Technical Memorandum

Integrated Scenario Analysis for the 2009 California Water Plan Update

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STATE OF CALIFORNIA
DEPARTMENT OF WATER RESOURCES

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This Document Prepared by:

Brian Joyce, PhD
Stockholm Environment Institute
Senior Scientist

David Purkey, PhD
Stockholm Environment Institute
Water Group Leader

David Yates, PhD
National Center for Atmospheric Research
Scientist

David Groves, PhD
The RAND Corporation
Policy Researcher

Andy Draper, PhD, PE
MWH Americas, Inc.
Principal Engineer

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Acronyms and Abbreviations

°C ..... degrees Celsius
ANN ..... Artificial Neural Network
BO ..... Biological Opinion
cfs ..... cubic feet per second
CalFed ..... CalFed Bay-Delta Program
CARs ..... Computer Assisted Reasoning system
CDFG ..... California Department of Fish and Game
Central Valley PA model ..... Central Valley Planning Area Model
CMIP3 ..... Coupled Model Intercomparison Project, Phase 3
COA ..... Coordinated Operations Agreement
CVP ..... Central Valley Project
CVPIA ..... Central Valley Project Improvement Act
CWP ..... California Water Plan
D-1641 ..... Water Rights Decision 1641
Delta ..... Sacramento-San Joaquin Delta
DMC ..... Delta-Mendota Canal
DWR ..... California Department Water Resources
EBMUD ..... East Bay Municipal Utility District
E:I ..... export to inflow ratio
EIS/EIR ..... Environmental Impact Statement / Environmental Impact Report
ESA ..... Endangered Species Act
ET ..... evapotranspiration
EWA ..... environmental water account
GCM ..... general circulation model
GIS ..... geographical information system
HR ..... hydrologic region
LLNL ..... Lawrence Livermore National Laboratory
M&I ..... municipal and industrial
MAF ..... million acre-feet
MF ..... multifamily
mgd ..... million gallons per day

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NLCD .... National Land Cover Data set
NMFS................................ National Marine Fisheries Service
ppt .... part per thousand
Reclamation .... U.S. Department of the Interior, Bureau of Reclamation
RMSE................................ root mean squared error
ROD .... Record of Decision
SCU .... Santa Clara University
SF .... single-family
State.................................. State of California
Statewide HR model .... Statewide Hydrologic Region Model
SWAN .... Statewide Water Analysis Network
SWP.................................. State Water Project
SWRCB............................. State Water Resources Control Board
TM..................................... Technical Memorandum
USFWS .... United States Fish and Wildlife Service
USGS................................ U.S. Geological Survey
VAMP................................ Vernalis Adaptive Management Program
WCRP .... World Climate Research Programme
WEAP .... Water Evaluation and Planning (System)
WQCP............................... Water Quality Control Plan
WSE.................................. water surface elevation

1.0 Introduction

This Technical Memorandum (TM) describes the development of two water resources planning models to support the California Department of Water Resources (DWR) long-term planning. The first model is a low-resolution representation of the water resources of the entire State of California (State) based on DWR's hydrologic regions. The second model is a more spatially detailed model of the water resources of the Central Valley based on DWR's Planning Areas.

1.1 Background

DWR is mandated by the California Water Code (Section 10005 et seq) to produce a comprehensive water resources management study, known as the California Water Plan (CWP), on a 5-year schedule.

Before the 2005 CWP update, plans typically focused on aggregating data gathered at the local level with the primary goal of estimating the statewide gap between water supply and water demand. This supply gap analysis did not consider uncertainty in the underlying assumptions about demand growth or supply availability. The analysis also did not explicitly weigh the advantages and disadvantages of various management response packages available to expand supply or moderate demand, such as increasing surface storage, reusing wastewater, conjunctively managing surface supplies and groundwater basins, increasing water use efficiency, or desalinating sea water.

In response to these shortcomings, the 2005 CWP update moved away from supply gap analysis and toward integrated scenario analysis by prominently featuring future demand uncertainty and multi-component water management response packages as key elements of the CWP. The 2005 CWP update presented a graphical framework that described what stakeholders considered to be the key components of integrated scenario analysis. This framework, presented in Figure 1-1, has three tiers.

The top tier includes planning assumptions about demand drivers (e.g., population growth), geophysical parameters (e.g., climate change impact on the spatial and temporal patterns that characterize flow in California's rivers and streams), and water management objectives (e.g., future instream flow regimes designed to protect aquatic ecosystems). The uncertainty in projecting the future water management landscape is captured by defining scenarios based on the range of plausible demand drivers, geophysical states, and objectives.

The second tier evaluates future levels of human and environmental water demand, and how different water management response packages (comprising individual management options or strategies) can meet these demands within the context of the California water management system.

The third tier of the framework evaluates the water management response packages in terms of specific evaluation criteria defined by stakeholders and decision makers. While different stakeholders may place more or less importance on any one evaluation criterion, if the range of criteria is wide enough, each stakeholder should be able to assess whether a particular water management response package evaluated for a specific scenario represents an improvement for their particular constituency.

This planning process is designed to encourage water managers to identify water management response packages that help meet multiple objectives, including water supply reliability at the local level. Obviously, for particular regions in California, imported supplies from other regions will be critical to achieving reliability objectives, although such a strategy should not be assumed desirable *a priori*. Rather than identifying actions needed at the statewide level to balance all of California's potential supplies and demand, the 2009 CWP update and future water plans will instead seek to assess the compatibility of regional plans with system-level opportunities and constraints after regional scenario analysis is complete.

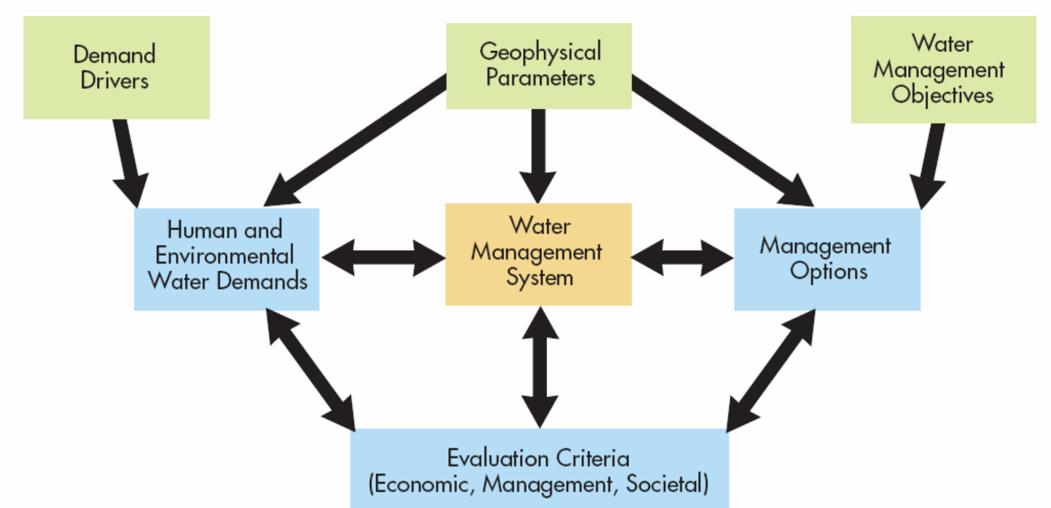

Figure 1-1. Integrated Scenario Analysis Framework
Source: DWR, 2005 California Water Plan Update

1.2 Project Approach

The CWP, from 2009 onward, will seek to evaluate the impacts of different water management response packages under different future scenarios (reflecting plausible future water conditions) through the application of two new water-planning models developed within the Water Evaluation and Planning (WEAP) modeling environment.

The first model, known as the Statewide HR model, is a low-resolution representation of monthly applied water demand and available supply for each of the 10 hydrologic regions in California. The second model is a higher resolution representation of monthly streamflows, demand, water use and return flow, and groundwater use and storage for the hydrologic regions in the Central Valley. This latter model is generally organized around DWR's planning areas, and is referred to as the Central Valley PA model. Both models are calibrated against historical data, and estimate future water management outcomes from 2005 to 2050. The Central Valley PA model coverage of the Tulare Lake hydrologic region is currently limited to the San Luis Unit of the Central Valley Project (CVP). However, additional coverage will be added under a later phase of model development.

The Statewide HR model and the Central Valley PA model are designed to evaluate a wide range of water management response packages under different future scenarios. To anchor the scenario analysis to concerns articulated by CWP stakeholders, three narrative growth scenarios were developed. Each scenario represents a specific story line of how conditions in California could evolve through 2050. These narrative growth scenarios generally do not include climate-related conditions, because these factors are to be considered by specified climate projections from a suite of downscaled global climate models. Specific model parameters have been developed for each planning model to develop quantitative projections consistent with the narrative growth scenarios. This approach was used to quantify three scenarios of water demand for the 2005 CWP Update.

Both models will evaluate a range of water management response packages. For the Statewide HR model, this is likely to be a coarse representation of how supplies and efficiency efforts could change as a result of different water management responses. Such an approach is demonstrated in Wilkinson and Groves (2006). For the Central Valley PA model, specific representations of alternative water management strategies will be developed. Water management response package consists of a set of water management strategies.

1.3 Technical Memorandum Organization

This TM describes work completed under the first phase of the *Work Plan for Near-Term Quantitative Support of Integrated Scenario Analysis for the 2009 California Water Plan Update* (MWH et al., 2008). The TM begins by describing the scenarios, against which, water management response packages will be evaluated (Chapter 2). Next, the TM describes the WEAP modeling platform for simulating scenarios and water management response packages (Chapter 3). The Statewide HR model is briefly described in Chapter 4. The remainder of the document discusses the more detailed Central Valley PA model and its calibration (Chapters 5, 6, and 7). Sources cited in this TM are contained in Chapter 8.

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2.0 Scenarios and Water Management Response Packages

The Central Valley PA model and the Statewide HR model will be used to evaluate water management response packages against different scenarios that impact water supply and water use. The scenarios reflect uncertain future conditions that are generally outside the control of water managers, including (but not limited to) weather-forced hydrologic conditions and demographic changes. Water management response packages reflect different water management decisions (or strategies) to be evaluated for the CWP. Water management response packages comprise portfolios of individual management strategies and can be defined in WEAP to be static (i.e., occur at a pre-specified schedule or adaptive (i.e., implemented dynamically in response to modeled-evolution of the water system).

Scenarios to be modeled are defined by combining individual scenarios reflective of plausible trends and changes in demographic and land-use conditions (growth scenarios) with sequences of weather conditions (climate scenarios). Each pair of growth and climate scenarios defines a water management scenario. Additional scenario dimensions that reflect other non-growth and climate related factors may be developed for Central Valley PA model in the future.

2.1 Demographic and Land-Use Scenarios

The Statewide HR model and Central Valley PA model estimate urban, agricultural, and environmental water demands based on: projections of the number and type of households and per household water use; level of commercial and industrial employment and per employee water use; agricultural activity (including acreage of different crop types and irrigation methods); and environmental flow objectives. The demographic and land-use scenarios reflect uncertainty about how these conditions may evolve in the future.

CWP staff used a stakeholder-driven process to develop three narratives for alternative growth scenarios: Current Trends, Blueprint Growth, and Expansive Growth. These growth scenarios are described in the Public Review Draft (Volume 1, Chapter 5) of the CWP 2009 Update, as follows (DWR, 2009):

- **Scenario 1 – Current Trends.** For this growth scenario, recent trends are assumed to continue into the future. In 2050, nearly 60 million people live in California. Affordable housing has drawn families to the interior valleys. Commuters take longer trips in distance and time. In some areas, where urban development and natural resources restoration have increased, irrigated crop land has decreased. The State faces lawsuits on a regular basis, from flood damages to water quality and endangered species protections. Regulations are not comprehensive or coordinated, creating uncertainty for local planners and water managers.

- **Scenario 2 – Strategic Growth.** Private, public, and governmental institutions form alliances to provide for more efficient planning, and development that is less resources-intensive than current conditions. Population growth is slower than currently projected—about 45 million people live in the State. Compact urban development has eased commuter travel. Californians embrace water and energy conservation. Conversion of agricultural land to urban development has slowed and conversion occurs mostly for environmental restoration and flood protection. State government implements comprehensive and coordinated regulatory programs to improve water quality, protect fish and wildlife, and protect communities from flooding.

- **Scenario 3 – Expansive Growth.** Future conditions are more resource-intensive than existing conditions. Population growth is faster than currently projected with 70 million people living in California in 2050. Families prefer low-density housing, and many seek rural residential properties, expanding urban areas. Some water and energy conservation programs are offered but at a slower rate than trends in the early part of the century. Irrigated crop land has decreased significantly where urban development and natural restoration have increased. Protection of water quality and endangered species is driven mostly by lawsuits, creating uncertainty.

These three narratives of alternate growth scenarios primarily consider demographic conditions, lifestyle choices, land-use, trends in regulation and legislation, and lawsuits. For the modeling analyses, these alternate growth scenarios are reflected in alternate water demand estimates.

2.2 Climate Scenarios

Each of the growth scenarios described above will be evaluated under a set of monthly time sequences of weather derived from downscaled general circulation model (GCM) simulations. These data include monthly temperature and precipitation on a one-eighth-degree grid derived from six GCMs run under two global emissions scenarios—the same scenarios selected by the Governor's Climate Action Team. The GCMs used are as follows:

- CNRM-CM3 (France)
- GFDL-CM21 (U.S.A.)
- Micro32med (Japan)
- MPI-ECHAM5 (Germany)
- NCAR-CCSM3 (U.S.A.)
- NCAR-PCM1 (U.S.A.)

The two global emissions scenarios used are the "A2" and "B1" scenarios which are defined as follows:

> *The* ***A2 SRES global emissions scenario*** *represents a heterogeneous world with respect to demographics, economic growth, resource use and energy systems, and cultural factors. There is a de-emphasis on globalization, reflected in heterogeneity of economic growth rates and rates and directions of technological change. These and other factors imply continued growth throughout the 21st century of global GHG* [Green House Gas] *emissions. By contrast,* ***B1 is a "global sustainability" scenario****. Worldwide, environmental protection and quality and human development emerge as*

> *key priorities, and there is an increase in international cooperation to address them as well as to converge in other dimensions. Neither scenario entails explicit climate mitigation policies. The A2 and B1 global emission scenarios were selected to bracket the potential range of emissions and the availability of outputs from global climate model.* (California Climate Action Team, 2009).

Downscaled monthly temperature and climate projections were obtained from the downscaled climate data set jointly developed by the Lawrence Livermore National Laboratory (LLNL), the U.S. Department of the Interior, Bureau of Reclamation (Reclamation), and Santa Clara University (SCU, 2009). These data were derived from the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set. This latter data set includes results from 112 different global climate simulations of 16 global models with different starting conditions, evaluated for three global emissions scenarios. The projections are available from 1950 to 2099 (data for past time periods are back-casted). This data set includes the 12 projections chosen by the California Climate Action Team (Maurer and Hidalgo, 2008) as a representative sample of GCM projections for California climate studies.

For the Statewide HR model, two sets of spatially averaged monthly temperature and precipitation sequences were developed. One set corresponds to the urban areas and the other set corresponds to agricultural areas. Using a geographical information system (GIS), each of the one-eighth-degree grid points was classified as urban, agricultural, or other land use. Subsequently, this classification was used to develop spatially averaged data by averaging the climate data of each grid cell that corresponded to one of three categories. This would be problematic if the location of agricultural land-use types within a hydrologic region varied dramatically, but it was found that the majority of cells of any one type generally occurred together or resided within a similar climatic zone.

Because Central Valley PA model is more finely disaggregated than the Statewide HR model, elevation bands were used to define climate for banded catchments. For the valley floor catchments, a common but unique climate timeseries was used for both the urban and agricultural land uses. This is described more fully in Chapter 6.

2.3 Water Management Response Packages

Water management response packages will be evaluated against pairs of growth and climate scenarios described above. Water management response packages comprise individual resource management strategies. Volume 2 of the CWP Update 2009 describes 28 categories of different resource management strategies (DWR, 2009). These water management strategies range from specific structural modifications of California’s water storage and conveyance system to more general approaches aimed at changing water use patterns through adoption of new policies. The Central Valley PA model and the Statewide HR model will address many of these strategies, either singularly or as groups of strategies. However, the ability to quantify the impacts of these strategies within the two models will vary depending on the specific nature of the strategy.

In general, the Statewide HR model and the Central Valley PA model are designed to address strategies that have a measurable impact on water supply and demand at the scale of the hydrologic region and planning area, respectively. Where the model(s) cannot address certain strategies, these strategies are generally defined at a level of specificity that is inconsistent with the model(s) or outcomes of the strategies are measured using metrics that are not simulated within the model environment. Table 2-1 indicates the extent to which each strategy identified in CWP Update 2009 can be represented within the two models.

