means that the model prioritizes irrigation in the Sacramento Valley over Delta exports. This was not intended to suggest a preference for irrigators in the Sacramento Valley, but reflects a priority structure that mimics the observed historical system operations. Under the historical reference case, much of the water delivered to irrigators on the Westside of the San Joaquin Valley comes from San Luis Reservoir, which pumps water from the Delta at a time of year when its demands are not in direct competition with those of irrigators in the Sacramento Valley.

Sacramento Valley

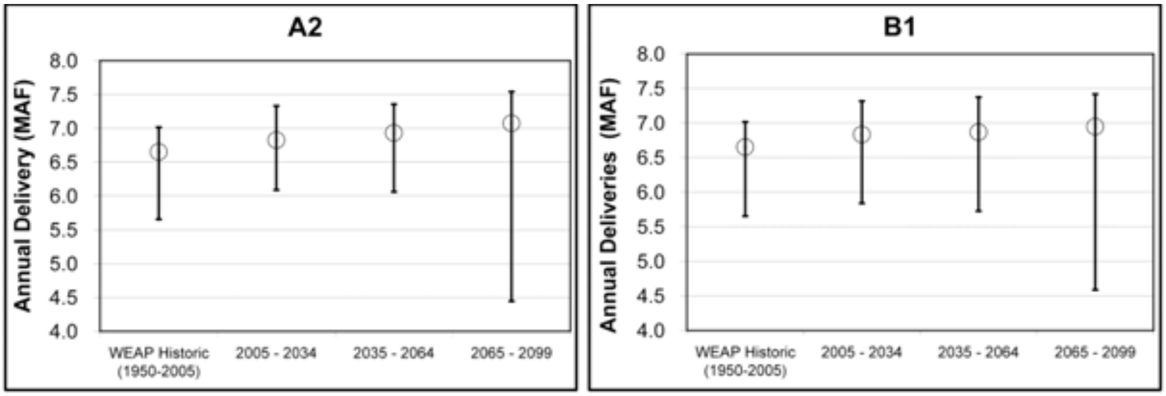


Figure 15. Sacramento Valley agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

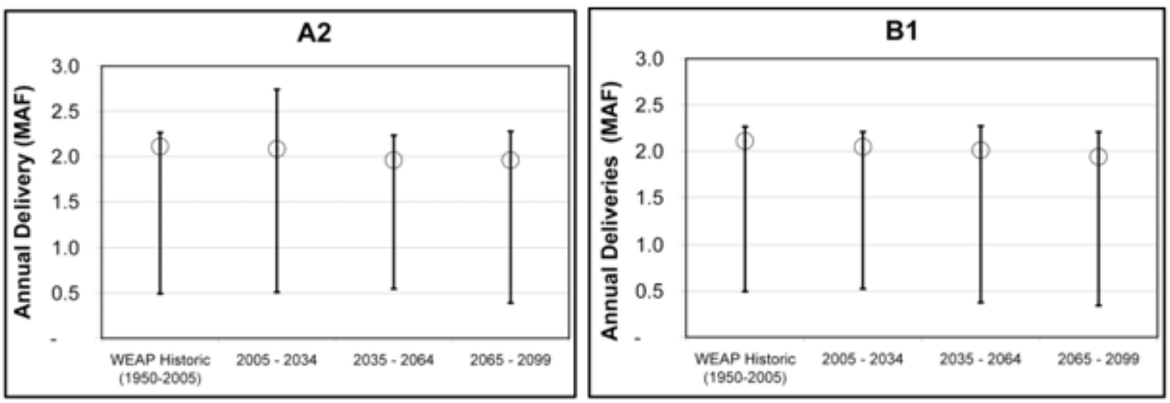


Figure 16. Western San Joaquin and Tulare Lake agricultural surface water deliveries for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values.

Thus, the decline in Delta exports under future scenarios suggests that the environmental requirements within the Delta may represent the biggest constraint on Delta exports. This situation is compounded by irrigators in the Sacramento Valley using more water at the expense of inflows to the Delta. Figure 15 and Figure 16 suggest that there may be opportunities for a reallocation and/or transfer of water rights among irrigators in the Sacramento and San Joaquin Valleys.

In addition to changing patterns in surface water deliveries, increasing crop water requirements led to a greater usage of groundwater resources in both the Sacramento and San Joaquin Valleys (Figure 17 and Figure 18). The pattern of increasing groundwater pumping corresponded with the drought periods observed in Figure 12 and resulted in greater groundwater drawdown during these periods (Figure 19). The higher groundwater pumping, however, was not maintained across all years, resulting in only a marginal increase in total groundwater pumping.

Sacramento Valley

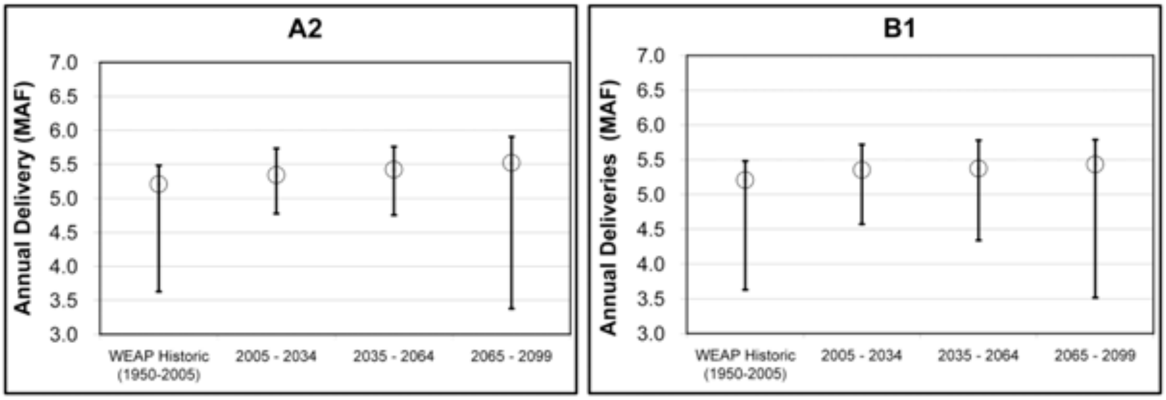


Figure 17. Sacramento Valley annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

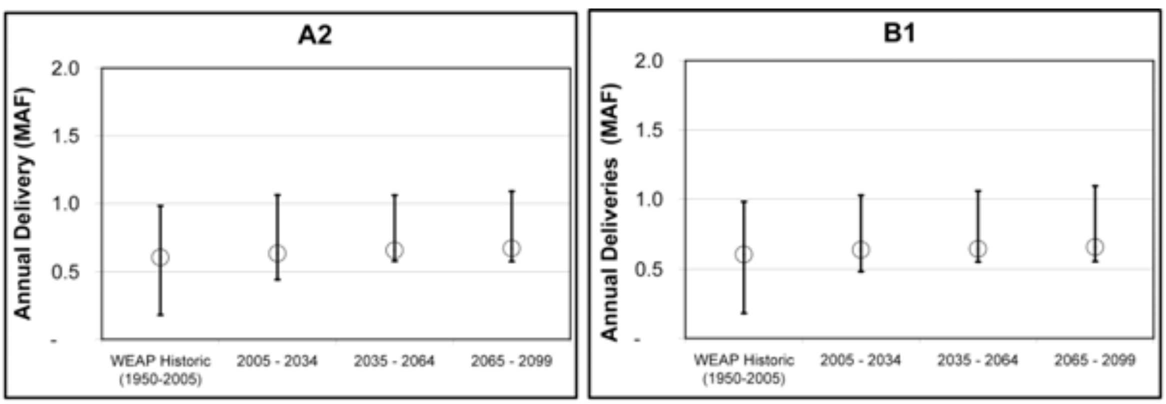


Figure 18. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios without adaptation. Circles indicate period median, and hash marks indicate minimum and maximum values.

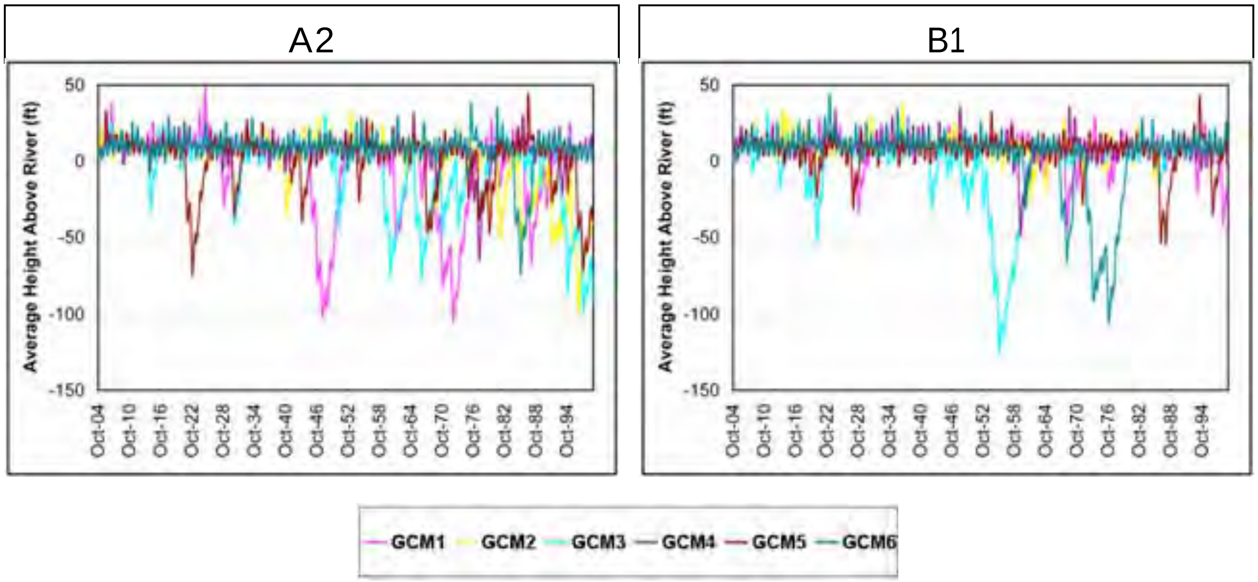


Figure 19. Average groundwater depths in the western San Joaquin Valley for A2 and B1 emission scenarios

Whereas regional deliveries and groundwater pumping trends are indicative of differences in priorities assigned to various water users, end-of-year (or carryover) storage is reflective of total annual deliveries to all water users represented in the model. Figure 20 shows exceedance probability plots for carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios. Future scenarios consistently suggest that carryover storages will be much lower by the end of the century. Since there was no corresponding decrease in reservoir inflows for this same period (Figure 11), this change is primarily due to increases in surface water deliveries. Thus, in addition to modifying the allocation of surface water supplies among irrigators, reservoir operations should also be updated to preserve the inter-annual water supply objectives (i.e., drought protection) of these reservoirs.