Table 2-1. Model Representation of California Water Plan Strategies

Strategy	Able to Represent in Model
Reduce Water Demand	
Agricultural Water Use Efficiency	Yes
Urban Water Use Efficiency	Yes
Improve Operational Efficiency	
Conveyance - Delta	Yes
Conveyance - Regional/Local	Yes
System Reoperation	Yes
Water Transfers	Yes
Increase Water Supply	
Conjunctive Management and Groundwater Storage	Yes
Desalination - Brackish and Seawater	Yes
Precipitation Enhancement	Yes
Recycled Municipal Water	Yes
Surface Storage - CalFed/State	Yes
Surface Storage - Regional/Local	Yes
Improve Water Quality	
Drinking Water Treatment and Distribution	Partially
Groundwater Remediation/Aquifer Remediation	Partially
Matching Water Quality to Use	Partially
Pollution Prevention	No
Salt and Salinity Management	No
Urban Runoff Management	No
Practice Resource Stewardship	
Agricultural Lands Stewardship	No
Economics Incentives Policy	Partially
Ecosystem Restoration	No
Forest Management	No
Land Use Planning and Management	Yes
Recharge Area Protection	Partially
Water-Dependent Recreation	No
Watershed Management	No
Improve Flood Management	
Flood Risk Management	Partially

Key:
CalFed = CalFed Bay-Delta Program
State = State of California
Delta = Sacramento-San Joaquin Delta

The Statewide HR model and the Central Valley PA model will be configured to evaluate both static and adaptive (dynamic) water management response packages. Static water management response packages consist of a collection of specific pre-defined water management strategies that are implemented at a pre-defined date. Adaptive water management response packages consist of pre-defined strategies, which are implemented or adjusted based on measures or triggers, and deferred actions. An example of an adaptive management response package is shown in Figure 2-1.

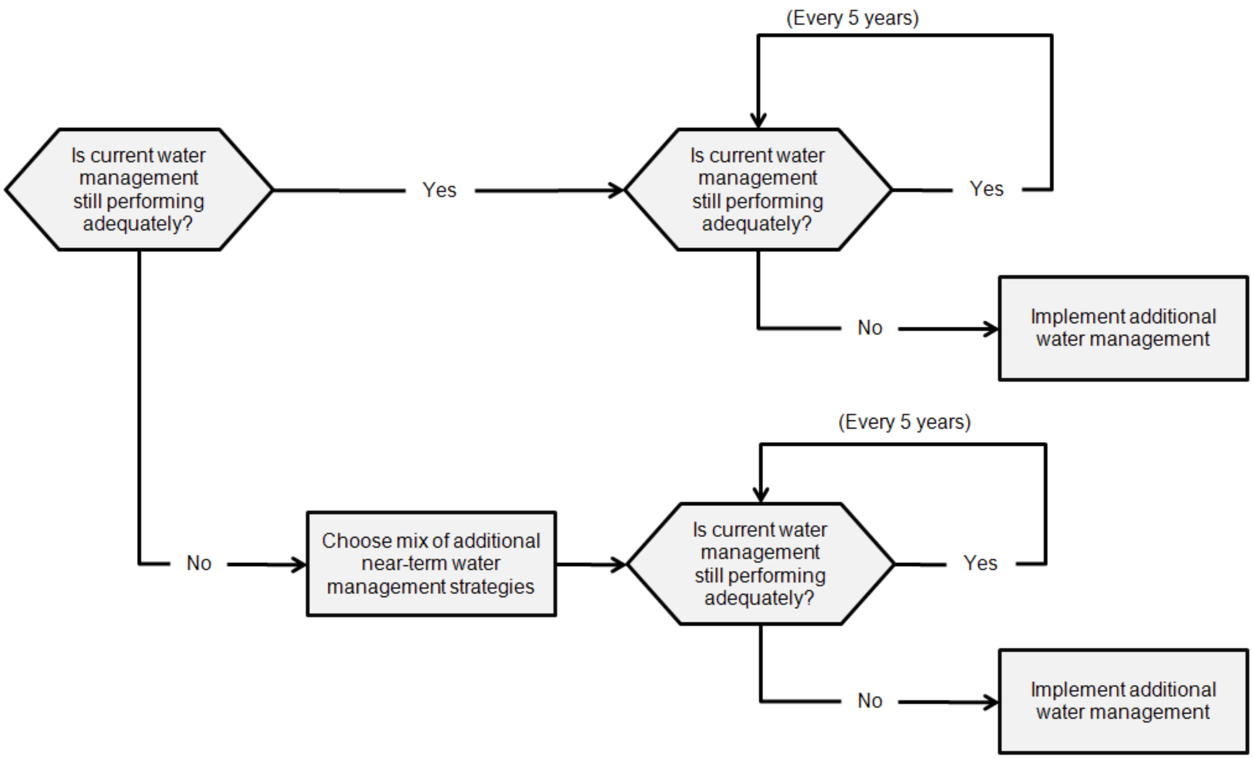

Figure 2-1: Schematic Defining a Simple Adaptive Management Response Package

(Source: adapted from Groves and Lempert, 2010)

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3.0 Water Evaluation and Planning System

This Chapter presents an overview of the WEAP modeling environment that provided the framework for developing both the Statewide HR model and Central Valley PA model. Particular focus is given to the hydrology routines in WEAP that allow simulation of climate driven snow-melt and rainfall-runoff, and dynamic calculation of irrigation demands.

3.1 General Description

The WEAP system is a comprehensive, fully integrated river basin analysis tool. It is a simulation model that includes a robust and flexible representation of water demands from different sectors, and the ability to program operating rules for infrastructure elements such as reservoirs, canals, and hydropower projects (Purkey and Huber-Lee, 2006; Purkey et al., 2007; Yates et al., 2005a, 2005b; Yates et al., 2008; and Yates et al., 2009). 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. This functionality allows the modeler to analyze how specific configurations of infrastructure, operating rules, and operational priorities will affect water uses as diverse as instream flows, irrigated agriculture, 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 WEAP ideally suited to study the potential impacts of climate change and other uncertainties internal to watersheds.

3.2 WEAP Approach

The development of all WEAP applications follows a standard approach, as illustrated in Figure 3-1. The first step in this approach is the study definition, wherein the spatial extent and system components of the area of interest are defined and the time horizon of the analysis is set. The user subsequently defines system components (e.g., rivers, agricultural and urban demands) and the network configuration connecting these components. Following the study definition, the "current accounts" are defined, which is a baseline representation of the system – including existing operating rules to manage both supplies and demands. The current accounts serve as the point of departure for developing scenarios, which characterize alternative sets of future assumptions pertaining to policies, costs, demand factors, pollution loads, and supplies. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. In this context, scenarios represent evaluations of water management response packages under uncertain future conditions. The steps in the analytical sequence are described in greater detail in the following sections.

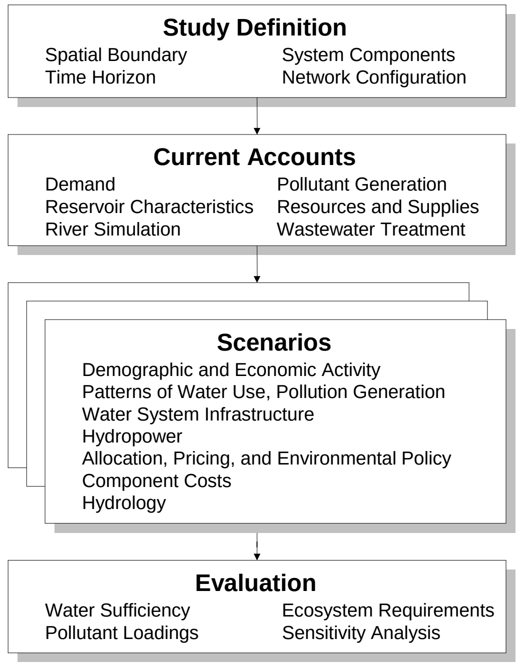

Figure 3-1. Components of a WEAP Application

3.2.1 Study Definition

Evaluating the implications of diversions and impoundments along a river, and how they are managed, requires consideration of the entire land area that contributes flow to the river, i.e., the river basin. Within WEAP, it is necessary to set the spatial scope of the analysis by defining the boundaries of the river basin. Within these boundaries, there are smaller rivers and streams (or tributaries) that flow into the main river of interest. Because these tributaries determine the distribution of water throughout the whole basin, it is also necessary to divide the study area into subbasins, or catchments, such that the spatial variability of stream flows can be characterized.

3.2.2 Current Accounts

Current accounts represent the basic definition of the water system as it currently exists. Current accounts include specification of supply and demand infrastructure (e.g., reservoirs, pipelines, treatment plants). Establishing current accounts also requires the user to calibrate system data and assumptions so as to accurately mimic the observed operation of the system. This calibration process also includes setting parameters for defined catchments so that WEAP can simulate snowmelt and rainfall-runoff using input climate data (i.e., temperature and precipitation) and also estimate evaporative water demand in the delineated basins.

3.2.3 Scenarios

At the heart of WEAP is the concept of scenario analysis. Scenarios are story-lines of how a future system might evolve over time. The scenarios can address a broad range of “what if” questions. In this manner, the implications of changes to the system can be evaluated, and subsequently how these changes may be mitigated by policy and/or technical interventions. For example, WEAP may be used to evaluate the water supply and demand changes for a range of future changes in demography, land use, and climate. The result of these analyses will be used to guide the development of response packages, which are combinations of non-structural and/or infrastructural changes that enhance the productivity of the system.

3.2.4 Evaluation

Once the performance of a set of response packages has been simulated within the context of future scenarios, the response packages can be compared relative to key metrics. Typically, these metrics relate to water supply reliability, water allocation equity, ecosystem sustainability and cost. However, any number of performance metrics can be defined and quantified within WEAP.

3.3 WEAP Water Allocation

Two user-defined priority systems are used to determine allocations of supplies to meet demands (modeled as demand sites and as catchments objects for irrigation), instream flow requirements, and for filling reservoirs. These are: (1) demand priorities, and (2) supply preferences.

A demand priority is attached to a demand site, catchment, reservoir, or flow requirement, and may range from 1 to 99, with 1 being the highest priority and 99 the lowest. Demand sites can share the same priority, which is useful in representing a system of water rights, where water users are defined by their water usage and/or seniority. In cases of water shortage, higher priority users are satisfied as fully as possible before lower priority users are considered. If priorities are the same, shortage will be shared equally (as a percentage of their demands).

When demand sites or catchments are connected to more than one supply source, the order of withdrawal is determined by supply preferences. Similar to demand priorities, supply preferences are assigned a value between 1 and 99, with lower numbers indicating preferred water sources. The assignment of these preferences usually reflects economic, environmental, historical, legal, and/or political realities. In general, multiple water sources are available when a preferred water source is insufficient to satisfy all of an area's water demands. WEAP treats additional sources as supplemental supplies and will draw from these sources only after it encounters a capacity constraint (expressed as either a maximum flow volume or a maximum percent of demand) associated with a preferred water source.

WEAP's allocation routine uses demand priorities and supply preferences to balance water supplies and demands. To do this, WEAP must assess the available water supplies each timestep. While total supplies may be sufficient to meet all of the demands within the system, it is often the case that operational considerations prevent the release of water to do so. These rules are usually intended to preserve water in times of shortage so that long-term delivery reliability is maximized for the highest priority water users (often indoor urban demands). WEAP can represent this controlled release of stored water using its built-in reservoir routines.

WEAP uses generic reservoir objects, which divide storage into four zones, or pools, as illustrated in Figure 3-2. These include, from top to bottom, the flood-control zone, conservation zone, buffer zone, and inactive zone. The conservation and buffer pools together constitute a reservoir's active storage. WEAP always evacuates the flood-control zone, so that the volume of water in a reservoir cannot exceed the top of the conservation pool. The size of each of these

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pools can change throughout the year according to regulatory guidelines, such as flood control rule curves.

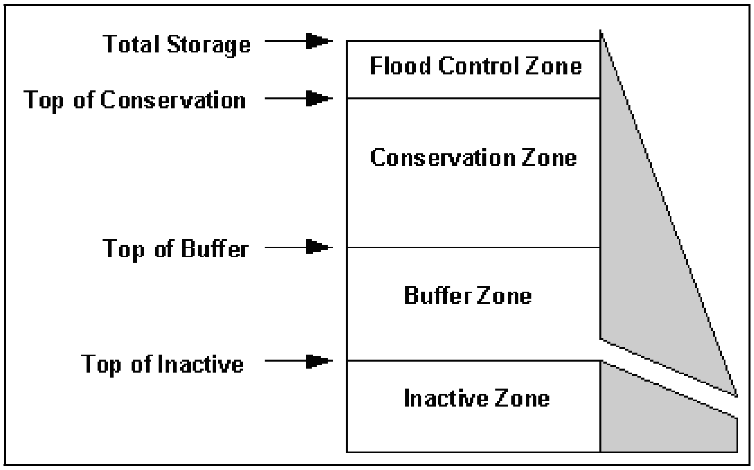

Figure 3-2. WEAP Reservoir Zones

WEAP allows reservoirs to freely release water from the conservation pool to fully meet withdrawal and other downstream requirements. Once the reservoir storage level drops into the buffer pool, the release is restricted according to the buffer coefficient, to conserve the reservoir's dwindling supplies. The buffer coefficient is the fraction of the water in the buffer zone available each month for release. Thus, a coefficient close to 1.0 will cause demands to be met more fully, while rapidly emptying the buffer zone. A coefficient close to zero will leave demands unmet while preserving the storage in the buffer zone. Water in the inactive pool is not available for allocation, although under extreme conditions evaporation may draw the reservoir below the top of the inactive pool.

3.4 WEAP Hydrology

The hydrology module in WEAP is spatially continuous, with a study area configured as a contiguous set of catchments that cover the entire extent of the represented river basin. 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 (Yates et al., 2005a and 2005b). Each catchment is fractionally subdivided into a unique set of independent land-use or land-cover classes that lack detail regarding their exact location within the catchment, but which sum to 100 percent of the catchment's area. A unique climate data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each catchment.

A one-dimensional, quasi-physical water balance model depicts the hydrologic response of each fractional area within a catchment and partitions water into surface runoff, infiltration, evapotranspiration (ET), interflow, percolation, and baseflow components. Values from each fractional area (fa) within the catchment are then summed to represent the lumped hydrologic response for all land cover classes, with surface runoff, interflow, and baseflow being linked to a river element; deep percolation being linked to a groundwater element where prescribed; and ET being lost from the system.

The hydrologic response of each catchment is depicted by a "two-bucket" water balance model as shown in Figure 3-3. The model tracks soil water storage, in the upper bucket, z_{fa}, and in the lower bucket, Z. Effective precipitation, Pe, and applied water, AW, are partitioned into evapotranspiration (ET), surface runoff/return flow, interflow, percolation and baseflow. Effective precipitation is the combination of direct precipitation (P_{obs}) and snowmelt (which is controlled by the temperatures at which snow freezes, T_s, and melts, T_l). Soil water storage in the shallow soil profile (or upper bucket) is tracked within each fractional area, fa, and is influenced by the following parameters: a plant/crop coefficient (kc_{fa}); a conceptual runoff resistance factor (RRF_{fa}); water holding capacity (WC_{fa}); hydraulic conductivity (HC_{fa}); upper and lower soil water irrigation thresholds (U_{fa} and L_{fa}); and a partitioning fraction, f, which determines whether water moves horizontally or vertically. Percolation from each of these fractional areas contributes to soil water storage (Z) in the deep soil zone (or lower bucket) and is influenced by the following parameters: water holding capacity (WC_{fa}), hydraulic conductivity (HC_{fa}), and the partitioning fraction, f.

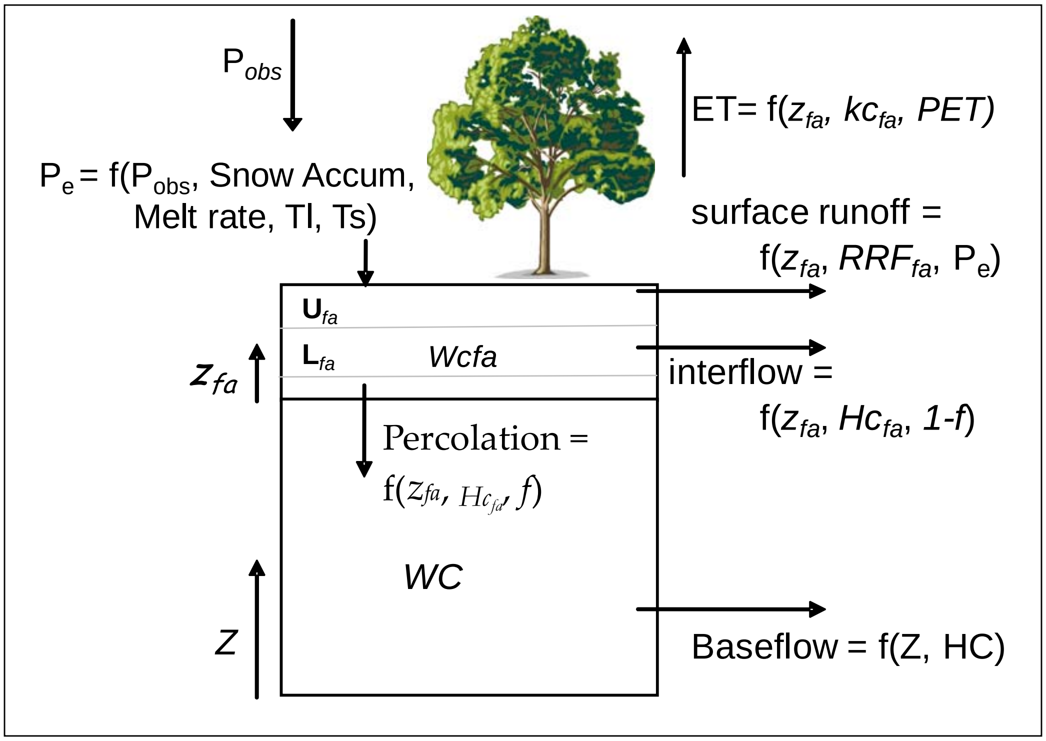

Figure 3-3. Two-Bucket WEAP Hydrology Model

Where stream-aquifer interactions are significant, representation within select catchments can be reformulated by recasting the lower storage zone of the two bucket model (upper storage zone represents soil moisture in the root zone) as a simplified groundwater element that is hydraulically connected to associated river reaches.