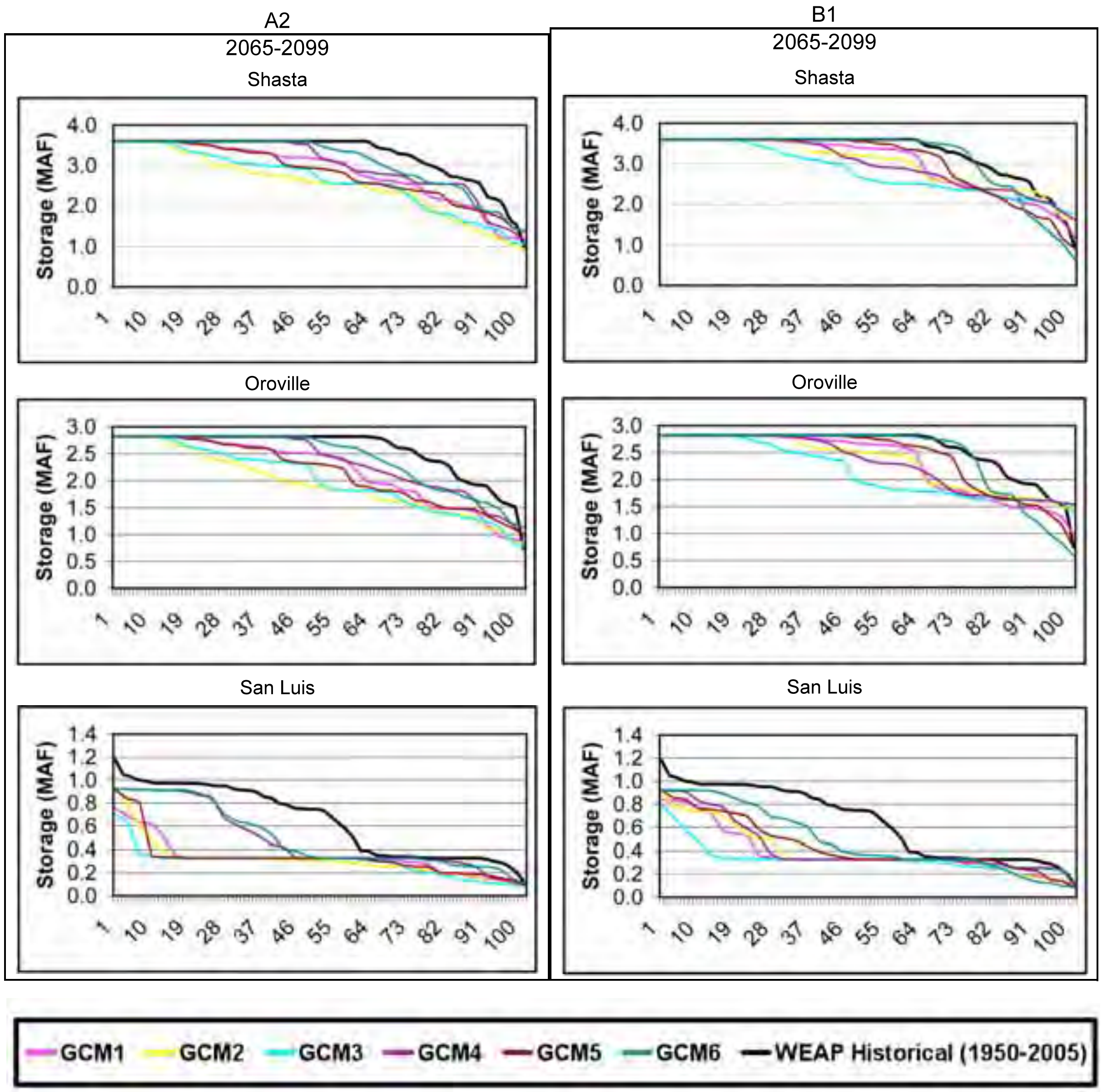


Figure 20. Carryover storage for A2 and B1 scenarios without adaptation

3.5. Operations Analysis with Adaptation

The previous section presented results suggesting that increasing crop water demands in the future will alter the water management regime such that certain water users will divert more water at the expense of others. It should be noted now that these changes may be overstated, because simulations assumed fixed cropped acreages for all commodities—implying that the modeled changes in demand were entirely driven by changes in climate. It can be reasonably assumed that, as crop water demands rise, farmers will adopt new strategies of growing crops using fixed water resources. This may involve planting fewer acres of higher valued crops, switching to crops with lower water needs, and/or improving irrigation technology such that the same crops can be grown with less applied water. The implications of two adaptation strategies—irrigation technology and shifting cropping patterns—are discussed below.

3.5.1. Water Supply Requirements with Adaptation

Improved Irrigation Efficiency

For the purposes of this study, it was assumed that external regulatory pressures motivated irrigators to improve irrigation efficiency without regard to future climatic conditions. These improvements in irrigation efficiency were phased in gradually throughout the first half of the twenty-first century and reached a maximum in 2050, after which efficiencies remained constant.

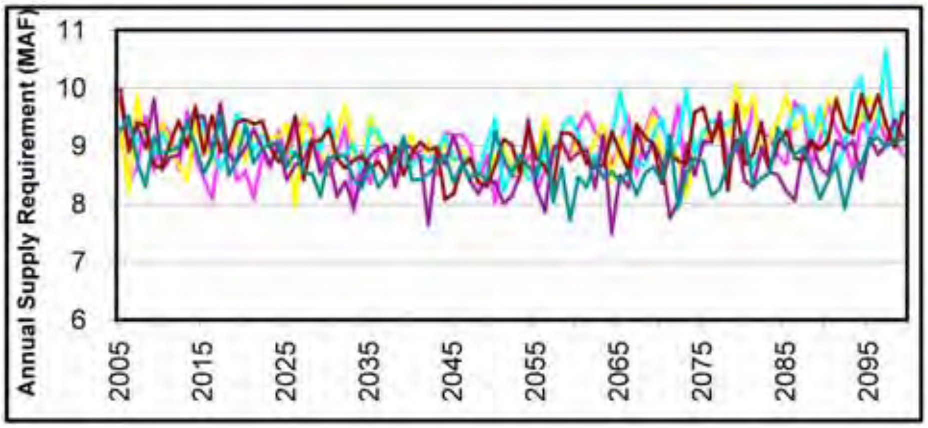
Changes in irrigation efficiency differed among crops based upon assumptions made in the amount of land converted to low-volume (e.g., drip) irrigation systems. It was assumed that orchards, vineyards, and row crops (including tomatoes and truck crops) would be entirely irrigated with low-volume irrigation systems, while field crops (including cotton, sugar beet, alfalfa, grain, and pasture) would convert only half of the irrigated land. Rice acreage, on the other hand, will be irrigated by gravity-fed irrigation in 2050, as it is today.

The implications of improvements in irrigation efficiency on water supply requirements in the Sacramento and San Joaquin Valleys are shown in Figure 21 and Figure 22. These results suggest that improvements in irrigation efficiency could largely offset the increases in water demand anticipated with increasing temperatures (see Figure 13 and Figure 14). In fact, in some cases, water demands actually decrease by the end of the century.

In general, the offset in crop water demand was greatest for the B2 emission scenarios and more pronounced in the San Joaquin Valley. The difference in forecasted temperatures between emissions scenarios accounted for the greater capacity of improvements in irrigation efficiency to offset water demands in the B2 scenario. That is, changes in irrigation technology were more effective when the counteracting changes in temperature were lower. The larger impact in the San Joaquin Valley was due to the predominance of orchard, row crops, and field crops, which all have a high potential for improvements in irrigation technology. Water demands in the Sacramento Valley, on the other hand, were largely driven by rice acreage, which has little potential for improved irrigation technology because it relies on flooded fields.