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WEAP's hydrology module also includes a temperature-index based snowmelt model, which computes an effective precipitation, P_e, from the accumulated snowpack in the catchment, where m_c is the melt coefficient given as,

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 \quad if & T_i > T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & T_s \le T_i \le T_l \end{cases} \qquad \text{Eq. 1}$$

Where:

T_i = observed temperature for month i
T_l = melting temperature threshold
T_s = freezing temperature threshold.

Snow accumulation, Ac_i, is a function of the melt coefficient, m_c, and the monthly precipitation, P_i as follows:

$$Ac_i = Ac_{i-1} + (1 - m_c)P_i, \qquad \text{Eq. 2}$$

The melt rate, m_r, is calculated as follows:

$$m_r = Ac_i m_c \qquad \text{Eq 3}$$

The effective precipitation, P_e, is then computed as:

$$P_e = P_i m_c + m_r \,. \qquad \text{Eq. 4}$$

For modeling the Sacramento and San Joaquin river watersheds, the Ts and Tl thresholds were set everywhere to a value of -3 degrees Celsius (ºC) and 7ºC, respectively. These values cause precipitation to fall as all snow at and below -3ºC, and as all rainfall at and above 7ºC, and to fall as a mix of snow and rainfall between those two temperature thresholds.

At each timestep, WEAP first computes the horizontal and vertical fluxes, which it passes to each river and groundwater object. Next, water allocations are made for the given timestep by passing constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, and the priorities and preferences assigned to demand sites to a linear programming optimization routine that maximizes demand "satisfaction" to the greatest extent possible (Yates et al., 2005a). All flows are assumed to occur instantaneously; thus, demand sites can withdraw water from the river, use some of the water consumptively, and optionally return the remainder to a receiving water body in the same timestep. 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 timestep should be at least as long as the residence time of water within the study area. For this reason, a monthly timestep was adopted for the Statewide HR model and Central Valley PA model.

4.0 Statewide Hydrologic Region Model

DWR has taken the lead in developing a low-resolution regional demand and supply balance representation of each of the 10 hydrologic regions in California using WEAP. This application is known as the Statewide Hydrologic Region Model (Statewide HR model).

Supply projections in the Statewide HR model are based on correlations developed between recent past historical inventories of available supplies and climate. Because of the coarse nature of this analysis, only a rough comparison of the independent projections of demand to supply is possible. DWR staff members are exploring ways of how the model can be used to evaluate the water management response packages developed by the CWP advisory committee.

This Chapter discusses the following technical aspects of the Statewide HR model development:

- Development of climate input data used to estimate agricultural and outdoor irrigation demands.
- Calibration of agricultural and outdoor urban irrigation demands.
- Evaluation of the model under 36 scenarios (the product of 12 climate scenarios and 3 growth scenarios).
- Development of select Statewide HR model results to be used by Central Valley PA model to maintain consistency in projected demands across the two models.

For the second and third activities, the Statewide HR model was connected to exploratory modeling software[1] to facilitate development and analysis of multiple scenarios. The following sections provide a brief overview of the Statewide HR model and then describe each of the four activities listed above.

4.1 Model Overview

To date, the Statewide HR model has evaluated demand conditions consistent with three growth scenarios through specification of parameters that affect urban, agricultural, and environmental water demand.

4.1.1 Urban Demand

Indoor urban demand is represented in a manner similar to that used for the 2005 CWP Update. Indoor urban demand is estimated through multiplying projections of the number of water-use entities by sector-specific water-use rates. The key water-use entities adjusted by scenario factors are as follows:

[1] The Computer Assisted Reasoning ® system (CARs™), developed and maintained by Evolving Logic.

- Single-family (SF) households
- Multifamily (MF) households
- Commercial employees
- Industrial employees
- Total population (for institutional demand)

Water-use rates are influenced by the following factors:

- Income (SF and MF household use)
- Household size (SF and MF household use)
- Water price (SF and MF household use, commercial, and industrial water use)
- Naturally occurring conservation

It is assumed that indoor urban demand is not affected by weather conditions.

Outdoor urban demand is estimated using the WEAP hydrology module, and is a function of irrigated landscape area (assumed to be turf), water-use rate factors, parameters defining soil and landscape characteristics, and monthly weather sequences. DWR estimated the irrigated landscape area independently for each urban land use class (SF households, MF households, commercial, and large landscape). This was achieved in two steps: firstly by estimating the existing area of irrigated landscape; and secondly projecting this area into the future based on demographics. The changes to water-use rates due to the water-use rate factors estimated for indoor urban water demand are applied to outdoor urban water demand by adjusting the landscaped area proportionally.

The watershed response is calibrated so that WEAP-calculated irrigation water demand by crop type and hydrologic region under historical hydrologic conditions matches the estimated water use for the portfolio years (1998 – 2005) (see Section 4.3 below).

DWR staff members have developed three different projections of the number of water-use entities and water-use rate factors, each corresponding to one of the three growth scenarios (described in Chapter 2).

4.1.2 Agricultural Demand

Irrigated agricultural demand in the Statewide HR model is estimated using the WEAP hydrology module and is a function of the irrigated area of 21 different crop types, parameters defining soil and land cover characteristics, and a timeseries of weather sequences (see Section 4.2). DWR staff members developed three different projections of future irrigated land area (by crop and hydrologic region), each corresponding to one of the three growth scenarios. Under each scenario, future change in irrigated agricultural acreage was estimated based on population growth and assumptions of urban encroaching into agricultural lands.

The Statewide HR model uses these projections of future irrigated acreage, together with monthly sequences of weather parameters (primarily temperature and precipitation), to calculate future water demand by crop.

4.1.3 Unmet Environmental Water Demand

For the three growth scenarios, unmet environmental objectives are used as a surrogate to estimate additional requirements that may be enacted in the future. These unmet objectives are instream flow needs or additional deliveries to managed wetlands that have been identified by regulatory agencies or pending court decisions, but are not yet required by law. These future needs are supplemental to the current base environmental demands.

To model these future additional demands in the Statewide HR model, recent unmet historical environmental objectives for 1998 – 2007 were indexed to historical climate and grouped into 3 categories based on year type classes (Critical and Dry, Below Normal and Above Normal, and Wet). Unmet demands for each growth scenario was determined by assigning the minimum, average and maximum values of each of the 3 year-type categories to the 3 growth scenarios, Expansive Growth, Current Trend and Strategic Growth, respectively. Finally, future annual precipitation (2005-2050) under each of the 12 climate scenarios was referenced back to year type and the corresponding environmental water demand determined in respective future years as the Statewide HR model steps through time from 2005 to 2050.

4.2 Development of Climate Data

Outdoor urban and agricultural water demands are estimated using WEAP's internal soil moisture mass balance model. Inputs to this model include precipitation, temperature, wind speed, and relative humidity, which together are used to estimate the monthly total potential evapotranspiration using a standard Penman-Monteith model. For each hydrologic region, a unique climate timeseries was prescribed based on the one-eighth degree data set of Maurer for the period of 2001 through 2005. This data set was developed for hydro-meteorological modeling applications and includes climate variables used by WEAP to simulate the full hydrologic cycle. For each hydrologic region, GIS was used to locate the geographic centroid of both the agricultural and urban demand types.

4.2.1 Outdoor Urban and Agricultural Water Demand Calibration

WEAP's watershed routine is calibrated so that calculated outdoor urban and agricultural irrigation water demand by crop type and hydrologic region conditions matches the estimated water use for historical years represented by the Water Plan portfolios (1998 – 2005).[2] Because the Statewide HR model estimates crop water use for each hydrologic basin using a single catchment object, it is not possible to develop an accurate characterization of the catchment properties for each hydrologic region *a priori*. Instead, a calibration procedure was developed to identify a set of plausible model parameters that would lead to WEAP-calculated water demand to match historical estimates of water use. The goal of the calibration process was to minimize the average differences in water demand by crop type across the portfolio years by crop and hydrologic region.

[2] At the time of calibration, Summer 2009, portfolio data for outdoor irrigation water use was limited to 1998-2001. The model's calibration will be updated in the future to reflect data for the entire Water Plan portfolio period (1998-2005), when available.

The following steps were used to calibrate irrigation demand in the WEAP model:

1. **Identify calibration factors:** We selected three factors in consultation with WEAP developers and DWR—two associated with soil characteristics (root zone conductivity and soil water capacity) and one of the two irrigation parameters (lower threshold).

2. **Define plausible parameter ranges for calibration factors:** DWR planning staff developed parameter ranges through consultation with agricultural specialists within DWR.

3. **Calculate water demand for the calibration period:** The WEAP model was evaluated for the calibration periods (1998-2005 for agricultural irrigation and 1998-2001 for outdoor urban irrigation) under 100 different combinations of calibration parameters. Section 4.3.2 describes this process.

4. **Choose set of calibration parameters:** We compared the WEAP-calculated water demand to historical estimates of water use and identified the set of calibration parameters that minimized the average difference between the calculated values and historical estimates of water use.

4.2.2 Calibration parameters

The first two steps in the calibration procedure were to define the calibration parameters and specify the ranges of parameter values to use in the calibration. The following WEAP catchment model parameters and ranges were modified: lower threshold [percent], root zone conductivity [inches/month], and soil water capacity [inches].

The table below shows the parameter ranges used for agricultural irrigation by 20 crop types. The same ranges were used for each of the ten hydrologic regions.

Table 4-1: Crop-Specific Calibration Parameters

No.	Crop Category	Lower Threshold (percent)		Root Zone Conductivity (inches/month)		Soil Water Capacity (inches)	
		Min	Max	Min	Max	Min	Max
1	Grain	30	60	3.9	7.9	11.8	15.7
2	Rice	80	90	2.0	5.9	7.9	15.7
3	Cotton	40	75	3.9	7.9	3.9	21.7
4	Sugar Beet	40	70	5.9	11.8	3.9	15.7
5	Corn	40	75	3.9	5.9	11.8	21.7
6	Dry Bean	40	65	3.9	9.8	7.9	17.7
7	Safflower	20	40	2.0	5.9	3.9	7.9
8	Other Field	30	80	3.9	7.9	7.9	23.6
9	Alfalfa	30	70	3.9	15.7	7.9	15.7
10	Pasture	30	65	3.9	13.8	7.9	17.7
11	Processed Tomato	40	85	3.9	9.8	7.9	13.8
12	Fresh Tomato	45	80	3.9	7.9	3.9	19.7
13	Cucurbits	35	65	3.9	7.9	3.9	11.8
14	Onion and Garlic	35	75	3.9	9.8	3.9	15.7
15	Potato	35	70	3.9	7.9	7.9	19.7
16	Other Truck	45	80	3.9	7.9	7.9	19.7
17	Almond and Pistachio	30	65	3.9	7.9	3.9	5.9
18	Other Deciduous	40	70	3.9	7.9	5.9	7.9
19	Sub-Tropical	35	60	3.9	7.9	1.6	4.7
20	Vine	30	55	3.9	7.9	3.9	5.9

Notes:

1. Values converted from millimeters/month and millimeters to inches/month and inches respectively
2. Identical values used for all hydrologic regions

For urban irrigation, the same parameter ranges were used for single-family, multi-family, commercial, and large-landscape outdoor catchment areas. Some variation in the parameter ranges across the hydrologic region was introduced to ensure well-calibrated results for the San Francisco, South Coast, and Tulare Lake hydrologic regions. Table 4-2 shows the parameter ranges used for each hydrologic region.

Table 4-2: Outdoor Urban Irrigation Calibration Parameters by Hydrologic Region

Hydrologic Region (HR)		Lower Threshold (percent)		Root Zone Conductivity (inches/month)		Soil Water Capacity (inches)	
		Min	Max	Min	Max	Min	Max
HR 1	North Coast	40	80	3.9	9.8	5.9	11.8
HR 2	San Francisco	40	80	3.0	7.9	5.9	11.8
HR 3	Central Coast	40	80	3.9	9.8	5.9	11.8
HR 4	South Coast	20	80	3.0	7.9	3.9	9.8
HR 5	Sacramento River	40	80	3.9	9.8	5.9	11.8
HR 6	San Joaquin River	40	80	3.9	9.8	5.9	11.8
HR 7	Tulare Lake	40	80	3.0	7.9	3.9	9.8
HR 8	North Lahontan	40	80	3.9	9.8	5.9	11.8
HR 9	South Lahontan	40	80	3.9	9.8	5.9	11.8
HR 10	Colorado River	40	80	3.9	9.8	5.9	13.8

Notes:
1. Values converted from millimeters/month and millimeters.
2. The same values were used for each land use classification

4.2.3 Evaluate WEAP model for 100 combinations of calibration parameters

The Statewide HR model was connected to the Computer Assisted Reasoning system (CARs) to evaluate agricultural and outdoor urban irrigation demand under 100 different combinations of calibration parameters. CARs was used to specify an experimental design using a Latin Hypercube sampling procedure (Saltelli et al. 2000).[3] Next, CARs evaluated the WEAP model for each of the 100 sets of calibration parameters for each hydrologic region. CARs then collected the agricultural and outdoor irrigation demand results for the historical year period (1998-2005, for agricultural demand, and 1998-2001, for outdoor urban demand) and compared them to historical estimates of irrigation use. Figure 4-1 shows a comparison of average simulated water demand by agricultural crop (y-axis) for each of the 100 calibration parameter sets to the historical estimates of water use (x-axis) for the Sacramento River hydrologic region. Figure 4-2 shows similar results for urban irrigation demand by landscape type (y-axis) for the Sacramento River hydrologic region.

[3] A Latin Hypercube sample is quasi-uniform across the specified parameter ranges. It is designed to efficiently sample across all parameter ranges simultaneously while minimizing large gaps in the sampling space.

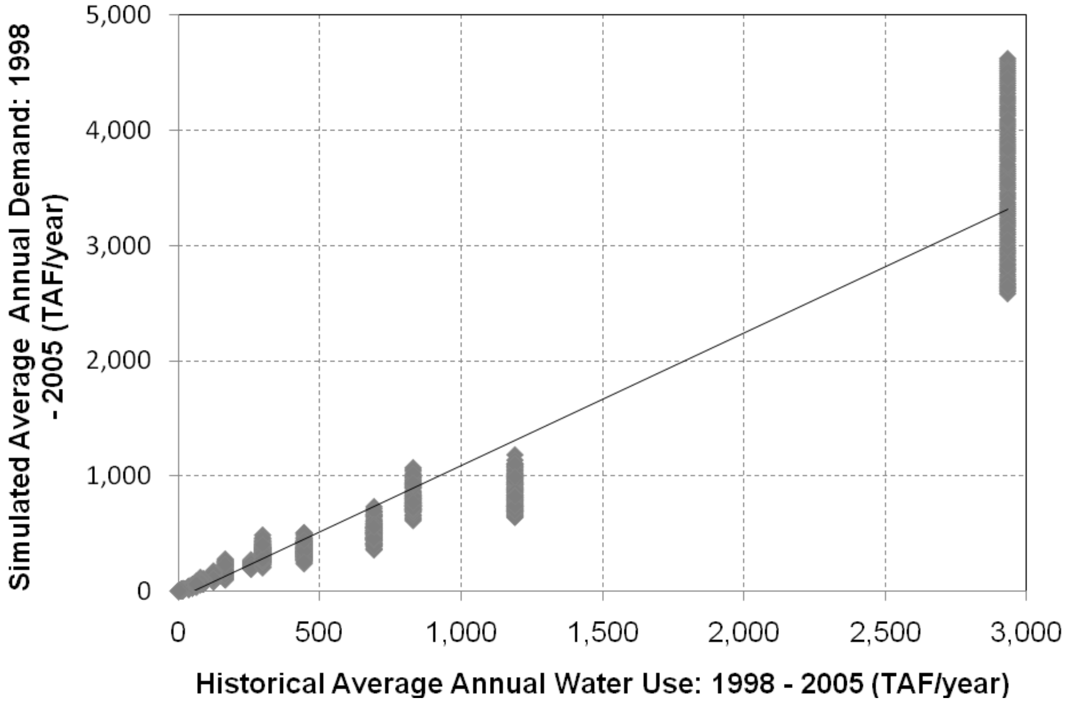

Figure 4-1. Simulated Agricultural Water Demand and Historical Water Use

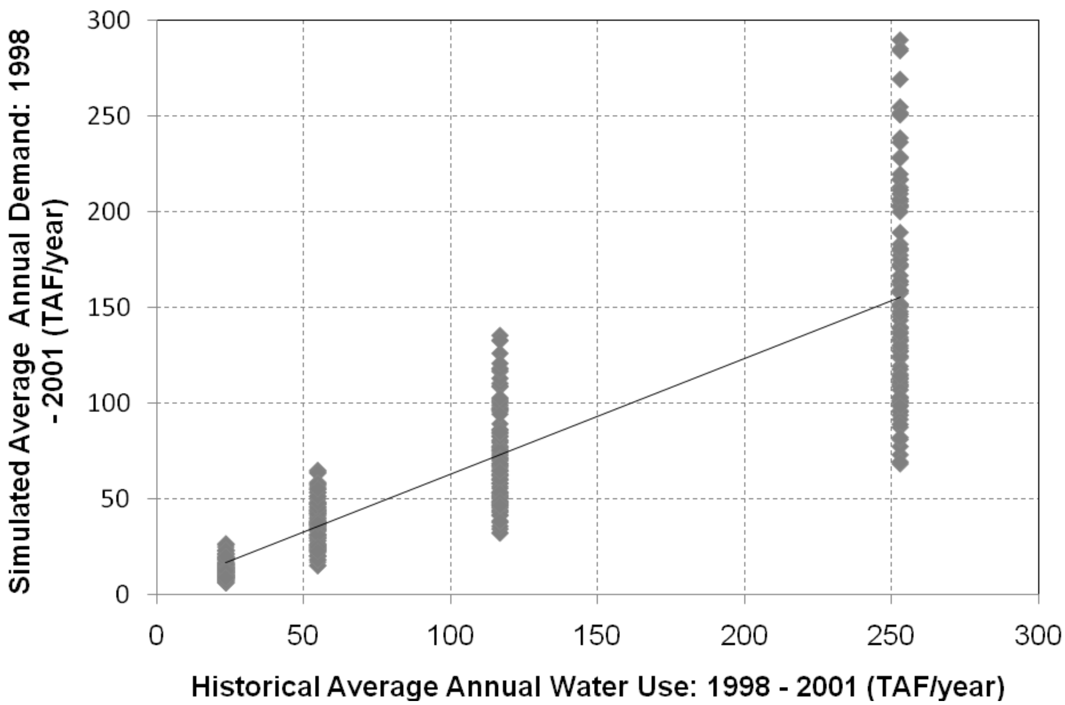

Figure 4-2. Simulated Outdoor Urban Irrigation Demand and Historical Water Use

Lastly, for each (for the agricultural sector) and landscape type (for the urban sector), we identified the set of calibration parameters that minimized the average difference between demand estimated by WEAP and historical use estimates for the calibration period (for each hydrologic region). The set of calibration parameters corresponding to the result that lies most closely to the black diagonal line (indicating equal modeled demand and estimated use) for each crop were selected as the final calibration parameters. Calibration parameters were identified for each crop type and land use type by hydrologic region that produced nearly perfect matches between the historical water use and WEAP-modeled water demand. Figure 4-3 shows the final comparison of average historical agricultural irrigation water use (blue bars) and average simulated agricultural irrigation water demand (red bars) for the Sacramento River hydrologic region. Figure 4-4 shows comparable results for outdoor urban irrigation demand (by urban landscape type) for the Sacramento River hydrologic region.

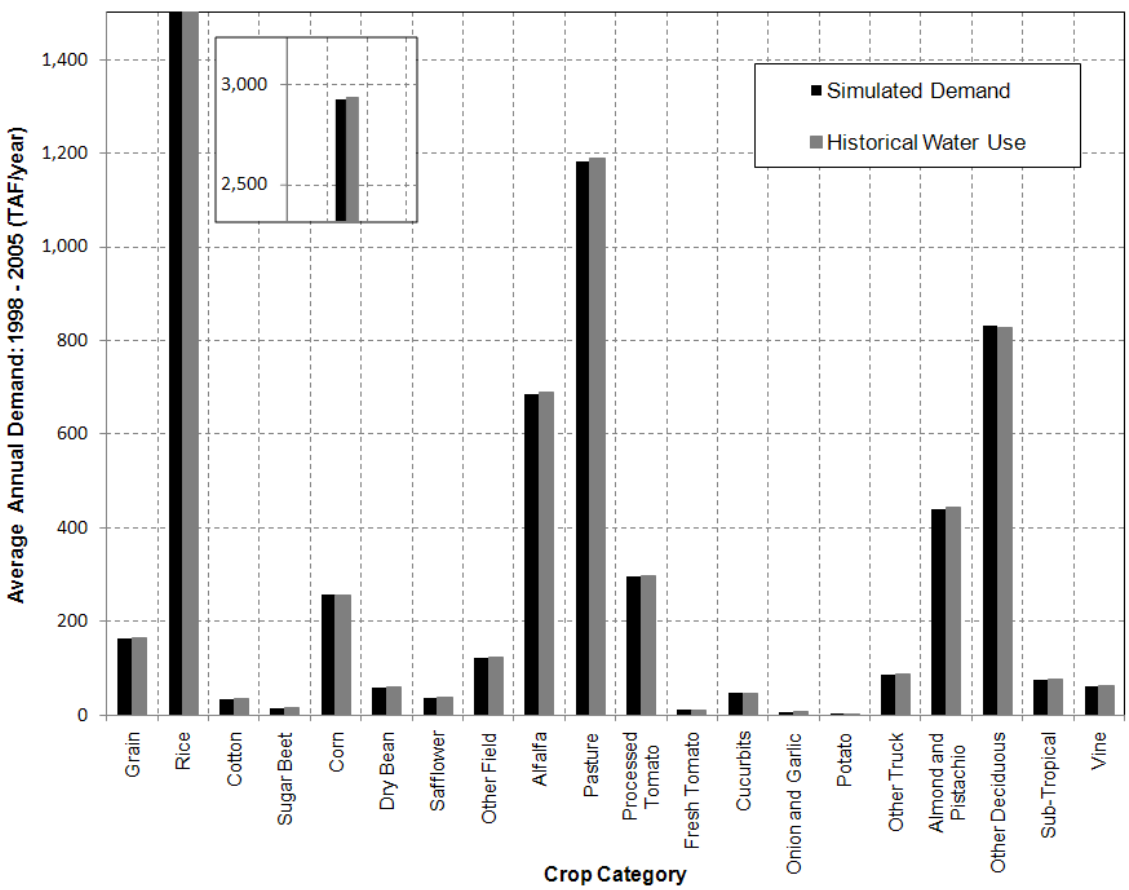

Figure 4-3. Simulated Agricultural Demand and Historical Water Use by Crop

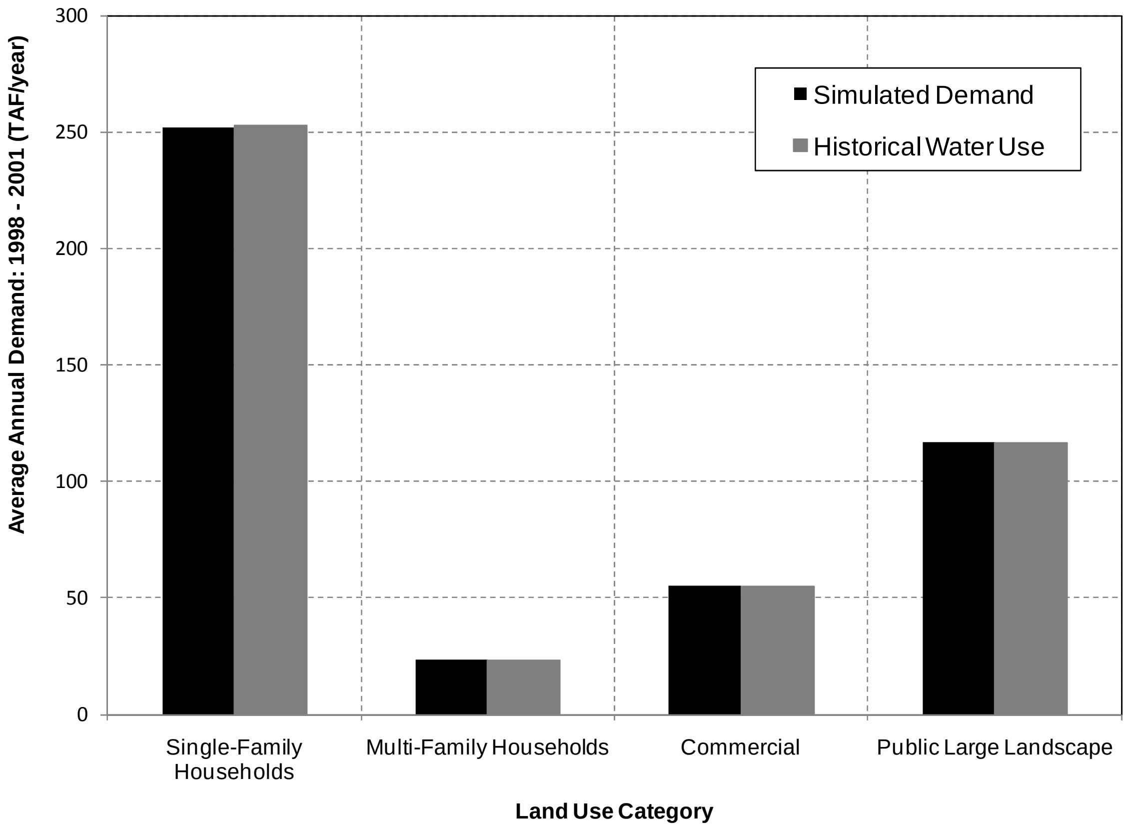

Figure 4-4. Simulated Outdoor Urban Irrigation Demand and Historical Water Use by Sector

4.3 Evaluation of Water Management Scenarios

Using the final outdoor urban and agricultural irrigation calibration parameters, CARs was used to evaluate the WEAP model under different scenarios for the current management system. In contrast to the calibration procedure, a full factorial experimental design was evaluated (e.g. all 36 combinations of the 12 climate scenarios (see section 4.2) and 3 growth scenarios). These results are presented in Chapter 6, Volume 1 of the 2009 CWP.

4.4 Linking the Statewide HR model to Central Valley PA model

One of the goals of the model development is to maintain consistency (as appropriate) between the results of the Statewide HR model results and the Central Valley PA model (described in detail in Section 5). To date, efforts have focused on making demand projections for both models consistent.

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4.6.1 Indoor Water Demand

Due to its increased spatial complexity, the Central Valley PA model does not include logic for calculating how indoor urban demand changes in response to the broad array of scenarios developed for the Statewide HR model. Instead, the Central Valley PA model takes as input estimates of future counts of water demand units (e.g. households and employees) and water use rates that are consistent with the outputs of the Statewide HR model.

Projections of water demand units (DU), e.g. households and employees by year (y) and Planning Area (PA) are calculated by disaggregating the annual projections of demand units by hydrologic region from the Statewide HR model for each growth scenarios (s) using 2005 breakdown of demand units by planning area:

$$DU_{y,PA,s} = DU_{y,HR,s} \times \frac{DU_{2005,PA}}{DU_{2005,HR}}$$

Annual water use rates (UR) by planning area are then calculated by disaggregating annual water demand (D) projections by hydrologic region into demands by planning area using the observed year 2005 shares of demand by planning area, and dividing this by the demand unit by planning area:

$$UR_{y,PA,s} = \frac{D_{y,HR,s} \times {D_{2005,PA}}/{D_{2005,HR}}}{DU_{y,PA,s}}$$

These data are then used by the Central Valley PA model to calculate demand for each planning area and year by multiplying the number of demand units times the use rates:

$$D_{y,PA,s} = DU_{y,PA,s} \times UR_{y,PA,s}$$

These calculations can be readily modified to reflect different water management actions; e.g., reduction of water use rates by a specified percentage.

4.6.2 Outdoor Urban and Agricultural Irrigation Water Demand

As described in Section 4.1, the Statewide HR model estimates outdoor and agricultural irrigation water demand by using scenario-specific estimates of land area by urban land use and agricultural crop type. A calibration procedure then identified estimates for several irrigation-related model parameters for each land use type and crop by hydrologic region that best model historical water use. Finally, the WEAP rainfall-runoff and irrigation algorithms estimated future demand using specified changes in land use and crop type together with scenario-specific estimates of monthly weather conditions.

Because of the temporal resolution of Central Valley PA model, a slightly different procedure was used to calibrate outdoor urban and agricultural irrigation demand. As model development and model application continues, better options for reconciling these two approaches may be found.

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5.0 Central Valley Planning Area Model

The model application described in this chapter employs WEAP to simulate scenarios and evaluate water management response packages for the hydrologic regions located within the Central Valley. Specifically, this integrated hydrology and water operations model, known as Central Valley PA model, is being used to: (1) quantify the small set of handcrafted narrative scenarios developed by the CWP Update staff and advisory committee; and (2) to generate a larger ensemble of plausible scenarios to systematically evaluate the performance of various regional water management response packages in the face of a number of critical uncertainties, including climate change.

5.1 Model Domain

The domain represented by the Central Valley PA model is shown in Figure 5-1. The model primarily represents the Sacramento River and San Joaquin River hydrologic regions. However, the model also represents the major supply and demand drivers that control inter-basin transfers to and from these hydrologic regions. These include climate-driven estimates of water supplies in the upper Trinity River, which may be diverted to the Sacramento River, and agricultural demands on the west side of the Tulare Lake hydrologic region that receive water from the Sacramento-San Joaquin Delta (Delta) via the California Aqueduct.

The Central Valley PA model has been developed at a spatial scale appropriate to simulate major hydrologic flows and exchanges, surface and groundwater storage; to represent major demographic and land-use trends; and to evaluate the effects of water management responses. In general, the model is organized by DWR planning areas. There are 11 planning areas in the Sacramento River hydrologic region and 10 in the San Joaquin River hydrologic region. The 4 planning areas covering the southern Cascade and northern and central Sierra Nevada mountain ranges are further disaggregated along watershed boundaries and elevation bands to identify inflows to major reservoir and simulate elevation or temperature dependent hydrologic processes. For the remaining 17 planning areas, located primarily on the floor of the Central Valley, water demands and water supplies are specified at the planning area level, and only disaggregated as deemed necessary to properly reflect use of different water supplies or to evaluate particular scenarios or water management response packages. Tables 5-1 and 5-2 summarize the level of model disaggregation.

5.2 Network Topology

Examples of the WEAP interface for the Central Valley PA model are presented in Figure 5-2. The Central Valley PA model network is depicted stylistically in Figure 5-3. The model includes the Sacramento and San Joaquin rivers and their major tributaries such as the Pit, Trinity, Feather, American, Mokelumne, and Stanislaus rivers. Each of these tributaries includes a set of catchment objects, which are defined according to land use and elevation band to capture the spatial heterogeneity of the watershed's hydrology for both natural and agricultural areas. A 100-

meter digital elevation model (DEM) and the U.S. Geological Survey (USGS) National Land Cover Data set (NLCD) were used to identify catchments according to 500-meter elevation bands and land-use categories that include forest, non-forest, barren, and urban lands.

Figure 5-1. Central Valley PA model Domain

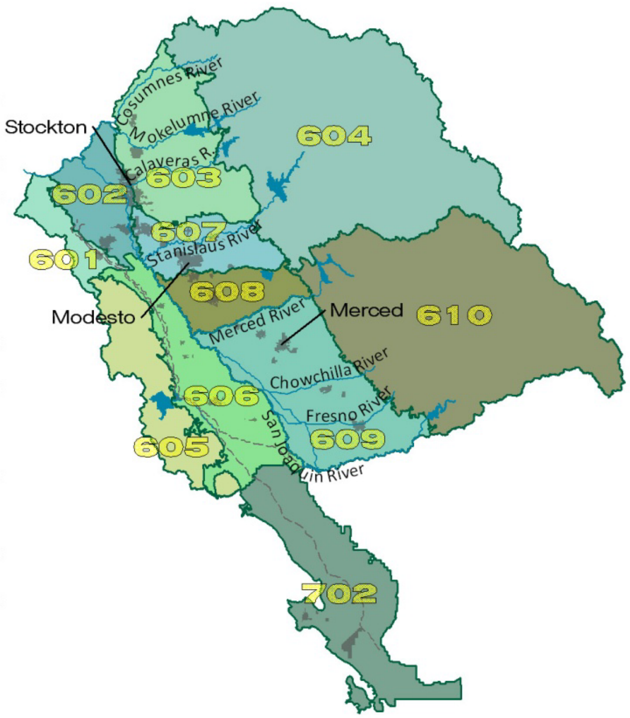
Many of the represented tributaries contain surface reservoirs, with the Central Valley PA model including 23 of the largest reservoirs, representing more than 25 million acre-feet (MAF) of surface storage. Agricultural demands are disaggregated by planning area (see Tables 5-1 and 5-2), while groundwater is broken into 15 basins, which are hydrologically connected to catchments to receive recharge and to the river network to exchange water. Urban land use includes several sub-categories to help identify outdoor urban irrigation demands (turf and garden).