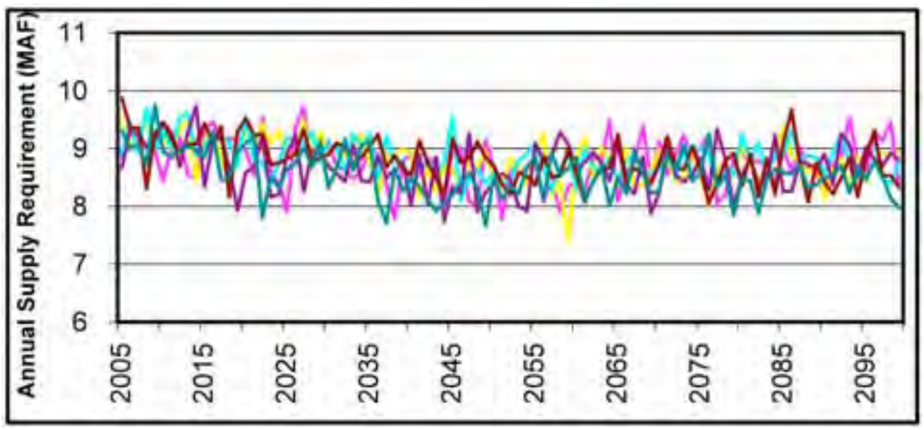
Sacramento Valley

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	8.98	8.83	-2%	8.81	-2%	9.14	2%
GCM2	9.09	9.02	-1%	8.88	-2%	9.27	2%
GCM3	9.08	9.07	0%	8.87	-2%	9.28	2%
GCM4	9.10	8.90	-2%	8.61	-5%	8.76	-4%
GCM5	9.09	9.07	0%	8.75	-4%	9.12	0%
GCM6	9.10	8.83	-3%	8.58	-6%	8.66	-5%

B1



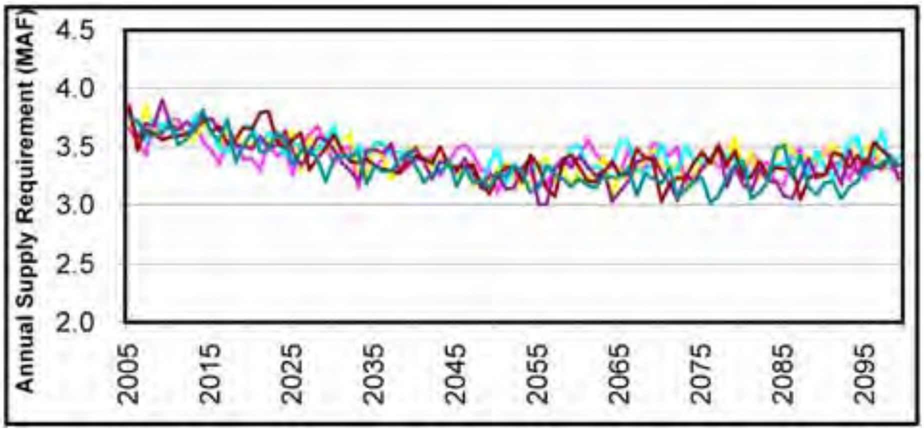
	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	9.08	8.94	-2%	8.56	-6%	8.79	-3%
GCM2	9.09	9.08	0%	8.63	-5%	8.68	-4%
GCM3	9.08	9.08	0%	8.69	-4%	8.80	-3%
GCM4	9.07	8.85	-2%	8.55	-6%	8.66	-5%
GCM5	9.06	9.04	0%	8.68	-4%	8.65	-4%
GCM6	9.07	8.84	-3%	8.37	-8%	8.49	-6%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 21. Changes in water supply requirement in Sacramento Valley associated with improvements in irrigation technology for A2 and B1 scenarios

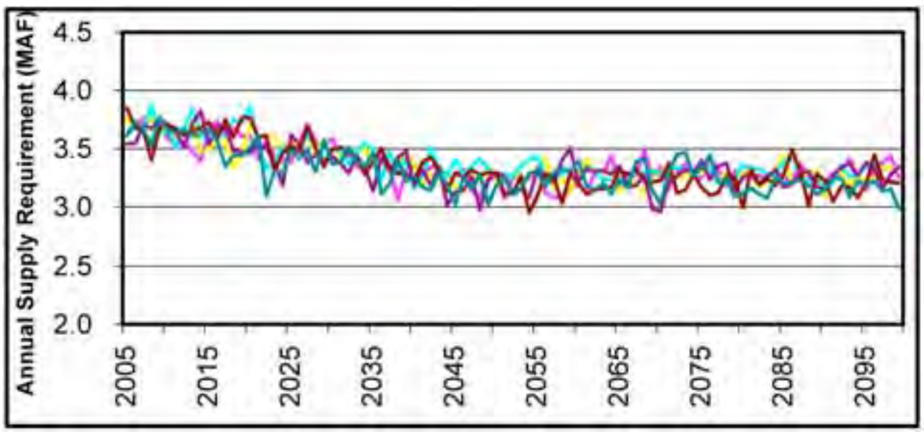
Western San Joaquin and Tulare Lake

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.67	3.50	-5%	3.35	-9%	3.34	-9%
GCM2	3.68	3.56	-3%	3.30	-10%	3.38	-8%
GCM3	3.68	3.58	-3%	3.36	-9%	3.39	-8%
GCM4	3.68	3.56	-3%	3.30	-10%	3.27	-11%
GCM5	3.67	3.56	-3%	3.30	-10%	3.33	-9%
GCM6	3.67	3.52	-4%	3.25	-11%	3.23	-12%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.68	3.55	-3%	3.24	-12%	3.28	-11%
GCM2	3.68	3.56	-3%	3.28	-11%	3.26	-11%
GCM3	3.67	3.58	-2%	3.32	-10%	3.29	-11%
GCM4	3.67	3.53	-4%	3.25	-11%	3.25	-11%
GCM5	3.66	3.57	-2%	3.24	-12%	3.22	-12%
GCM6	3.67	3.50	-5%	3.22	-12%	3.21	-12%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 22. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with improvements in irrigation technology for A2 and B1 scenarios

Shifting Cropping Patterns

In addition to improvements in irrigation technology, another potential adaptation to climate change involves adjusting cropping patterns as a function of the evolving status of available water supplies. At the beginning of the growing season, farmers decide which crops to plant based on anticipated surface water supplies and groundwater levels. How farmers respond to these changing conditions is a function of a number of factors, which change depending on the reliability of various available water sources. For example, farmers who rely solely on groundwater for irrigation base cropping decisions on the depth to groundwater, which relates directly to their operating costs. Central Valley Project settlement contractors in the Sacramento Valley, on the other hand, have guaranteed contracts for surface water deliveries that are only reduced when inflows to Lake Shasta reach a critical level (i.e., less than 3.4 million acre-feet). Their cropping choices are then more responsive to changes in surface water supplies. In the Sacramento and San Joaquin Valley there are many CVP and SWP agricultural contractors whose allocations for surface water deliveries vary from year to year based upon current storage and predicted inflows to the main project reservoirs.

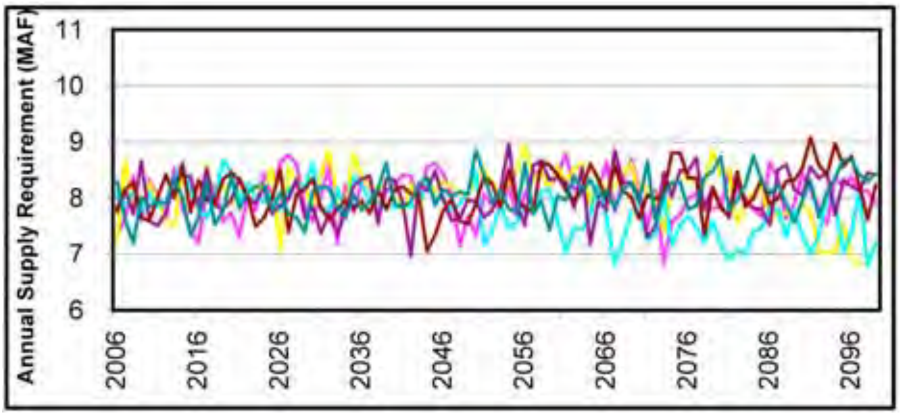
The implication is that indexes of available supply must be calculated for each year in order to permit the various types of water user to make appropriate cropping decisions. Based on the value of these supply indexes, a multinomial logit model of cropping shares, estimated from historical data, is employed to determine the distribution of crops and fallow land in that year for the given user. These logit equations were programmed into WEAP so that at the start of every cropping season over the course of the twenty-first century, an adaptive simulated cropping pattern was defined.

The impacts of these cropping shifts on water supply requirements are shown in Figure 23 and Figure 24. Here there are a couple of important things to note. The first thing to observe is that the average crop water demands in both regions are substantially less than those estimated in previous simulations. This change is due to the introduction of a fallow land class, which allows land to be put into or taken out of production. Since all scenarios (with and without adaptation) assumed the same amount of irrigable land, this meant that any land fallowed (i.e., idled or retired) as an adaptive response to climate change resulted in less land in production relative to the other simulations. In fact, it was observed that the minimum amount of land fallowed in any year for all adaptation scenarios was between 10% and 15%. It is important to note this difference in demands from the baseline scenarios, especially when considering the impacts on water supply and delivery. For our purposes here, we focus on how cropping patterns change and what impact these changes have on crop water demands relative to a modified baseline, where the model was run with changing cropping patterns over a historical time period, 1950–2005.

Second, unlike the previous simulations that contained either no adaptation or pre-defined changes in water usage (i.e., improvements in irrigation efficiency), these simulations exhibited similar impacts on water supply requirement for both the A2 and B1 emission scenarios. This would suggest that feedback between water supply and agricultural demands allows the model to compensate (or adapt) such that the system achieves similar water demands under different climate forcings.

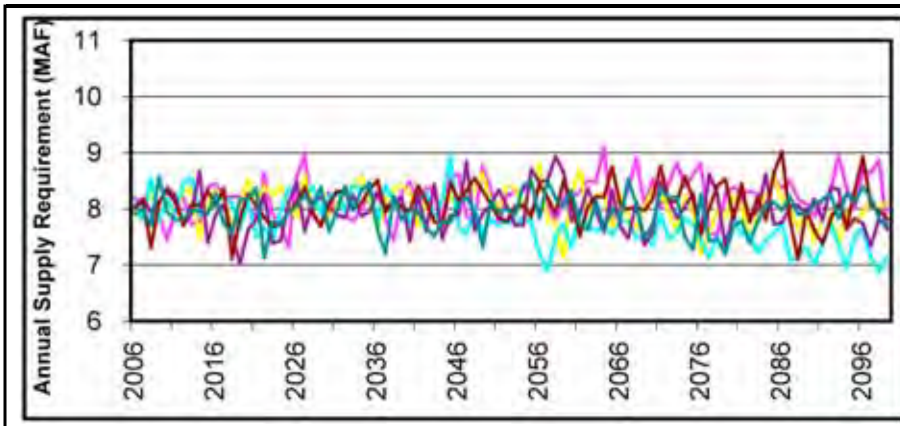
Sacramento Valley

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	7.87	7.95	1%	8.10	3%	8.02	2%
GCM2	7.91	8.07	2%	8.29	5%	7.86	-1%
GCM3	7.90	8.07	2%	7.83	-1%	7.45	-6%
GCM4	7.94	7.94	0%	8.06	2%	8.14	3%
GCM5	7.92	8.01	1%	8.00	1%	8.23	4%
GCM6	7.91	7.90	0%	8.08	2%	8.17	3%