There are 21 flow requirements represented in the model, from relatively simple constraints that describe fish flows on a monthly basis below Shasta Dam, to complex rules in the Delta to meet Delta salinity standards and outflow requirements. The Central Valley PA model includes several major conveyance systems, including Clear Creek and Spring Creek conduits, the Sutter and Yolo bypasses, the California Aqueduct, the Delta-Mendota Canal (DMC), and the Friant-Kern Canal.

Table 5-1. Central Valley PA Model Disaggregation for Sacramento Hydrologic Region

Sacramento River Hydrologic Region	Planning Area	Disaggregation by Watershed	Disaggregation by Demand Area
	501: Shasta – Pit	- Pit River - Upper Sacramento River	None
	502: Upper Northwest Valley	- Cottonwood Creek - Thomes/ Elder Creeks - Stony Creek	None
	503: Lower Northwest Valley	None	503_North: Sacramento River/Clear Creek Diverters 503_South: Sacramento River/Thomes/Stony Creek Diverters
	504: Northeast Valley	None	None
	505: Southwest	- Cache Creek - Putah Creek	None
	506: Colusa Basin	None	506_East: CVP Settlement Contractors 506_West: CVP Agricultural Contractors
	507: Butte-Sutter-Yuba	None	507_East: Feather/Yuba River Diverters 507_West: Sacramento River Diverters
	508: Southeast	- Feather River - Yuba River - Bear River - American River	508_North: Feather River Diverters 508_South: Bear/Yuba River Diverters
	509: Central Basin West	None	None
	510: Sacramento Delta	None	None
	511: Central Basin East	None	None

Table 5-2. Central Valley PA Model Disaggregation for San Joaquin River and Tulare Lake Hydrologic Regions

San Joaquin and Tulare Lake Hydrologic Regions	Planning Area	Disaggregation by Watershed	Disaggregation by Demand Area
	601: Upper West Side Uplands	None	None
	602: San Joaquin Delta	None	602_North: Delta Service Area 602_South: DMC diverters
	603: Eastern Valley Floor	None	603_North: Mokelumne River Diverters 603_South: Stanislaus/Calaveras River Diverters
	604: Sierra Foothills	- Cosumnes River - Mokelumne River - Calaveras River - Stanislaus River - Tuolumne River	None
	605: West Side Uplands	None	None
	606: Valley West Side	None	606_North: DMC Diverters 606_South: CA/DMC /Mendota Pool Diverters
	607: Upper Valley East Side	None	None
	608: Middle Valley East Side	None	None
	609: Lower Valley East Side	None	609_North: Merced River Diverters 609_South: Madera Canal/Fresno-Chowchilla River Diverters
	610: East Side Uplands	- Merced River - Chowchilla/Fresno River - San Joaquin River	None
Tulare Lake	702: San Luis West Side	None	None

Key: CA = California Aqueduct, DMC = Delta-Mendota Canal

5.3 Climate Data

The Central Valley PA model was calibrated and subsequently validated using the gridded, one-eighth degree daily climate data set of Maurer et al. (2002) for the period of 1970 through 2005. This data set was developed for hydro-meteorological modeling applications and includes climate variables used by WEAP to simulate the full hydrologic cycle. For each elevation-banded catchment, a single data point was selected to represent its climate for that band. Monthly precipitation is input as the sum of daily values. Other climate variables include temperature, wind speed, and humidity – each input as monthly mean values for each representative catchment.

5.4 Demands

There are 86 demand areas within the Central Valley PA model. These demands are grouped into four broad categories: agriculture, urban, managed wetlands, and instream flow requirements and are described in the following sections.

5.4.1 Agricultural Demands

Twenty-one irrigated crop categories are modeled for six planning areas located in the Sacramento River hydrologic region (503, 506, 507, 509, 510, and 511), for six planning areas in the San Joaquin River hydrologic region (602, 603, 606, 607, 608, and 609), and one planning area in the Tulare Lake hydrologic region (704). For the remaining planning areas which cover the upland areas in the Sacramento River and San Joaquin River hydrologic regions, irrigated agriculture is represented using two generic agricultural classes: cultivated and pasture. Table 5-4 summarizes the different crop categories considered, and their irrigation schedule and irrigation thresholds. Table 5-5 presents the average depth of applied water for water years 1998, 1999, 2000, and 2001, as reported by DWR's portfolio data. In addition to the 20 crops listed in Table 5-3, a "multi-crop" category was considered. It is assumed that lands under the multi-crop category are irrigated year-round.

To simplify the data input requirements, for model calibration the Central Valley PA model land use does not vary with time, but is held constant. This fixed land use is calculated as the average of the reported cropped acreage for water years 1998, 1999, 2000 and 2001. The observed irrigated land area for the model domain was at a low of 4,422 acres in 2001 and a high of 4,560 acres in 2000 (see Table 5-3). This represents a variation of approximately 1.5 percent around the mean value.

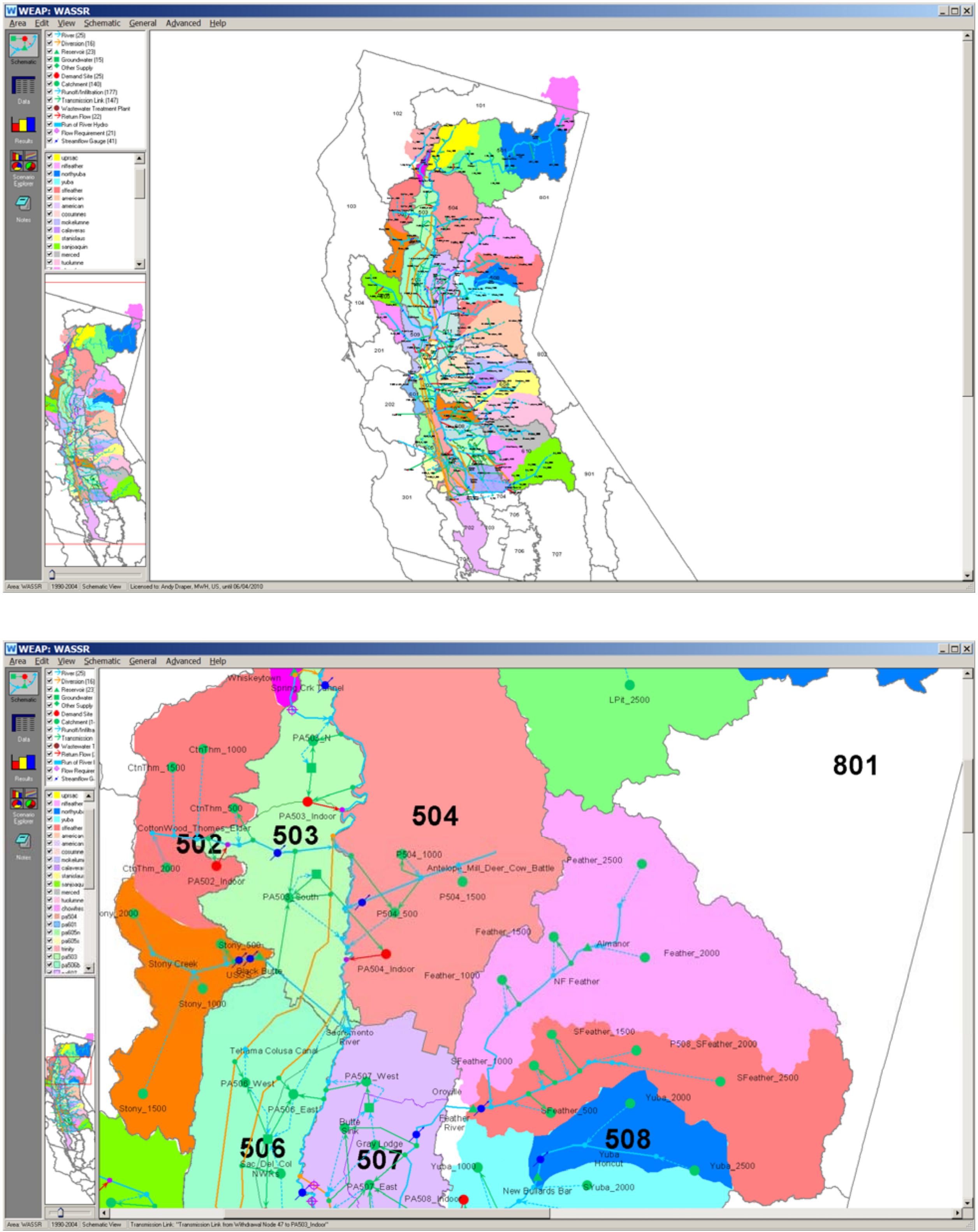


Figure 5-2. WEAP Interface for the Central Valley PA Model

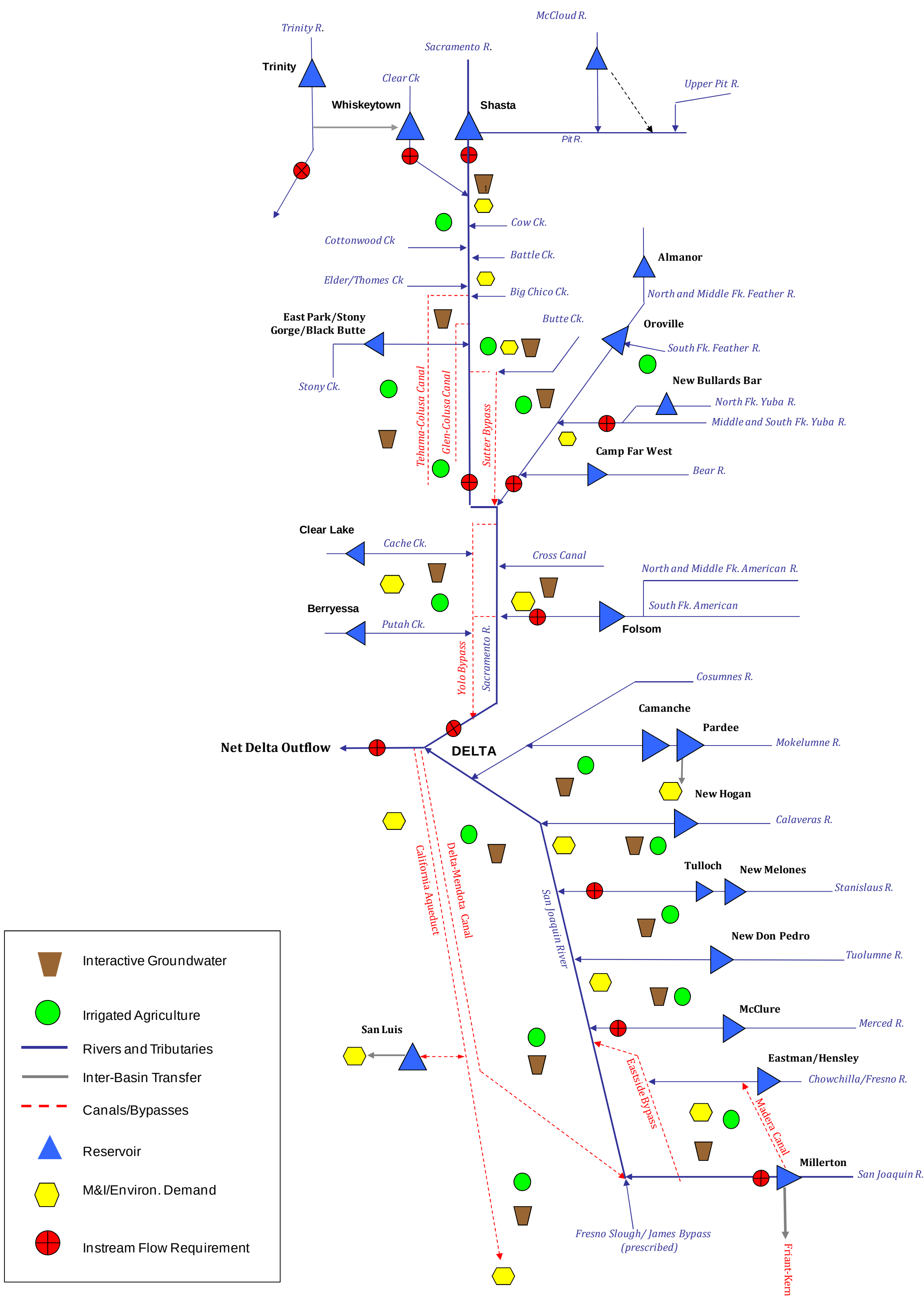


Figure 5-3. Simplified Schematic for the Central Valley PA Model

Table 5-3. Observed Land Use for Central Valley PA Model Domain

Year	Irrigated Crop Area (thousand acres)	Irrigated Land Area (thousand acres)	Multi-Cropping (thousand acres)
1998	4,652	4,538	114
1999	4,659	4,531	129
2000	4,682	4,560	122
2001	4,544	4,422	122
Average	4,634	4,513	122

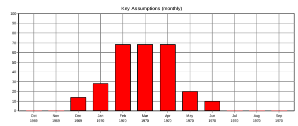
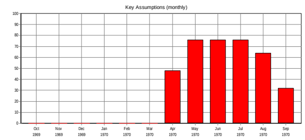
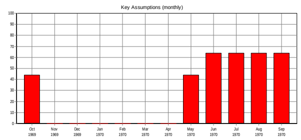
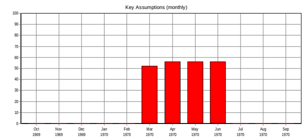
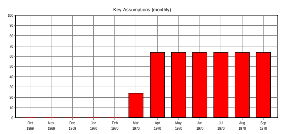
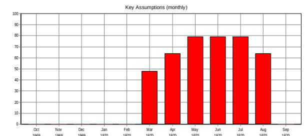
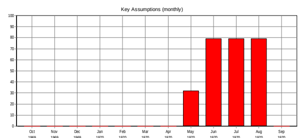
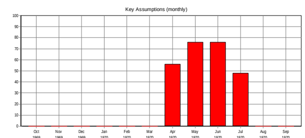
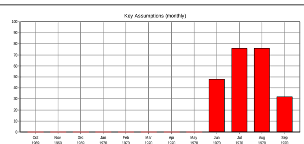
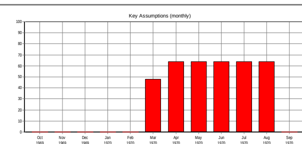
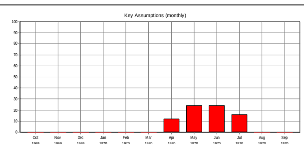
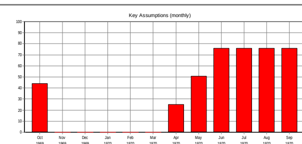
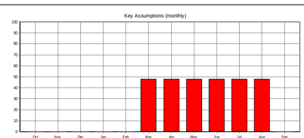
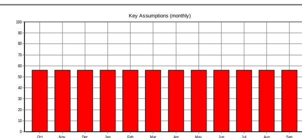
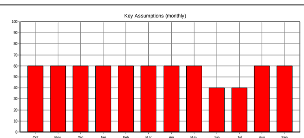
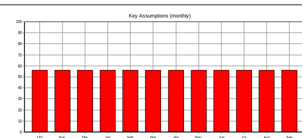
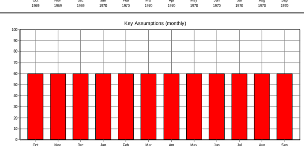
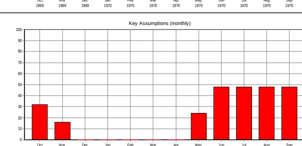
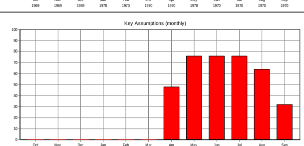
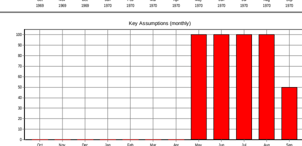
5.4.1 Urban Demands

Municipal and industrial (M&I) demands include both outdoor urban water use for landscape irrigation and indoor urban water use. The indoor urban water use is based on per household and employee water use estimates derived by the Statewide HR model and subsequently disaggregated to the planning area level based on population. Indoor water use is defined on an annual basis. Single family (SF) and multi-family (MF) indoor water use is defined for each planning area in terms of number of households, with a growth-scenario specific annual rate and percentage monthly use rates. Commercial and industrial water use is defined for each planning area based on the number of individuals employed and a growth-scenario specific annual rate and percentage monthly use rates.