B1



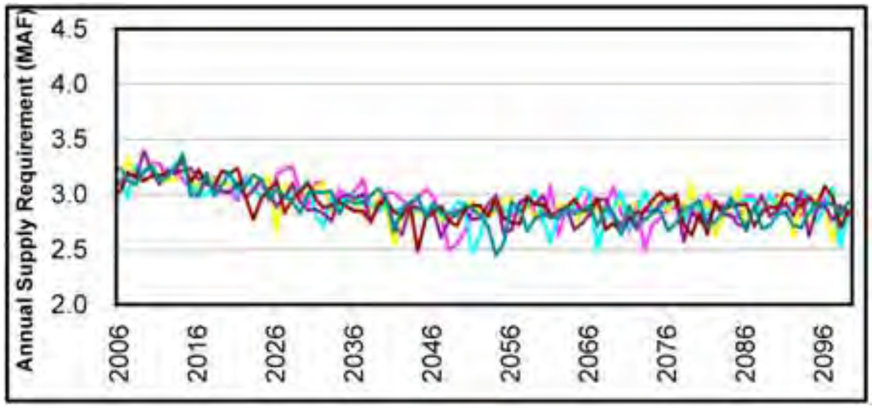
	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	7.89	8.06	2%	8.22	4%	8.30	5%
GCM2	7.89	8.16	3%	8.15	3%	7.92	0%
GCM3	7.89	8.08	2%	7.83	-1%	7.44	-6%
GCM4	7.91	7.93	0%	8.09	2%	7.94	0%
GCM5	7.89	8.00	1%	8.12	3%	8.10	3%
GCM6	7.88	7.98	1%	7.95	1%	7.92	0%

GCM1 — GCM2 — GCM3 — GCM4 — GCM5 — GCM6

Figure 23. Changes in water supply requirement in Sacramento Valley associated with changes in cropping patterns for A2 and B1 scenarios

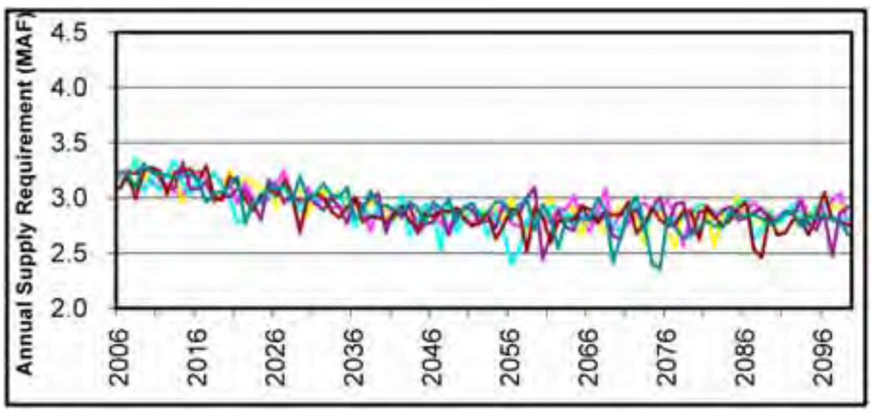
Western San Joaquin Valley and Tulare Lake

A2



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.12	3.10	-1%	2.87	-8%	2.87	-8%
GCM2	3.10	3.09	-1%	2.85	-8%	2.86	-8%
GCM3	3.12	3.06	-2%	2.85	-9%	2.88	-8%
GCM4	3.13	3.06	-2%	2.84	-9%	2.83	-10%
GCM5	3.12	3.07	-1%	2.84	-9%	2.86	-8%
GCM6	3.10	3.08	-1%	2.83	-9%	2.81	-9%

B1



	1950 - 2005 average (maf)	2006 - 2034 average (maf)	2006 - 2034 difference (%)	2035 - 2064 average (maf)	2035 - 2064 difference (%)	2065 - 2099 average (maf)	2065 - 2099 difference (%)
GCM1	3.12	3.08	-1%	2.85	-8%	2.87	-8%
GCM2	3.11	3.10	0%	2.87	-8%	2.83	-9%
GCM3	3.13	3.06	-2%	2.80	-11%	2.84	-9%
GCM4	3.12	3.06	-2%	2.83	-9%	2.83	-9%
GCM5	3.11	3.08	-1%	2.81	-10%	2.80	-10%
GCM6	3.10	3.10	0%	2.88	-7%	2.77	-11%

GCM1 GCM2 GCM3 GCM4 GCM5 GCM6

Figure 24. Changes in water supply requirement in western San Joaquin/Tulare Basin associated with changes in cropping patterns for A2 and B1 scenarios

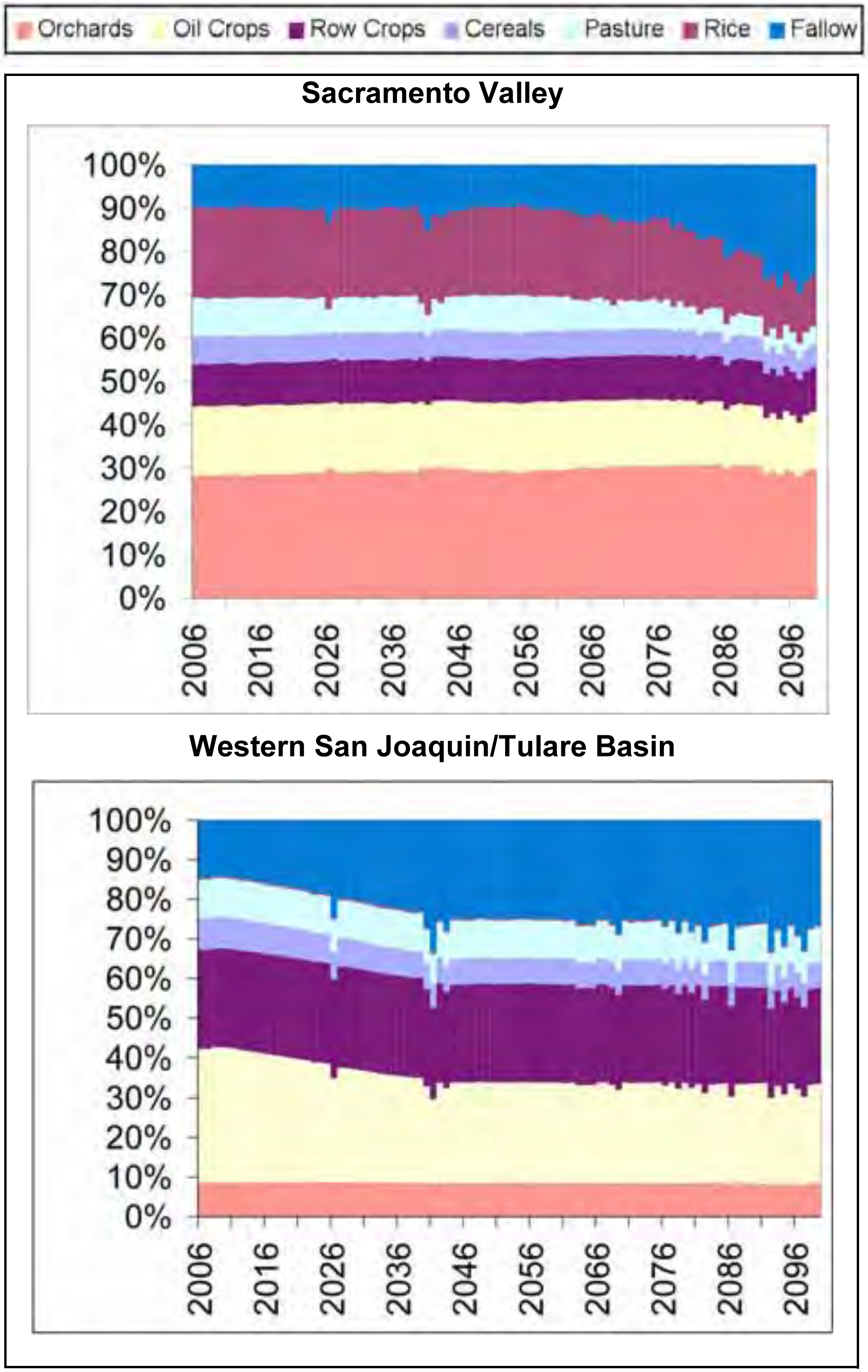


Figure 25. Simulated changes in cropping patterns in the Sacramento[4] and San Joaquin Valleys for A2/GFDL-CM21 scenario

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[4] Row crops include truck crops as well as process and market tomatoes. Oil crops include cotton, sugar beet, and field crops. Pasture includes alfalfa. Orchards include subtropical and vineyard. Cereals include grain.

The last thing to note is that there is a very clear decrease in water supply requirements for the western San Joaquin and Tulare Basins under both emission scenarios. Further, the trend in the Sacramento Valley shows more variability and, as such, is ambiguous. These general trends are again indicative of the mix of crops in the two regions. Figure 25 shows an example of how the cropping pattern changed in both regions under one climate change scenario, A2 / GFDL-CM21 (or A2 / GCM2). This shows that, for both regions, the decrease in water supply requirement was due to an increase in the amount of retired (or fallowed) land. In the Sacramento Valley, rice accounted for the greatest decrease in cropped acreage, while in the western San Joaquin / Tulare Basin, the crop most affected was cotton.

It is interesting to observe that in this particular scenario there appear to be two different water supply conditions that lead to the large increases in fallowed lands in the two regions. In the Sacramento Valley, a prolonged drought at the end of the century led to low water supplies in several consecutive years. This prompted irrigators in this region to increase the amount of fallow land from a base of about 10% to as much as 30% in the driest years. Curiously, irrigators in the western San Joaquin Valley did not show the same type of response to the drought at the end of the century. While there was some variability from year to year, the models suggested that farmers' cropping decisions appeared to be relatively insensitive to changes in water supply. San Joaquin Valley irrigators, however, did increase the idled irrigated area by about 10% over the first half of the century, by retiring land that is currently being used to grow cotton. This trend was related to increasing pumping costs as groundwater heads declined—a trend that was as least partly due to underestimating the availability of supplemental surface water supplies from the San Joaquin and Kings Rivers.