Outdoor urban water use is estimated based on analysis of the 2001 NLCD urban land-use classes. The urban area is defined by six land-use categories, five built-up areas consisting of 2 irrigated classes and 3 non-irrigated classes. The built-up, irrigated classes are residential and commercial landscape, while the built-up, non-irrigated land covers are low, medium and high density housing. The non-built category is referred to as open space. It is assumed that the sum of the six land-use classes encompasses the total built-out urban landscape. From this, scenarios about future urbanization assume that the open space urban category either grows or is replaced by declining or growing built-up land classes, respectively.

Hydrologic parameters for the non-irrigated, built-up areas assumed soil water capacities and runoff resistance factors roughly one-quarter those for non-built environments. These parameters lead to greater surface runoff, lower soil moisture, reduced groundwater recharge, and reduced ET. The residential and commercial landscape category is described using “grassland” hydrologic parameters, but with assumed year-round irrigation with irrigation triggered if the soil moisture deficit falls below a specified threshold of 60 percent of saturation. The fraction of irrigated urban landscape is treated as a calibration parameter and set to reproduce the amount of outdoor urban applied water use reported by DWR’s portfolio data.

Table 5-4. Modeled Crop Categories, Irrigation Patterns and Thresholds

Crop	Irrigation Pattern and Threshold	Crop	Irrigation Pattern and Threshold
Grain		Market Tomato	
Cotton		Cucumber	
Sugar Beet		Onion/ Garlic	
Corn		Potato	
Dry Bean		Other Trucked	
Safflower		Almond/ Pistachio	
Other Field		Other Deciduous	
Alfalfa		Sub-Tropical	
Pasture		Vine	
Process Tomato		Rice[2]	

Notes:
1. The y-axis varies from 0 to 100 percent, indicating the crop relative threshold; the x-axis shows the months of the water year. Values on the y-axis greater than zero indicate the crop irrigation period.
2. Rice irrigation includes a characterization of ponding depth and flow -through.
3. The multi-crop category is not shown.

Table 5-5. Estimated On-Farm Applied Water by Planning Area

Crop	On-Farm Applied Water by Planning Area (acre-feet/acre)																					
	501	502	503	504	505	506	507	508	509	510	511	601	602	603	604	605	606	607	608	609	610	702
Grain	1.3		0.4	0.4	0.3	0.8	0.8	1.7	1.2	1.2	1.1	1.1	0.9	0.5			1.2	0.9	1.1	1.1		1.5
Rice	4.7		5.8		4.7	5.5	5.5	5.4	5.5	5.8	5.1			5.3			3.9	5.3		5.3		
Cotton						3.0	3.1		3.1								2.8			2.9		2.6
Sugar Beet	2.4		3.0	3.0		3.3	3.5		3.8	4.1	3.7	4.2	4.1	3.6			1.7		1.7	1.5		3.2
Corn			2.3	2.1	1.8	2.5	2.5		2.9	3.2	2.9	2.8	2.7	2.5			2.6	2.5	2.4	2.4		2.5
Dry Bean			1.8	1.7		2.0	2.2		2.4	2.7	2.3	2.5	2.3	2.2			2.2	2.1	1.9	1.9		1.8
Safflower			0.2	0.4		0.4	0.6		0.7	0.6	0.6	1.3	1.1	0.7			1.3	1.2	0.8	1.2		1.4
Other Field	1.0		1.6	1.7	0.0	2.1	2.0		2.5	2.5	2.4		3.0	2.7			2.7	2.4	2.4	2.4	1.7	1.2
Alfalfa	2.6		3.8	4.0	3.5	4.5	4.3	2.6	5.2	5.3	4.9	5.4	5.1	4.5			4.7	4.6	4.4	4.2		3.9
Pasture	2.6	4.0	4.1	3.5	3.8	4.3	4.7	3.5	5.6	5.8	5.5	5.6	5.5	5.2	4.7		4.7	4.6	4.4	4.4	3.5	4.0
Process Tomato						2.9	2.9		3.1	3.2	3.0	3.3	3.1	2.7			2.0	2.8	2.7	2.1		1.7
Fresh Tomato						2.8			3.0	2.9		2.4	2.2	2.0			1.8	2.3	1.7	1.9		1.5
Cucurbits			1.2	1.2		1.3	1.9		1.8	1.6	1.8	2.0	1.9	1.7			1.9	2.0	2.0	1.6		1.5
Onion/Garlic	2.7					3.4	3.8		4.0	3.6	4.3	2.3	2.5	1.8			2.4	2.2	2.8	2.7		1.8
Potato										2.9			3.0				0.7					
Other Truck	1.9		2.0	2.2	2.1	2.8	2.5	2.1	4.0	2.4	3.9		2.5	3.5	2.0		0.9	1.5	1.0	0.9		1.4
Almond/Pistachio			3.0	2.9	2.8	3.2	3.3		4.2		3.7	4.0	3.7	3.5			3.4	3.5	3.1	3.2		3.7
Other Deciduous	1.6	3.2	2.8	2.3	2.7	3.3	3.7	3.6	4.1	4.5	3.8	4.3	4.1	3.5	3.6		3.4	3.5	3.3	3.3	2.5	4.0
Subtropical		2.4	2.0	1.4		2.6	2.1	2.3	3.6	3.7	3.7			2.8			2.6	3.1	2.8	2.6		3.1
Vine				1.2	1.0	2.3	1.8	1.1	1.9	1.9	2.1	2.1	1.6	1.4	1.4		2.2	1.7	1.9	2.1	1.9	2.5

Note: Missing values indicate that crop in the crop category are not grown within the planning area.

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Using PA 511 as an example, the urban area encompasses approximately 200,000 acres. NLCD reports that roughly 65 percent or 135,000 acres are built-up, with the remainder open space. DWR portfolio data reports that applied outdoor water use ranges from 160,000 to 210,000 acre-feet during the three reporting years. If the average outdoor urban water use is 2.5 acre-feet per acre and if 100 percent of the built-up area were irrigated, this would equate to annual outdoor urban water use in PA 511 of more than 300,000 acre-feet. A parameter for the “fraction of built-up landscape that is irrigated” is introduced to limit the volume of irrigation demand. The residential landscape factor is 60 percent, while the commercial landscape factor is 20 percent.

5.4.2 Instream and Delta Flow Requirements

The Central Valley PA model considers specific river flow requirements for water quality, fish and wildlife, navigation, recreation, downstream, and others through specification of a flow requirement object associated with points on a river or diversion. Flow requirements are treated as a demand and are satisfied in accordance with the user-defined priority structure.

The Central Valley PA model may be used to evaluate major river flows on a monthly basis for each scenario. Flow requirements are evaluated for a variety of locations. Additionally, flow objectives are evaluated for the environmental sites considered in CWP Update 2005 (Rosekrans and Hayden 2003) and flow recommendations contained in the May 2008 California Department of Fish and Game (CDFG) report to the State Water Resources Control Board (SWRCB). These requirements/objectives are summarized in Table 5-6. The Central Valley PA model also includes a schedule of minimum Delta outflow requirements to support and protect estuarine habitat for anadramous fish and other estuarine-dependent species based on the 1995 *Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary* (1995 WQCP) (SWRCB, 1995). These flow requirements vary seasonally and are adjusted depending on year-type.

Table 5-6. Instream Flow Requirements Represented in the Central Valley PA Model

River	Location	Description	Water Year Adjustment
Trinity River	Below Lewiston Dam	Flow protection	Trinity River Index
Clear Creek	Below Whiskeytown Dam	Flow protection	None
Sacramento River	Below Shasta Dam	Anadromous fish restoration	Shasta Storage Index
Sacramento River	Below Shasta Dam	Temperature release	Shasta Storage Index
Sacramento River	Wilkins Slough	Navigation Control Point	Shasta Storage Index
Sacramento River	Rio Vista	Fish and wildlife (1995 WQCP)	Sacramento Valley 40-30-30 Index
Feather River	Below Sunset Pumps	Anadromous fish restoration	None
Yuba River	Below Englebright Dam	Anadromous fish restoration	None
American River	Below Folsom Dam	Anadromous fish restoration	Folsom Storage Index
Stanislaus River	Above mouth	Anadromous fish restoration	Stanislaus River Index
Merced River	Above mouth		None
San Joaquin River	Below Friant Dam	Settlement	San Joaquin Basin Index
Sacramento-San Joaquin Delta	Delta outflow	Fish and wildlife (1995 WQCP)	Sacramento Valley 40-30-30 Index

CDFG defines "managed wetlands" as lands that are "flooded and drained during specific periods of the year utilizing dikes, water control structures, pumps, and/or other structures to enhance wildlife habitat values for specific species." Within the Central Valley, numerous managed wetlands are located within State wildlife area, federal national wildlife refuges, and private lands. For the purpose of the Central Valley PA model, managed wetlands are represented as portions of these larger managed units, which also include non-irrigated areas.

Within the model, wildlife areas and refuges are represented as catchments that are divided into non-irrigated "upland" areas and irrigated "managed wetlands." Managed wetlands are divided further into four subclasses using CDFG classifications. These classifications include seasonal wetlands, which are flooded in the fall and drawn down in the late winter to late spring; semi-permanent wetlands, which are flooded in the fall or winter and retain water into midsummer; reverse-cycle wetlands, which are flooded only during spring and summer months; and permanent wetlands, which remain flooded year-round, with only occasional draw-downs.

For the wildlife areas and refuges, the Central Valley PA model uses WEAP's hydrology module to calculate the partitioning of precipitation and applied water (where applicable) among surface water runoff, interflow, groundwater percolation, ET, and soil water storage. These ET estimates are used together with a ponding routine to estimate water requirements for each managed wetland.

Catchment objects within WEAP contain a ponding routine that represents flooding practices for rice cultivation and wetlands. For each subclass of managed wetlands, a set of parameters controls the timing and magnitude of water deliveries to wetlands. These parameters include a flooding season that defines the time period for water deliveries; a minimum depth of water above the ground surface that is required for healthy plant growth; a maximum depth of water above ground, which is typically the height of a dike that contains water; a target depth of water above ground, which WEAP tries to maintain during the flooding season; and a release requirement, which is flow-through water intended to maintain water temperature and salinity conditions and reduce the risk of disease. These parameters are set uniformly for all wildlife managed wetlands in the model. Parameter values are summarized in Table 5-7.

Table 5-7. Ponding Parameters for Managed Wetlands

	Permanent	**Semi-permanent**	**Seasonal**	**Reverse-Cycle**
Flooding Season	**Oct-Sep**	**Oct-Jul**	**Oct-Mar**	**Apr-Aug**
Minimum Depth (inches)	1	1	1	1
Maximum Depth (inches)	24	24	12	12
Target Depth (inches)	24	24	12	12
Release Requirement (inches)	10	10	6	6

Note: WEAP uses metric units. Reported values are the approximate equivalent in inches

5.5 Operations

The Central Valley PA model attempts to satisfy demands by diverting surface water and pumping groundwater. The extent to which the model is able to meet the full water requirements depends on the availability of surface water supplies, and capacity constraints on canals and groundwater pumping. These limitations on water supply availability and conveyance reflect physical, contractual, and legal constraints and regulatory guidelines that govern system operations. Within the Central Valley PA model, actual operational rules are approximated using a combination of demand priorities, supply preferences, conveyance capacities, and buffer storage coefficients. These are discussed in the following sections.

5.5.1 Connecting Supplies and Demands

As described in Section 3.3, WEAP allocates water to meet demands using a system of demand priorities and supply preferences. In the Central Valley PA model, demand priorities are assigned to each of the 86 demands within the model by demand sector. These demand sectors are defined using four broad water use categories as summarized in Table 5-8.

Table 5-8. Demand Priorities

Demand Sector	Priority
Indoor Urban	1
Managed Wetland	1
Instream Flow	2
Agriculture	3
Outdoor Urban	3

There are 49 surface water and groundwater sources from which the demands can take water. Each demand can draw from a limited set of these supplies, with no demand in the Central Valley PA model having access to more than five water supply sources. For any single demand, there is a preferred order for taking water. The model will deliver water according to these preferences, subject to water supply and conveyance capacity constraints. Physical capacity constraints are expressed in the model as a maximum percentage of the demand that can be delivered from any water supply source. These constraints were estimated by calibrating to historical records (see Chapter 6). Water source, supply preference, and conveyance constraints are summarized for all demands in Tables 5-9, 5-10 and 5-11.

Table 5-9. Urban Demands in the Central Valley PA Model

Demand Area	Water Source	Preference	Maximum Flow (percent of demand)
PA 501	Pitt River	1	100
PA 502	Groundwater	1	100
PA 503	Sacramento River, Trinity Imports	1	100
	Groundwater	2	100
PA 504	Groundwater	1	100
PA 505	Cache Creek	1	100
PA 506	Groundwater	1	100
PA 507	Feather River	1	100
	Groundwater	2	100
PA 508	Yuba River	1	100
PA 509	Groundwater, Putah Creek	1	100
PA 510	Groundwater	1	100
PA 511	American River	1	100
	Sacramento River	1	100
	Groundwater	2	100
PA 601	Sacramento-San Joaquin Delta	1	100
PA 602	Calaveras River	1	100
	Groundwater	2	100
PA 603	Calaveras River	1	100
	Groundwater	2	100
PA 604	Groundwater	1	100
PA 606	Groundwater	1	100
PA 607	Tuolumne River	1	100
	Groundwater	2	100
PA 608	Groundwater	1	100
PA 609	Groundwater	1	100
	Groundwater	1	100
PA 610	Chowchilla/Fresno Rivers	1	100
EBMUD	Mokelumne River	1	100
South Bay[1]	South Bay Aqueduct via California Aqueduct	1	100
San Felipe Unit	San Luis Reservoir via Delta-Mendota Canal	1	100
South Coast	California Aqueduct	1	100

Notes:
1. South Bay demand represents Santa Clara Valley Water District, Alameda County Water District, and Alameda County Flood Control and Water Conservation District (Zone 7)

Key:
EBMUD = East Bay Municipal Utility District
PA = Planning Area

Table 5-10. Agricultural Demands in the Central Valley PA Model

Demand Area	Water Source	Preference	Max Flow (percent of demand)
PA 501	Pitt River	1	100
PA 502 North	Cottonwood/Thomes/Elder Creeks	1	100
PA 502 South	Stony Creek	1	100
PA 503	Cottonwood/Thomes/Elder Creeks	1	17
	Stony Creek	1	17
	Sacramento River	1	17
	Groundwater	2	50
PA 504	Antelope/Mill/Deer/Cow/Battle Creeks	1	100
PA 505 North	Cache Creek	1	100
PA 505 South	Putah Creek	1	100
PA 506 East	Sacramento River	1	40
	Glenn-Colusa Canal	1	40
	Groundwater	2	30
PA 506 West	Tehama-Colusa Canal	1	75
	Groundwater	2	100
PA 507 East	Feather River	1	45
	Yuba River	2	15
	Sutter Bypass	2	15
	Groundwater	3	100
PA 507 West	Sacramento River	1	75
	Groundwater	2	50
PA 508 Feather	Feather River	1	100
PA 508 Yuba	Yuba River	1	100
PA 508 Bear	Bear River	1	100
PA 508 American	American River	1	100
PA 509	Putah Creek	1	30
	Cache Creek	2	10
	Yolo Bypass	2	10
	Groundwater	3	50
PA 510	Yolo Bypass	1	48
	Sacramento River	1	48
	Groundwater	2	100
PA 511	Bear River	1	35
	Sacramento River	1	35
	Groundwater	2	40
PA 601	Local Inflows	1	100
PA 602 North	San Joaquin River	1	90
	Groundwater	2	15
PA 602 South	Delta-Mendota Canal	1	90
	Groundwater	2	15
PA 603 North	Mokelumne River	1	75/25[1]
	Groundwater	2	25/75[1]

Table 5-10. Agricultural Demands in the Central Valley PA Model (continued)

Demand Area	Water Source	Preference	Max Flow (percent of demand)
PA 603 South	Calaveras River	1	40/10[1]
	Stanislaus River	1	40/10[1]
	Groundwater	2	25/75[1]
PA 604 Cos	Cosumnes River	1	100
PA 604 Mok	Mokelumne River	1	100
PA 604 Calaveras	Calaveras River	1	100
PA 604 Stanislaus	Stanislaus River	1	100
PA 604 Tuolumne	Tuolumne River	1	100
PA 605	Local Inflows (no demand)	1	100
PA 606	Delta-Mendota Canal (above check 13)	1	20
	Delta-Mendota Canal (below check 13)	1	20
	San Joaquin River	1	20
	James Bypass	2	20
	Groundwater	3	25
PA 607	Stanislaus River	1	35
	Tuolumne River	1	45
	Groundwater	2	20
PA 608	Tuolumne River	1	40
	Merced River	1	40
	Groundwater	2	20
PA 609 North	Merced River	1	30
	Eastside Bypass	1	30
	Groundwater	2	60
PA 609 South	Chowchilla/Fresno Rivers	1	30
	Madera Canal	1	30
	Groundwater	2	60
PA 610 Merced	Merced River	1	100
PA 610 Ch/Fr	Chowchilla/Fresno Rivers	1	100
PA 610 San Joaquin	San Joaquin River	1	100
PA 702	San Luis Canal	1	40
	James Bypass	2	40
	Groundwater	3	20
	Mendota Pool	4	40
Friant-Kern[2]	San Joaquin River	1	100

Notes:
1. San Joaquin Index > 6 / San Joaquin Index < 6
2. Friant-Kern represents CVP water users in the Tulare Lake Hydrologic Region that receive water from the Friant-Kern Canal

Key:
PA = Planning Area

Table 5-11. Managed Wetland Demands in the Central Valley PA Model

Demand Area	Water Source	Preference	Max Flow (percent of demand)
Modoc NWR	Pitt River	1	100
Ash Creek WA	Pitt River	1	100
Butte Sink NWR	Feather River	1	100
	Sutter Bypass	2	100
Gray Lodge WA	Feather River	1	100
Sutter NWR	Sutter Bypass	1	100
Sacramento/Delevan/Colusa NWRs	Glenn-Colusa Canal	1	100
Stone Lakes NWR	Sacramento River	1	100
Sherman Island WA	Bay-Delta	1	100
San Luis/ Los Banos/San Joaquin/ Volta NWRs, Grassland WD, Mendota WA	Delta-Mendota Canal	1	100
	San Joaquin River	2	100
Merced NWR	Eastside Bypass	1	100

Key:
NWR = National Wildlife Refuge
WA = Wildlife Area
WD = Water District

5.5.2 Reservoirs

As described in Section 3.3, WEAP divides reservoir objects into different storage zones or pools as follows: flood control, conservation, buffer, and inactive. These storage zones are intended to reflect operational guidelines, such as flood control management. Storage zones for reservoirs in the Central Valley PA model are summarized in Tables 5-12 and 5-13. In the model, only the flood control zone is assumed to change throughout the year. This is accomplished by adjusting the maximum storage volume of the conservation storage zone.