3.5.2. Water Supply and Delivery

Improved Irrigation Efficiency

This section focuses on the cumulative effect of updating irrigation technology in the Central Valley. The analysis here presents WEAP simulations wherein changes in irrigation technology were applied across all agricultural areas of the model.

Figure 26 and Figure 27show annual surface water deliveries from the rivers and streams in the Sacramento Basin and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. These graphs are companions to Figure 15 and Figure 16, which presented the same metric for scenarios run without adaptation. By comparing these graphs, we observe that improving irrigation efficiencies reduced the annual surface water deliveries from the rivers of the Sacramento Basin such that they are comparable to those simulated in the historic baseline. These reductions, however, had little effect on the ability to deliver water to irrigators in the western San Joaquin / Tulare Basin during dry years. This was likely due to a combination of decreasing crop water demands in the export zone and because environmental constraints in the Delta prevented the export of any additional water. Thus, the benefit of reduced water demands in the export zone materialized primarily in the form of reduced unmet demands.

Sacramento Valley

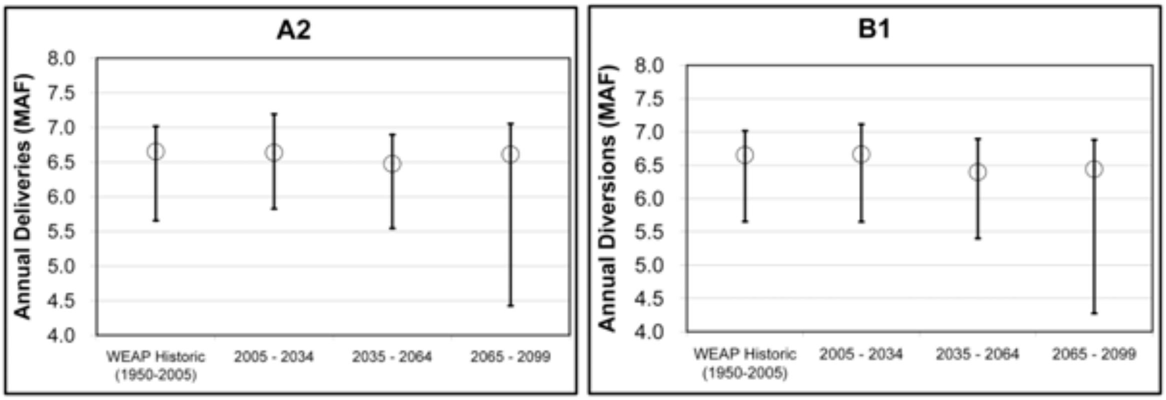

Figure 26. Sacramento Valley agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

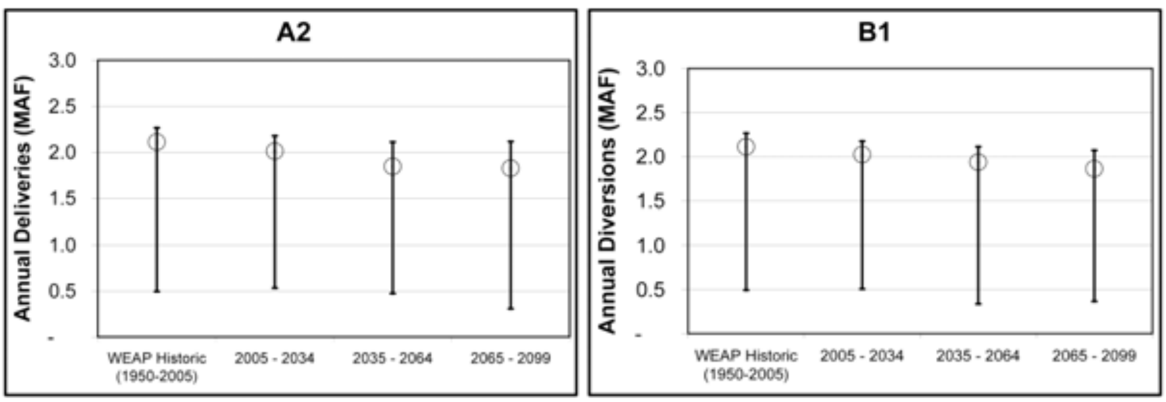

Figure 27. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with improved irrigation technology. Circles indicate period median and hash marks indicate minimum and maximum values.

Increasing irrigation efficiency through improvements in technology also led to an overall stabilization of annual groundwater pumping as compared to the historical period (Figure 28 and Figure 29). In fact, reductions in crop ET appeared to result in a reduction in groundwater pumping over the first half of the century, but this effect was lost as temperatures drove crop water demands higher toward the end of the century.

Sacramento Valley

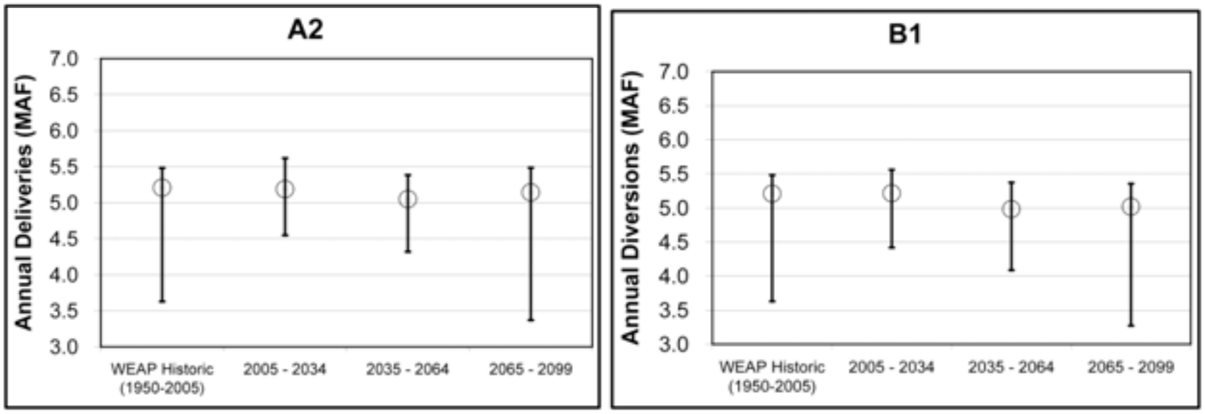

Figure 28. Sacramento Valley annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

Western San Joaquin and Tulare Lake

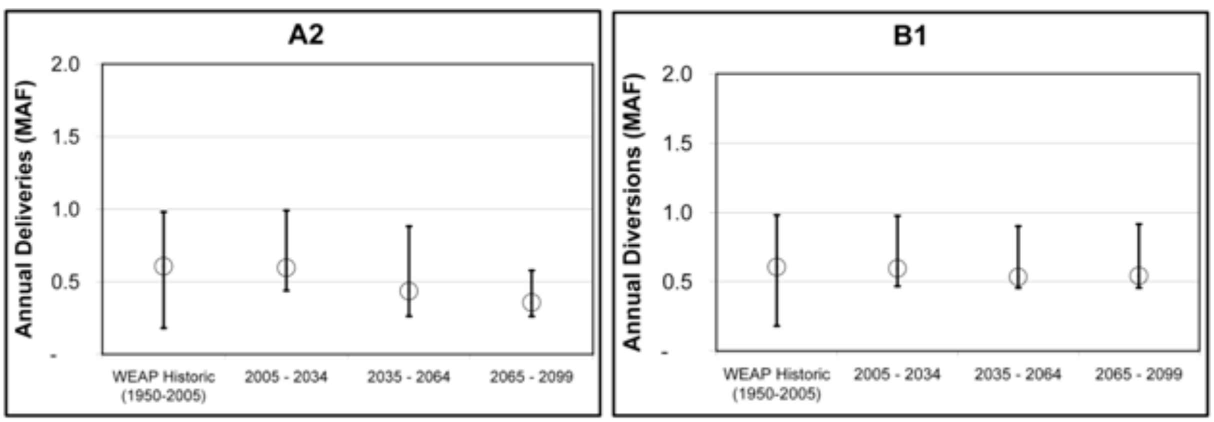

Figure 29. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios with improved irrigation technology. Circles indicate period median, and hash marks indicate minimum and maximum values.

Figure 30 shows carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios run with improved irrigation technology. Again, this graph is a companion to Figure 20, which shows the same metric for scenarios run without adaptation. These plots suggest that reduced surface water deliveries from the Sacramento and Feather rivers had little impact on carryover storage. The implication of this was that there was more water released from storage to meet the environmental requirements within the Delta.