Also associated with each reservoir object is a demand priority that is used in the allocation procedure to determine whether water should be held in storage or released for use downstream. The reservoir demand priority is assessed relative to other reservoirs and downstream demands within the model. All reservoir demand priorities within the Central Valley PA model have lower priorities than downstream demands. This implies that the model will attempt to meet all downstream water uses before trying to fill reservoirs.

The extent to which the model releases water from a given reservoir depends on its physical position in the system and its demand priority relative to other reservoirs. For example, a demand that lies downstream from multiple reservoirs (e.g., Delta outflow requirements) will draw water first from reservoirs that have the lowest demand priority. The demand will draw water from other reservoirs only when releases from reservoirs with the lowest demand priority become restricted. These restrictions are imposed in the model using buffer coefficients that limit the amount of water that can be released from a buffer zone in any given timestep. The combination of demand priorities, buffer storage zones, and buffer coefficients serves to limit the amount of surface water that can be released from reservoirs in a manner consistent with recent reservoir management. These model parameters were determined by calibrating the model to delivery records and historical reservoir storage (see Sections 6.2 and 6.3).

Inter-annual variability in water supply motivates many 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. The Central Valley PA 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 Central Valley Project (CVP) and State Water Project (SWP) water contractors. The Central Valley PA model does not calculate annual allocations for these two projects. Instead, the model imposes limits on the amount of water that can be released from reservoirs. When storage drops below certain thresholds (i.e., top of buffer storage) 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.

Table 5-12. Reservoirs Represented in the Central Valley PA Model

Reservoir	River	Demand Priority	Storage Capacity (TAF)	Top of Buffer (TAF)	Buffer Coefficient	Top of Inactive (TAF)
Shasta	Sacramento River	17	4,552	2,700	0.09	502
Trinity	Trinity River	17	2,447	1,500	0.08	10
Whiskeytown	Clear Creek	17	241	200	0.20	0
Almanor	North Fork Feather River	17	1,143	527-827	0.08	0
Oroville	Feather River	20	3,537	2,250	0.09	30
New Bullards Bar	North Fork Yuba River	17	966	600	0.08	50
Camp Far West	Bear River	17	104	62	0.08	0
East Park/Stony Gorge/Black Butte	Stony Creek	17	237	99	0.08	0
Clear Lake	Cache Creek	17	313	250	0.05	0
Berryessa	Putah Creek	17	1,600	900	0.08	0
Folsom	American River	18	977	450	0.13	83
Pardee	Mokelumne River	15	210	126	1.00	16
Camanche	Mokelumne River	16	416	265	1.00	1
New Hogan	Calaveras River	15	317	127	1.00	18
New Melones	Stanislaus River	17	2,420	1,500	0.15	1
Tulloch	Stanislaus River	15	67	40	1.00	11
New Don Pedro	Tuolumne River	17	2,030	1421	1.00	100
McClure	Merced River	15	1,025	615	0.15	0
Eastman/Hensley	Chowchilla/Fresno Rivers	17	240	129	1.00	15
Millerton	San Joaquin River	14	520	364	1.00	135
San Luis – CVP	Offstream	20	971	See Section 5.5.2		45
San Luis – SWP	Offstream	20	1,067	See Section 5.5.2		55

Key:
CVP = Central Valley Project
SWP = State Water Project
TAF = thousand acre-feet

Table 5-13. Reservoir Rule Curves for the Central Valley PA Model

Reservoir	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Shasta	3,450	4,040	4,500	4,500	4,500	4,500	4,500	4,200	3,850	3,550	3,380	3,340
Trinity	2,447	2,300	2,150	1,960	1,960	1,960	2,210	2,447	2,447	2,447	2,447	2,447
Whiskeytown	205	205	205	205	222	240	240	240	240	240	240	222
Almanor	608	575	543	527	546	669	787	827	783	736	684	640
Oroville	3,197	3,197	3,220	3,381	3,450	3,450	3,450	3,450	3,450	3,266	3,186	3,197
New Bullards Bar	525	550	600	643	700	800	950	950	800	650	574	525
Camp Far West	104	104	104	104	104	104	104	104	104	104	104	104
East Park/Stony Gorge/Black Butte	237	168	100	100	146	191	237	237	237	237	237	237
Clear Lake	313	313	313	313	313	313	313	313	313	313	313	313
Berryessa	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600	1,600
Folsom	594	592	596	609	713	818	906	977	977	917	803	667
Pardee	198	193	188	183	188	193	198	203	210	210	210	203
Camanche	284	285	293	297	300	314	350	393	409	410	410	367
New Hogan	253	170	131	141	159	178	243	293	296	296	296	296
New Melones	1,970	1,970	1,970	1,970	1,970	2,030	2,220	2,420	2,420	2,420	2,420	2,270
Tulloch	57	57	57	57	57	59	63	67	67	67	67	64
New Don Pedro	1,690	1,690	1,690	1,690	1,690	1,690	1,709	1,960	2,028	2,030	2,030	1,773
McClure	676	676	676	676	676	737	851	969	1,024	1,024	1,024	851
Eastman/Hensley	166	130	134	143	150	176	215	240	240	240	240	204
Millerton	436	436	436	436	457	520	520	520	520	520	520	520
San Luis – CVP	302	469	637	804	971	971	832	692	553	414	274	135
San Luis – SWP	345	525	706	887	1,067	1,067	917	766	616	465	315	165

Key:
CVP = Central Valley Project
SWP =State Water Project

Reservoir Spills and Flood Bypass Diversions

WEAP generates reservoir spills when storage exceeds the maximum volume allowed in the conservation zone. As previously mentioned, these volumes are generally set using flood control rule curves. Flood releases typically occur in the winter when precipitation and streamflow are greatest.

In the Sacramento Valley, two bypass systems exist to move flood flows around high density urban areas – the Yolo Bypass and Sutter Bypass. Within the Central Valley PA model, three weir structures divert some portion of these high-flow events into the two bypasses. Operational criteria for these structures are summarized in Table 5-14. The lowest demand priority has been assigned to each of these facilities so that they will divert streamflow only when reservoirs are spilling and streamflows exceed defined thresholds. In the San Joaquin Valley, the Chowchilla-Eastside Bypass conveys flood waters in the San Joaquin River around the Mendota Pool to Bear Creek reach of the river. Although this bypass is represented in the model, logic for flood control operations has not yet been added.

Table 5-14. Central Valley PA Model Flood Bypass Diversions

Diversions	Streamflow Threshold (cfs)	Demand Priority
Sutter Bypass[1]	40,000	99
Fremont Weir into Yolo Bypass	62,900	99
Sacramento Weir into Yolo Bypass	8,400	99

Notes:

1. Floodwaters in the Sacramento River overflow the river's east bank into the Butte Basin at three upstream sites in a reach known as the Butte Basin Overflow Area: M&T flood relief structure, 3B's natural overflow site, Goose Lake flood relief structure. Further downstream, flood water is diverted into the Sutter Bypass through the Moulton, Colusa, and Tisdale Weirs.

Key: cfs = cubic feet per second

Shared Storage in San Luis Reservoir

San Luis Reservoir is an off-stream facility located in the eastern part of the Diablo Range, west of the San Joaquin Valley. Water from the Delta is delivered to San Luis Reservoir via the California Aqueduct and Delta-Mendota Canal (DMC) 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 Delta. San Luis Reservoir also provides water to the Santa Clara Valley Water District and the San Benito County Water District. Water is delivered to these users through the CVP's San Felipe Division on the west side of the reservoir.

San Luis Reservoir is set up within the Central Valley PA model to fill during the fall and winter (October through March) and release during the spring and summer (April through September). This is accomplished by using a combination of priorities, target storages, and pumping limits. The priority for storage in San Luis Reservoir is set such that water is pumped into the reservoir only after all other demands (agricultural, urban, and environmental) have been met, including meeting target storage for CVP/SWP reservoirs north of the Delta. The target storage for San Luis Reservoir is set to fill the reservoir from its low point – generally at the end of August – to its maximum capacity (2.04 MAF) by the end of March. From April through September,

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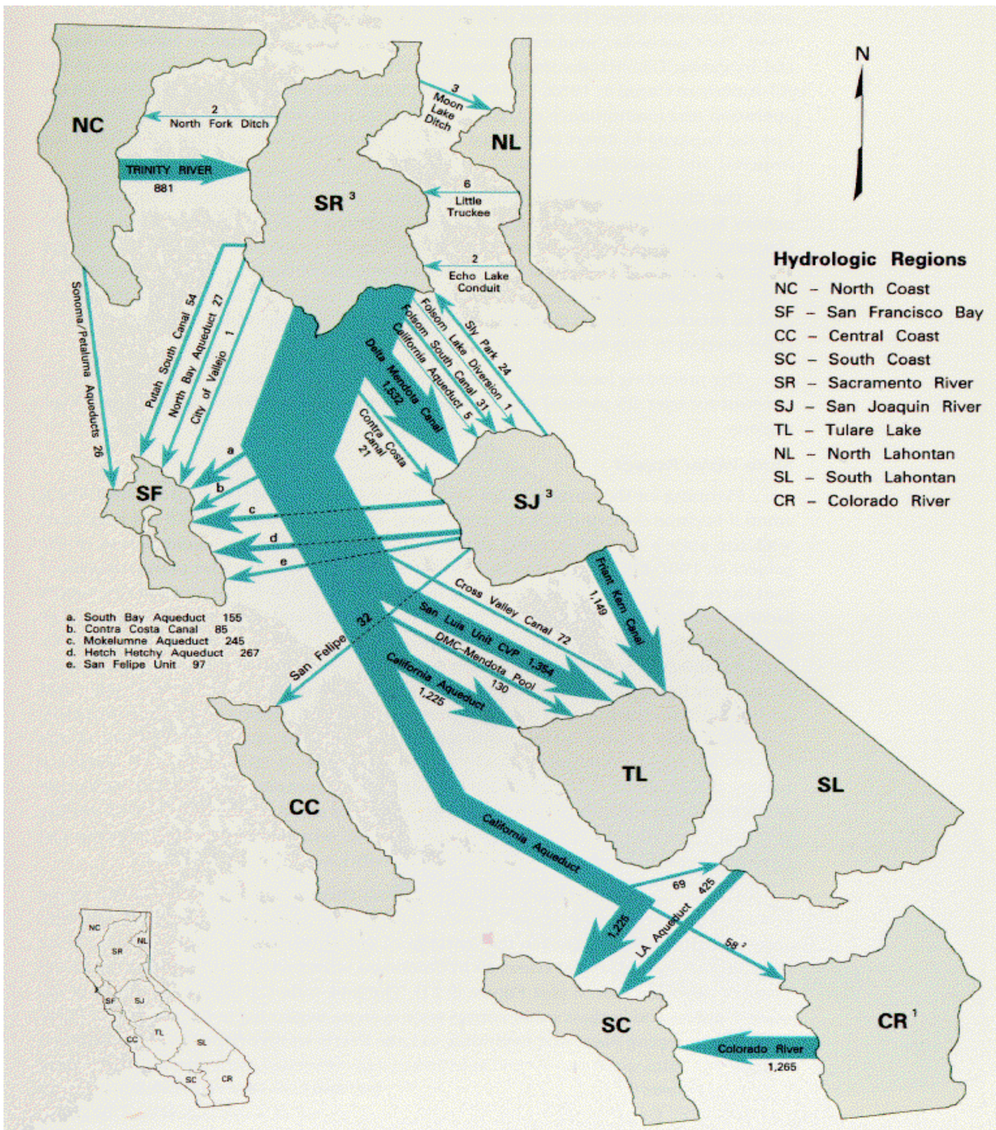
modeled pumping into the reservoir is discontinued and releases are limited to a fraction of the available storage. This fraction increases as the irrigation season proceeds, such that all of the available storage in San Luis Reservoir can be used (i.e., April = 1/6, May = 1/5, June = 1/4, July = 1/3, August = 1/2, and September = 1).

5.5.3 Inter-Basin Transfers

Several local, State, and federal water projects have been built to deliver water from water-rich parts of the State to the arid south. These projects transfer water between watersheds through a complex system of canals and tunnels that have been built over the last century. Figure 5-4 shows average annual volumes of water that are transferred between the State's 10 hydrologic regions. It is clear that many parts of the State rely heavily on water exports from the Sacramento River and San Joaquin River hydrologic regions. These inter-basin transfers have been included in the Central Valley PA model and are described in the following sections.



Source: California Department of Water Resources

Figure 5-4. California Inter-Basin Water Transfers

Delta Export Operations

Exports of water from the Delta represent the largest transfer of water among basins within the State. Two major pumping facilities located at the southern end of the Delta account for the bulk of these transfers – Banks (SWP) and Jones (CVP) pumping plants. Management of these facilities is influenced by many regulatory rules and operational objectives. The regulatory rules include export restrictions during critical migration periods for anadramous fish called for under Section 3406 b(2) of the Central Valley Project Improvement Act (CVPIA), flow objectives for the San Francisco Bay-Sacramento-San Joaquin Delta (Bay-Delta) estuary in accordance with SWRCB Water Rights Decision 1641 (D-1641), and discretionary use of the Environmental Water Account (EWA) to set limits on Delta exports. 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 Central Valley PA model includes restrictions on 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. 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 through May pulse period, when additional reservoir releases are made on tributaries to the San Joaquin River to facilitate juvenile salmon out-migration.

The Central Valley PA model uses a fixed set of rules, applied each year, to simulate b(2) and EWA operations. In practice, these programs include discretionary actions that vary from year to year. Implemented model rules for these programs are as follows:

- Between April 15 and May 15, combined CVP and SWP Delta exports are limited to 1,500 cubic feet per second (cfs).
- For CVP Delta exports, b(2) pulse period restrictions are extended to the end of May and ramped up to 3,000 cfs for June.
- For SWP, assumed EWA actions limit Delta exports at Banks Pumping Plant to 3,000 cfs from May 16 through June 30.

The Central Valley PA model 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 does, however, represent major infrastructural components that distribute surface water within the model domain. Implicitly, many of the principal water users are represented. For example, the main service areas of the DMC and California Aqueduct are modeled as distinct demand areas because the magnitude and seasonal pattern of their demands affect Delta exports and San Luis Reservoir operations. However, for reporting purposes, the aggregated deliveries to water use sectors are considered, and not the deliveries to each water user. Sharing of surplus Delta flows between the CVP and SWP under COA is not modeled. For sharing responsibility to satisfy Delta standards, reservoir storage priorities and buffer coefficients were used to train the model.

Delta Export Demands

The agricultural areas in the western San Joaquin River and Tulare Lake hydrologic regions represent only part of the demands within the CVP/SWP export zone. The SWP serves demands in the San Francisco Bay, Central Coast, South Coast, and Tulare Lake basin. The CVP also serves demands in the San Francisco Bay and Tulare Lake hydrologic regions. These demand areas, which lie outside of the geographic area covered by the Central Valley PA model, are summarized in Table 5-15, and are treated as boundary conditions to the current model.