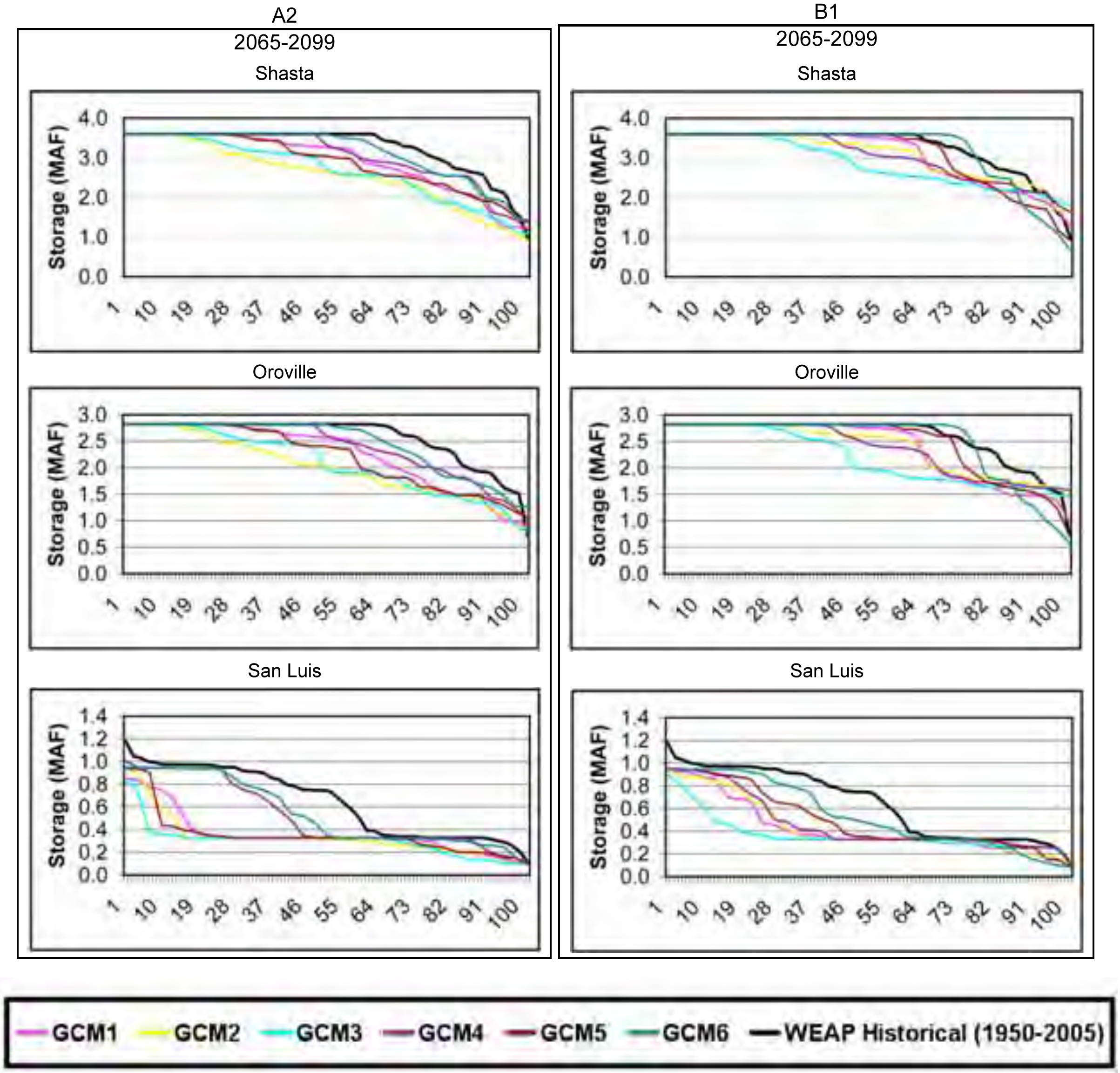

Figure 30. Carryover storage for A2 and B1 scenario with improved irrigation technology

Shifting Cropping Patterns

As previously mentioned, an analysis of water deliveries under the changing cropping patterns is not directly comparable to the model outputs for scenarios run with no adaptation and those run with increased irrigation efficiency, because the difference in the amount of land in production between the model runs alters the baseline water demands such that the impact on the water supply system is distorted. That is, the logit model presumed an ambient presence of fallowed land that was not considered in the other scenarios. This fallow land class accounted for a minimum of 10% of irrigated land in the Sacramento Valley and 15% of irrigated land in the San Joaquin Valley. Regardless of this incongruity in model runs, it is still illuminating to consider the modeled impacts on water supply.

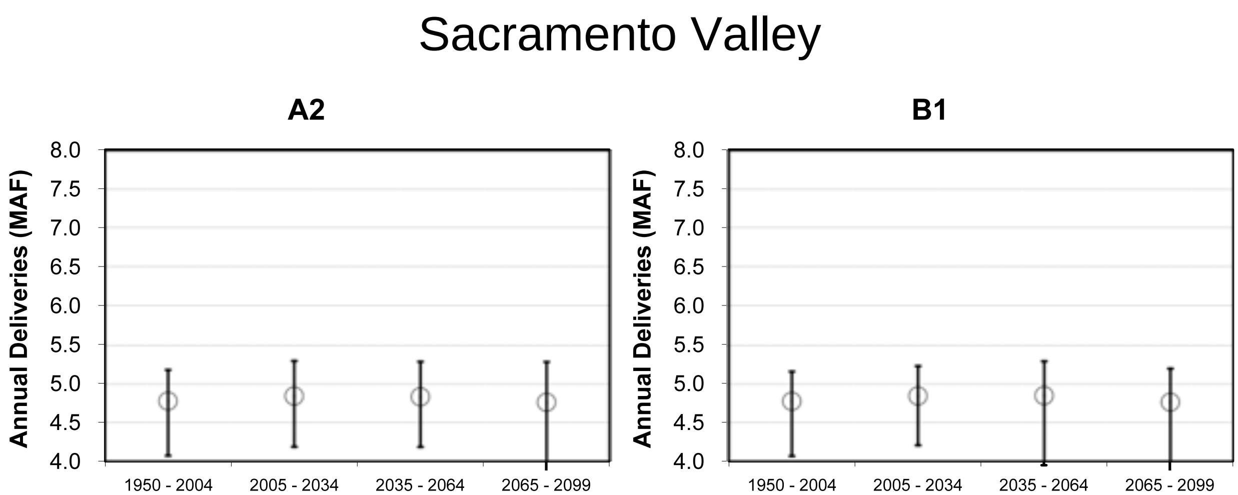

Figure 31. Sacramento Valley agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

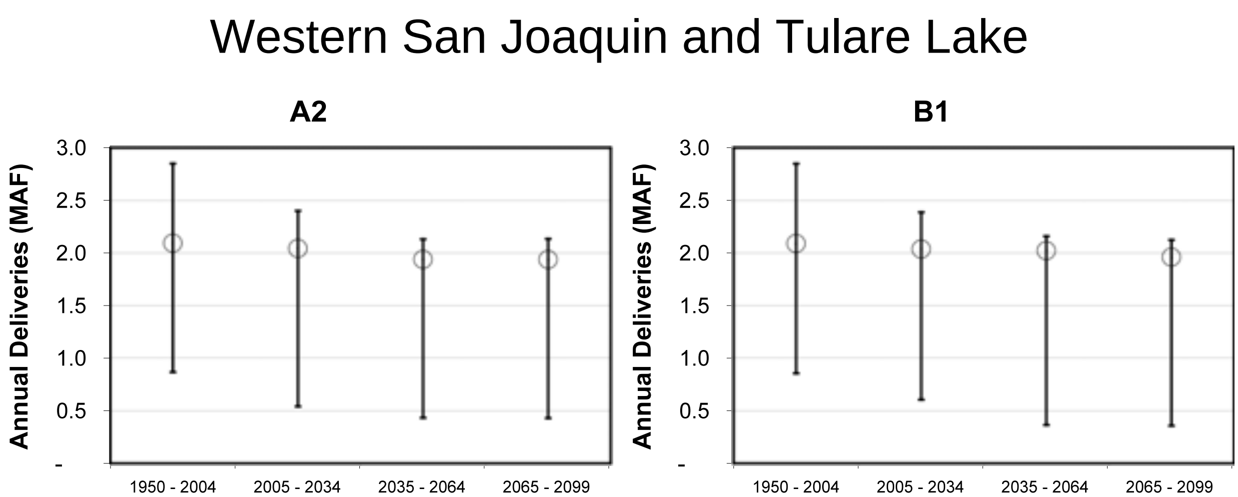

Figure 32. Western San Joaquin and Tulare Lake agricultural water deliveries for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

Figure 33 and Figure 34 show annual surface water deliveries from the rivers and streams in the Sacramento Basin and from the Sacramento-San Joaquin Delta for the A2 and B1 scenarios. There are a couple of features to note about these results. First, as expected, the Sacramento Valley water deliveries were much lower than those reported for the scenarios run without adaptation and with the adaptation strategy of improved irrigation efficiency. This reflects the decrease in irrigated areas introduced with the fallow land class. Water deliveries to the western San Joaquin and Tulare Lake Basins, however, were only marginally different from the other scenarios. This suggests that the deliveries to the export zone in all of the scenarios were being constrained by Delta export operations and environmental considerations within the Delta.

The other trend to note is that the annual surface water deliveries for each region and emission scenario follow the same trends observed for the agricultural supply requirement (Figure 23 and Figure 24). In the Sacramento Valley, surface water deliveries are relatively stable throughout the simulation. In the western San Joaquin and Tulare Lake Basins, surface water deliveries decline toward the middle and end of century.

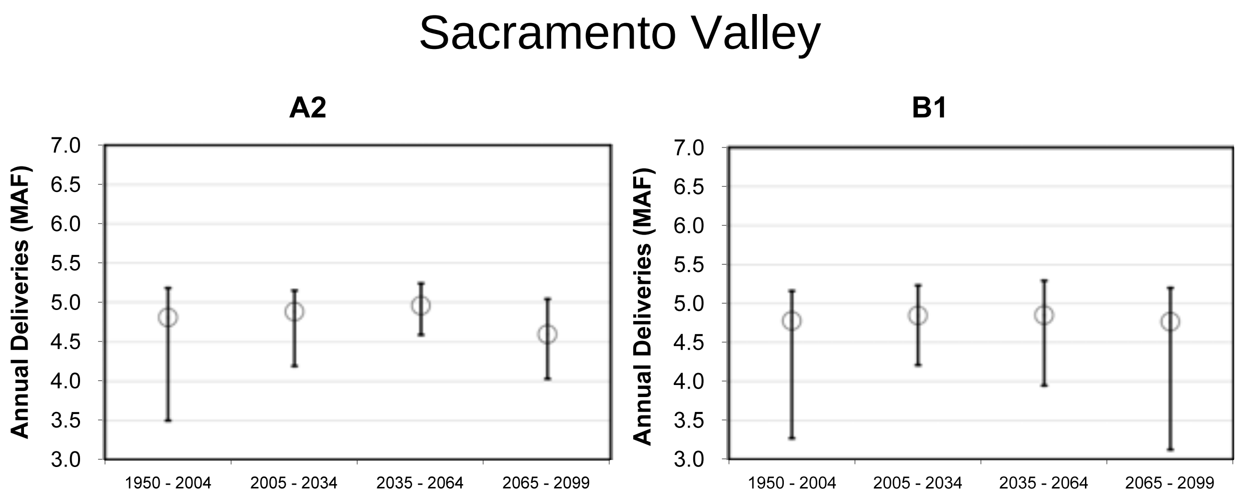

Figure 33. Sacramento Valley annual groundwater pumping for both emission scenarios with shifting cropping patterns. Circles indicate period median, and hash marks indicate minimum and maximum values.

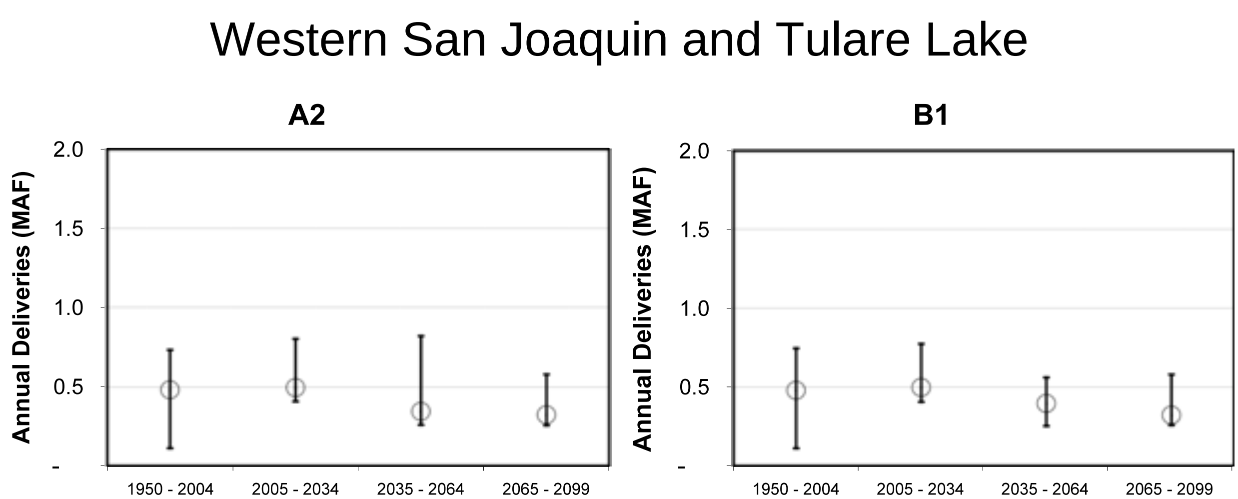

Figure 34. Western San Joaquin and Tulare Lake annual groundwater pumping for both emission scenarios shifting cropping patterns. Circles indicate period median and hash marks indicate minimum and maximum values.

Shifts in cropping patterns appeared to influence annual groundwater pumping within the two regions in a similar manner (Figure 33 and Figure 34). While the annual volumes were below those seen in other scenarios for reasons already discussed, the average volume of groundwater pumping in the two regions tended to follow the same pattern as changes in agricultural supply requirement (Figure 23 and Figure 24).

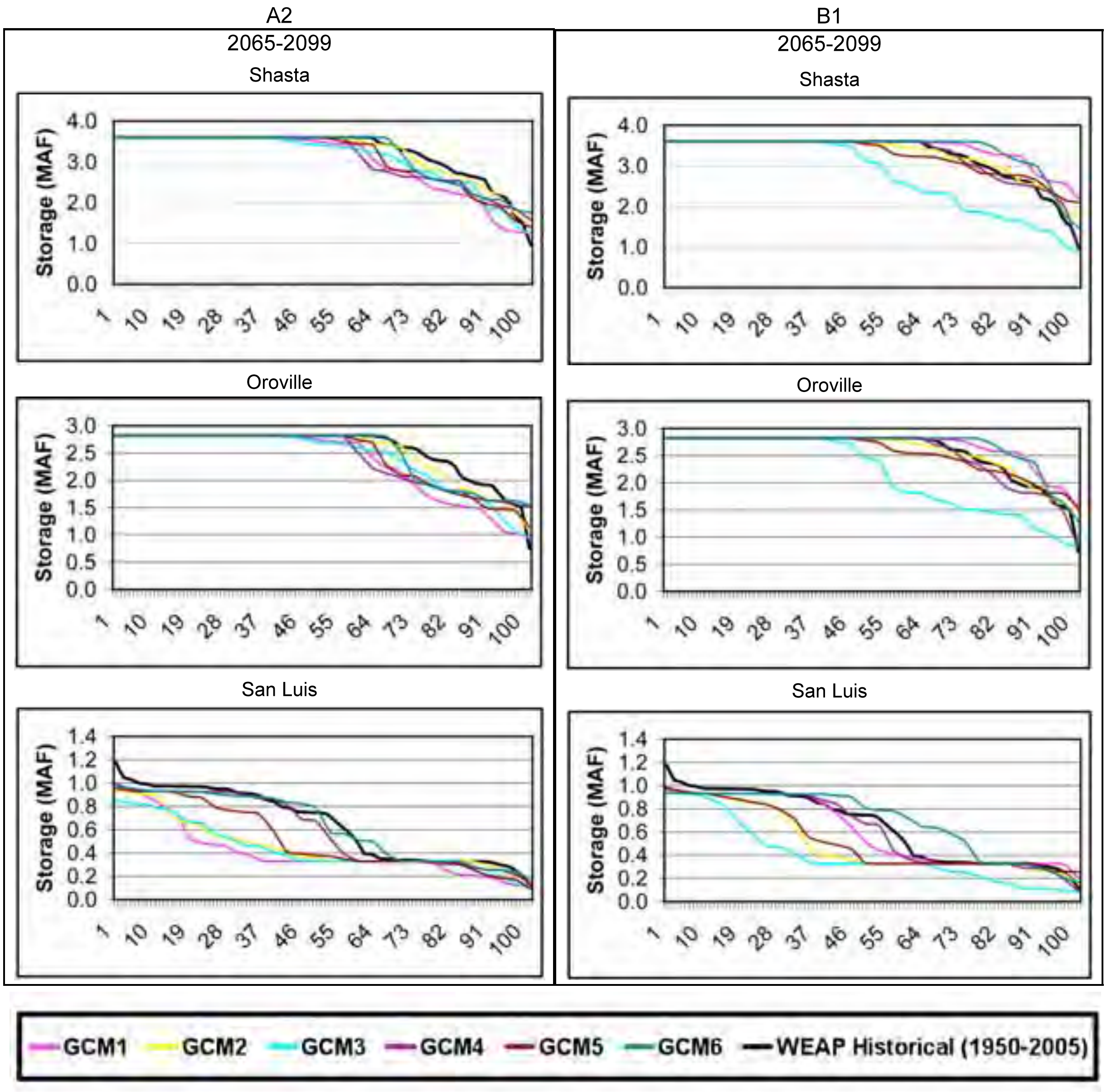

Figure 35. Carryover storage for A2 and B1 scenario with shifting cropping patterns

Figure 35 shows carryover storages at the end of century, 2065–2099, for both the A2 and B1 scenarios run with shifting cropping patterns. As expected, the lower overall demands and the subsequent lower agricultural water deliveries in these scenarios resulted in greater carryover storage than was simulated in scenarios run without adaptation and run with improved irrigation technology. Interestingly, the carryover storages in dry years for the main reservoirs in the Sacramento Valley (Shasta and Oroville) were somewhat higher than the 1950–2005 baseline for the B1 emission scenario and somewhat lower than the baseline in the A2 emission scenario. Carryover storage in San Luis reservoir exhibited greater variability and was generally lower than the baseline for both emission scenarios. This again suggests that Delta operations were limiting exports at the main pumping plants.

4.0 Conclusions

This study demonstrates how WEAP's integrated approach to modeling both the natural and managed components of the water resources system offers significant advantages for investigating climate change impacts in the water sector. Unlike standard water resources analysis models, 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 are included in the analysis in a more robust manner than with the other tools. This allows for the full evaluation of climate change impacts on both water supply and demand and their associated impacts on water management.

This study evaluated the potential implications on water management of twelve climate change scenarios. The consideration of these scenarios revealed a common theme that suggested increasing agricultural demands in the Sacramento and San Joaquin valleys may lead to increased stress on the management of surface water resources and, potentially, to over-exploitation of groundwater aquifers. Further, the model results suggest that water shortages may be felt more acutely in the western San Joaquin Valley and Tulare Basin as Delta exports become more constrained. As these simulations were run using the current set of operational rules for the system, these results suggest that there may be potential to reconfigure these rules such that a more equitable allocation among water users is achieved. Nevertheless, an overall decrease in system reliability is expected in the absence of any modification of operational rules and/or changes in agricultural practices.

Two examples of how agricultural practices may change in response to changing water supply conditions brought about by climate change include improvements in irrigation efficiency through the adoption of new technology and shifts in cropping patterns to crops with higher market value and/or lower water requirements. These two examples were considered in this study and both were found to offset the increasing demands caused by rising temperatures. However, the model suggested that changing climate patterns may limit water deliveries to agriculture in the western San Joaquin Valley and Tulare Basin despite the reduced demands, because Delta exports constrained by environmental requirements within the Delta.

5.0 References

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6.0 Glossary

CCSR	Center for Climate System Research
CCWD	Contra Costa Water District
CNRM	Center for National Weather Research
COA	Coordinated Operations Agreement
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CVPM	Central Valley Production Model
DMC	Delta Mendota Canal
ET	Evapotranspiration
EWA	environmental water account
GCMs	general circulation models
GFDL	Geophysical Fluid Dynamics Laboratory model
IPCC	Intergovernmental Panel on Climate Change
MAF	million acre feet
MPI	Max Planck Institute
MWDSC	Metropolitan Water District of Southern California
NCAR	National Center for Atmospheric Research
PCM	Parallel Climate Model
SBCWD	San Benito County Water District
SC	sub-catchment
SCVWD	Santa Clara Valley Water District
SWP	State Water Project
WEAP	Water Evaluation and Planning

Appendix A

Model Calibration

Appendix A: Model Calibration

Expanding the Sacramento WEAP model to include the western San Joaquin Valley and Tulare Basin required the characterization of agricultural regions and the disaggregation of urban demands within the export zone (i.e., those areas serviced by the Delta Mendota Canal and the California Aqueduct). These demand areas were all previously represented as a single fixed time series of demands taken from the observed historical record. In the previous version of the model, the simplified representation of demands within the export zone facilitated the model calibration, because it obviated the need to consider many regulatory and operational changes that occurred during the period of the model calibration, 1968–1999 (Yates et al. 2008). Many of these changes concerned the Sacramento-San Joaquin Delta and impacted the operations of the main facilities that pump water from the Delta.

In updating the model to include a representation of Delta export operations, it was necessary to recalibrate the model such that it reproduced the observed operations over a timeframe that reflects the current management regime. To this end, we selected the water years 1993–2001 as the calibration period, because the most significant recent changes in management occurred just prior to this period with the passage of the Central Valley Project Improvement Act and the Bay-Delta Accord (later SWRCB Decision 1641). The goal of the recalibration was to capture the general behavior of the system components that were added to the model (i.e., monthly pumping at Banks and Jones Pumping Plants, San Luis Storage) while preserving the overall system operations characterized in the previous model. As such, we focus here on a comparison of the operations of the new model features with observed records. For a presentation of a wider system calibration see Yates et al. (2008) and Joyce et al. (2006).

Total annual and average monthly delta exports are shown for the two main pumping plants, Jones and Banks, in Figure A.1 and Figure A.2.

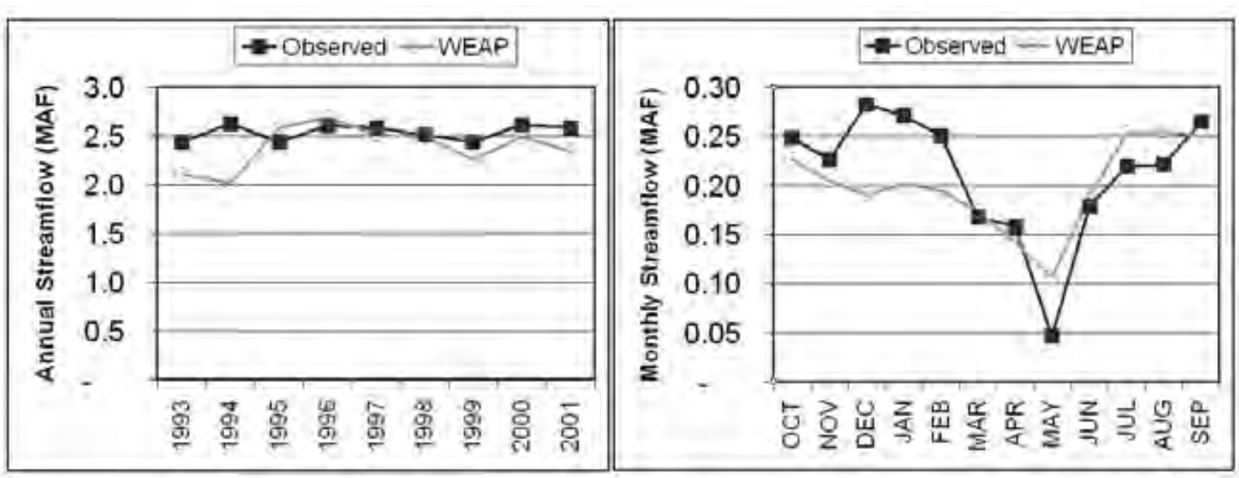

Figure A.1. Total annual and average monthly CVP pumping at Jones Pumping Plant (1993–2001)

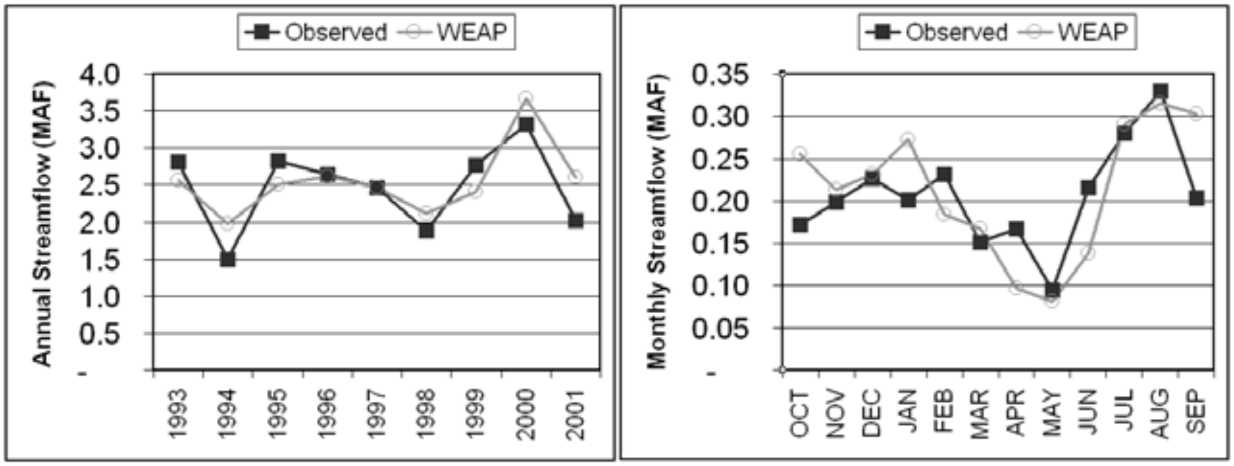

Figure A.2. Total annual and average monthly SWP pumping at Banks Pumping Plant (1993–2001)

For both pumping plants, the WEAP model approximates both the annual total exports and the monthly pattern of withdrawals. The agreement with monthly observed values, however, is less accurate than annual values, due largely to the fact that the model cannot duplicate with a uniform set of operating rules the many discretionary actions undertaken to limit delta pumping over this time frame.

The WEAP model represents San Luis operations using a fairly simple set of operating rules. By assigning the reservoir the lowest priority for storage, it acts to capture excess water (i.e., reservoir spills and unimpaired inflows) from the Delta in the Fall and Winter (Oct–Mar) and release it preferentially in the Spring and Summer to meet south of Delta water demands. Inflows to the reservoir are limited by pumping capacities at Banks and Jones Pumping Plants, which are subject to environmental constraints within the delta. Releases are limited in summer months to one-sixth of the storage available at the beginning of April. These simple rules suffice to operate San Luis reservoir storages in a manner consistent with observed records (Figure A.3).

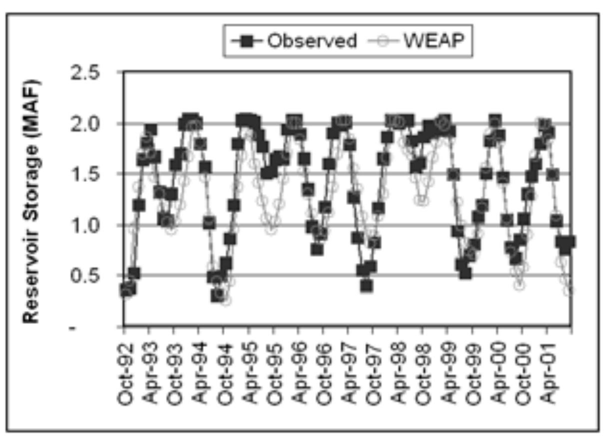

Figure A.3. San Luis storage (1993–2001)

The disaggregation of water demands in the export zone necessitated a reevaluation of the key indicator of Sacramento Valley operations—Sacramento River streamflows at Freeport—to judge whether the modifications influenced the behavior of water management in the Sacramento Basin. As the flows at Freeport are downstream of most of the diversions and return flows in the Sacramento Basin, they are presumed to reflect whether the model is capturing the overall management of water within the basin. Figure A.4 shows that with the modifications the model continues to recreate the overall system behavior in the Sacramento Valley for the calibration period.

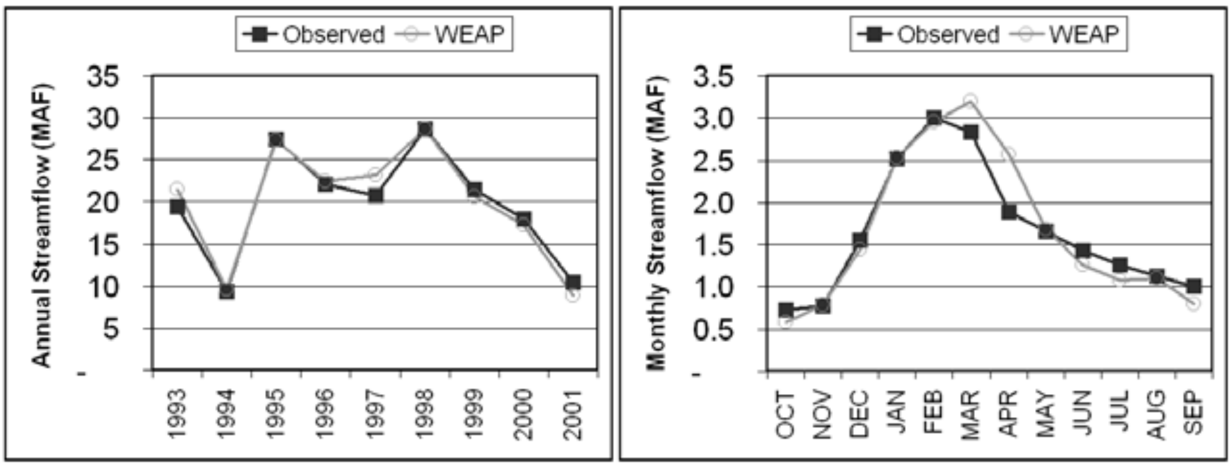

Figure A.4. Total annual and average monthly Sacramento River flows at Freeport (1993–2001)

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