Table 5-15. Delta Export Demands External to the San Joaquin Hydrologic Region

Demand	Water Source	Conveyance	Hydrologic Region	Average Annual Deliveries[1] (TAF)
Contra Costa WD	Delta	Contra Costa Canal	San Francisco Bay	109[2]
SWP contractors	California Aqueduct	South Bay Aqueduct	San Francisco Bay	102
CVP Contractors - San Felipe Unit	San Luis Reservoir	Santa Clara Tunnel	San Francisco Bay	124
SWP contractors	California Aqueduct	Coastal Branch	Central Coast	97
SWP contractors CVP Contractors - Cross-Canal	California Aqueduct	California Aqueduct	Tulare Lake	1,063 21
SWP contractors	California Aqueduct	East and West branches	South Coast	1,200

Notes:
1. Calculated for water years 1990 – 2005
2. Does not include water diverted under Contra Costa Water District's Los Vaqueros water right

Key: CVP = Central Valley Project, SWP = State Water Project, TAF = thousand acre-feet

For each of these demands, average historical monthly deliveries were used to estimate their total annual demands and their monthly variation. For the calibration period, a multiplier was applied to adjust the annual demands to the observed historical record.

Mokelumne Aqueduct

The East Bay Municipal Utility District (EBMUD) is a publicly owned utility that supplies water and provides wastewater treatment for communities in Alameda and Contra Costa counties on the eastern side of San Francisco Bay in Northern California. In 2000, EBMUD provided 216 million gallons per day (mgd) (approximately 242,000 acre-feet) of water to 1.3 million people. Most of this water was delivered through the Mokelumne Aqueduct, which takes water from Pardee Reservoir on the Mokelumne River. Additional surface water supplies are currently being added through the Freeport Regional Water Project, which will supply up to 100 mgd (approximately 112,000 acre-feet) of water from the Sacramento River during dry years. Both of these diversions are represented in the Central Valley PA model.

Hetch-Hetchy Aqueduct

The Hetch Hetchy Aqueduct conveys water from Hetch Hetchy Reservoir behind O'Shaughnessy Dam to the San Francisco Bay Area via a system of dams, reservoirs, tunnels, pump stations, aqueducts and pipelines. This export from the upper watershed of the Tuolumne River is not currently represented in Central Valley PA model. It is anticipated that this export will be added to the model in future updates. Currently, annual water deliveries to San Francisco through the Hetch Hetchy Aqueduct are approximately 330,000 acre-feet per year.

Friant-Kern Canal

Reclamation operates the CVP Friant Division to provide water from the San Joaquin River to irrigators in the San Joaquin Valley and Tulare Lake basin. The main features of this division are Friant Dam on the San Joaquin River below Millerton Lake; the Madera Canal that carries water north of Millerton Lake to irrigators in Madera County; and Friant-Kern Canal, which carries water south of Millerton Lake to irrigators in Fresno, Tulare, and Kern counties. From 1990 to 2005, the average annual diversion to the Friant-Kern Canal was 1.02 MAF, with a low of 0.46 MAF in 1990 and a high 1.69 MAF in 2005. For the purpose of model calibration, annual demands were set to the observed historical record, and the average historical monthly deliveries were used to estimate the monthly demand variation.

Trinity River Imports to the Sacramento Valley

Reclamation operates the CVP Trinity River Division to move water from the Trinity River to the Sacramento River for export to water-deficient areas of the Central Valley. These diversions are calculated dynamically in the Central Valley PA model by setting the demand priority, buffer storage, and buffer coefficient on Trinity Reservoir such that its storage is balanced relative to other CVP reservoirs in a manner reflecting historical operations.

James Bypass-Fresno Slough

Many of the water users in the San Joaquin Valley receive surface water deliveries from the Mendota Pool, which lies at the confluence of the San Joaquin River with the DMC and James Bypass/Fresno Slough. In dry years nearly all surface water that flows into the Mendota Pool is from the DMC. However, in exceptionally wet years, a significant fraction of Mendota Pool inflow may originate from flood releases from Friant Dam on the San Joaquin River and Pine Flat Dam on the Kings River. A portion of flood releases from Pine Flat Dam are directed north via the Fresno Slough and James Bypass to the Mendota Pool. Pine Flat Dam is not yet represented in the Central Valley PA model, and these inflows are exogenous to the model. For the purposes of model calibration and baseline historical runs, the Central Valley PA model uses historical James Bypass inflows to Mendota Pool.

5.5.4 Delta Water Quality

The Central Valley PA model includes Delta standards that are specified in the 1995 WQCP (SWRCB, 1995) and D-1641 (SWRCB, 2000). Modeled standards for the Delta include the following:

- Net Delta Outflow Index (NDOI), expressed as a flow
- Salinity standards at Emmaton and Jersey Point expressed in electrical conductivity (EC)
- X2 location, expressed in kilometers

The NDOI and the outflow requirements to meet the salinity and X2 standards, combine to determine the minimum required net Delta outflow.

Outflow requirements to meet Delta salinity standards are determined by linking the Central Valley PA model to Contra Costa Water District 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 G-model predicts salinity caused by seawater intrusion at a number of key locations in Suisun Bay and the western Delta as a function of antecedent Delta outflow. The antecedent Delta outflow is a surrogate for directly modeling salinity distribution within the Delta and incorporates the combined effect of all previous Delta outflows. That is, the G-model assumes that salinity is a function of both current outflow and outflows from the previous 3 to 6 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).

The G-model equations were developed under current sea level conditions. Options are being investigated for either updating these relationships to account for projected sea level rise, or alternatively incorporating the Delta Artificial Neural Network (ANN) model developed for CalSim. The ANN model has been trained to handle four sea level rise scenarios (1-foot rise, 2-foot rise, 1-foot rise plus 4-inch amplitude increase, and 2-foot rise plus 4-inch amplitude increase).

The X2 standard is expressed in terms of the location of the 2 parts per thousand (ppt) bottom isohaline as measured in kilometers upstream from the Golden Gate Bridge. To represent this standard, the Central Valley PA model uses the Kimmerer-Monismith equation to compute required net Delta outflow, based on the position of X2 in the previous month (Kimmerer and Monismith, 1992).

5.6 Model Summary

The Central Valley PA model developed to support the CWP Update covers much of the same area and water management features represented in other water planning models used in California, mainly CalSim-II and CALVIN. However, the Central Valley PA model differs from these tools in two important respects.

Firstly, unlike standard water resources planning tools that rely on exogenous information on water supply and demand, the Central Valley PA model uses an embedded watershed hydrology module to calculate water supplies and climate-influenced demands from climate input data. This integration of hydrologic processes into a water resources modeling framework allows for analysis of the future climate scenarios that are not reliant on historical hydrologic patterns. That is, stream flows are derived directly from the future climate scenarios and not from a perturbation of the historical hydrology.

Secondly, the Central Valley PA model contains a rather simplified representation of the rules that guide operations of CVP and SWP facilities. For example, there is no representation of the sharing agreements under COA, no calculation of project allocations based on estimated water supplies, and no limit to surface water deliveries based on contract amounts. Rather, the Central Valley PA model attempts to capture the main features that govern water resources management collectively. This choice was made in response to the main research objective which was to develop a tool that could illuminate high level implications of climate change and potential adaptive management responses. This is in contrast to an objective which would focus on impacts that may be felt by individual water rights and water contract holders.

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6.0 Central Valley Planning Area Model Calibration

This chapter discusses the calibration of the Central Valley PA model, and compares simulated and observed flows and storage across the entire model domain. The components of the model that were calibrated are as follows (the years in parenthesis indicates the period of calibration):

- Inflows to major reservoirs (1970 – 2005)
- Agricultural, urban and managed wetland water use (1998 – 2005)
- Reservoir storage (1998 – 2005)
- Groundwater use and groundwater elevations (1970 – 2005)
- Delta inflows, outflows and exports (1998 – 2005)

Observation data sources used to calibrate Central Valley PA model are presented in Table 6-1.

The Central Valley PA model was also calibrated to observed “impaired” streamflows, including flows along the Sacramento and San Joaquin rivers, diversions to major water uses, and water supply allocations (groundwater versus surface water to meet demands in different water year-types).

6.1 Reservoir Inflows

Historical flows for major tributaries in the Sacramento River and San Joaquin River hydrologic regions were simulated in Central Valley PA model from 1970 to 2005 using historical monthly climate forcing data from the Maurer data set (2002).

The watersheds of the Sacramento River and San Joaquin River hydrologic regions were delineated according to land use and elevation bands, with the land use taken from the USGS’s National Land Cover Database (NLCD) (USGS, 2001). This land-use data set contains more than 20 detailed land categories defined within eight broader types, which include: water, developed (four subclasses); barren (two subclasses); forested upland (three subclasses); shrub land (three subclasses); herbaceous (four classes including grassland); planted/cultivated (two subclasses); and woody wetlands and herbaceous wetlands (eight subclasses). The NLCD 2001 land cover map was aggregated into 6 broad categories, including forested, non-forested, barren, urban, and irrigated agriculture. The urban land-use categories were further subdivided into non-irrigated low-, medium-, and high-intensity covers and the irrigated land uses including residential landscape and commercial landscape.

Table 6-1. Observed Data used for Model Calibration

Metric	Figures and Tables	Location	Data Source
Reservoir Inflows	Figure 6-1	Trinity Lake	Reclamation, Central Valley Operations[1]
		Shasta Lake	Reclamation, Central Valley Operations[1]
		Lake Oroville	CDEC (ORO)[3]
		New Bullards Bar Reservoir[9]	USGS (11413520) North Yuba River below New Bullards Bar Dam near North San Juan[7]; USGS (11413517) North Yuba River low flow release below New Bullards Bar Dam[7]; USGS (11413510) New Colgate Powerhouse near French Corral[7]; CDEC (BUL): New Bullards Bar Reservoir
		Folsom Lake	Reclamation, Central Valley Operations[1]
		East Park/Stony Gorge/Black Butte[10]	Reclamation, Central Valley Operations[1], Corps, Water Control Data System[2]
		Clear Lake[11]	USGS (11451000) Cache Creek near Lower Lake[7]; CDEC (CLA) Clear Lake Storage[3]
		Lake Berryessa	Reclamation, Central Valley Operations[1]
	Figure 6-2	New Hogan Reservoir	Corps, Water Control Data System[2,11]
		Pardee Reservoir	East Bay Municipal Utility District
		New Melones Reservoir	Reclamation, Central Valley Operations[1]
		New Don Pedro Reservoir	Corps, Water Control Data System[2,11]
		Lake McClure	Corps, Water Control Data System[2,11]
		Eastman/Hensley Lakes	Corps, Water Control Data System[2,11]
		Millerton Lake	Reclamation, Central Valley Operations[1]
Applied Water Use	Figure 6-3	Irrigated Agriculture	Water Portfolio Data – Regional Reports (Row 37)[5,6]
	Figure 6-4	Outdoor urban	Water Portfolio Data – Regional Reports (Row 39b, 39d and 42)[5,6]
	Figure 6-5	Indoor urban	Water Portfolio Data – Regional Reports (Row 39a, 39c, 40 and 41)[5,6]
	Figure 6-6	Managed Wetlands	Water Portfolio Data – Regional Reports (Row 38)[5,6]
Reservoir Storages	Figures 6-7 to 6-10	Shasta Lake	CDEC (SHA)[3]
		Trinity Lake	CDEC (CLE)[3]
		Lake Oroville	CDEC (ORO)[3]
		Folsom Lake	CDEC (FOL)[3]
		New Melones reservoir	CDEC (NML)[3]
		New Don Pedro Reservoir	CDEC (DNP)[3]
		Lake McClure	CDEC (MCR)[3]
		Millerton Lake	CDEC (MIL)[3]
		San Luis CVP	CDEC (SLF)[3]
		San Luis SWP	CDEC (LUS)[3]

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Table 6-1. Observed Data used for Model Calibration (continued)

Metric	Figures and Tables	Location	Data Source
Delta Inflows, Outflows and Exports	Figure 6-11	Sacramento River at Freeport	USGS (11447650)[7]
	Figure 6-12	Sacramento River at Freeport plus Freemont and Sacramento weir spills	USGS (11447650)[7,]
	Figure 6-13	San Joaquin River at Airport Way Bridge, near Vernalis	USGS (11303500)[7]
	Figure 6-14	Net Delta Outflow	Dayflow (Q_{OUT})[8]
	Figures 6-15	Banks Pumping Plant	Dayflow (Q_{SWP})[8]
	Figures 6-16	Jones Pumping Plant	Dayflow (Q_{CVP})[8]
	Figure 6-17	Combined Banks and Jones Pumping Plants	Dayflow (Q_{SWP}, Q_{CVP})[8]
Groundwater Basins	Table 6-3 and 6-4	Groundwater deliveries by Planning Area - Sacramento River hydrologic region	Water Portfolio Data, Regional Reports (Rows 27-29)[5,6]
	Figure 6-18 to 6-22	Groundwater elevations	Water Data Library[4]

Notes:

1. http://www.usbr.gov/mp/cvo/
2. http://www.spk-wc.usace.army.mil/
3. http://cdec.water.ca.gov/
4. http://www.water.ca.gov/waterdatalibrary/groundwater/index.cfm
5. http://www.waterplan.water.ca.gov/planningareas/sr/index.cfm
6. http://www.waterplan.water.ca.gov/planningareas/sjr/index.cfm
7. http://waterdata.usgs.gov/ca/nwis/measurements
8. http://www.water.ca.gov/dayflow
9. Inflow calculated from mass balance based on reservoir releases, reservoir evaporation and change in storage.
10. Modeled as a combined reservoir. Inflow to East Park and Stony Gorge reservoirs from Reclamation, inflow to Black Butte from Corps.
11. Some of this data is available on the Corps web site, additional data was obtained directly from the Corps by request.

Key:

CDEC = California Data Exchange Center
Corps = U.S. Army Corps of Engineers
Reclamation = U.S. Bureau of Reclamation
USGS = U.S. Geological Survey

Table 6-2 summarizes the primary hydrologic parameters used in the Central Valley PA model to help characterize the hydrologic response of each catchment, leading to the overall response of the Sacramento River and San Joaquin River hydrologic regions. Model parameters were determined through a trial-and-error process, with initial values of soil water capacity set at twice the maximum effective precipitation depth. For example, over forested and non-forested land covers, the maximum monthly effective precipitation was approximately 14 and 8 inches respectively, therefore, soil water capacities were set at 28 and 16 inches, respectively, with final values as shown in Table 6-2[4]. Initial values of hydraulic conductivity were based on summer low-flow conditions. Most of the Sacramento and San Joaquin river tributaries do not have substantial flow in late summer, suggesting relatively undeveloped soils with marginal water retention capacity, and leading to a low relative soil moisture state by summer's end.

WEAP is based on a continuous accounting of the soil moisture storage, where the soil water state is considered unsaturated when $Z = 0.0$, and fully saturated, when $Z = 1.0$ (see Figure 3-3). To estimate initial conductivity values, it was assumed that average relative water storage during the low-flow period corresponded to a value of $Z = 0.10$ and using the historical average low-flow volume of several streamflow observations, an initial value of hydraulic conductivity (Hc) of 7 inches/month was calculated. Final conductivity values shown in Table 6-2 were achieved through a manual, trial-and-error process. It was assumed that non-forested and barren conductivity values were higher than forested land covers. Greater soil water capacity and higher conductivity will lead to lower peak flows and higher base flows. Forested land covers have greater soil water capacities and slightly lower conductivities, and thus tend to retain soil water longer into the summer months than non-forested and barren types. Given the lumped nature of the two-bucket hydrologic model in WEAP, it was decided to apply the same parameter values across all catchments.

Table 6-2. Central Valley PA Model Land Cover Classifications and Final Parameters

	Soil Water Capacity (inches)	Hydraulic Conductivity (inches/month)	Runoff Resistance Factor	Irrigated
Urban				
Low-Intensity	4	8	1.0	No
Medium-Intensity	4	8	1.0	No
High-Intensity	4	8	1.0	No
Commercial Landscape	14	6	5.0	Yes
Residential Landscape	14	6	5.0	Yes
Natural Vegetation				
Forested	28	6	4.0 to 7.0	No
Non-Forested	18	8	5.0	No
Barren	10	10	3.5	No
Agriculture				
Pasture	20	5	6.0	Yes
Cultivated	26	8	4.0	Yes

[4] Soil water capacity in WEAP is the max depth of water that can be stored in the root zone for plant consumptive use. It is a function of soil texture and plant rooting depth. Plants with deeper rooting depth (forest trees) will have larger available water (higher Z value).

Figure 6-1 shows the major reservoirs north of the Delta that are represented in the Central Valley PA model. Figure 6-2 presents a comparison of observed and simulated inflows to these reservoirs, including the following:

- Trinity Lake on the Trinity River
- Whiskeytown Reservoir on Clear Creek
- Shasta Lake on the Sacramento River
- Lake Oroville on the Feather River
- New Bullards Bar Reservoir on the North Fork of the Yuba River
- Camp Far West Reservoir on the Bear River
- Folsom Lake on the American River
- Combined East Park, Stony Gorge and Black Butte reservoirs on Stony Creek
- Inflow to Clear Lake on Cache Creek
- Inflow to Lake Berryessa on Putah Creek

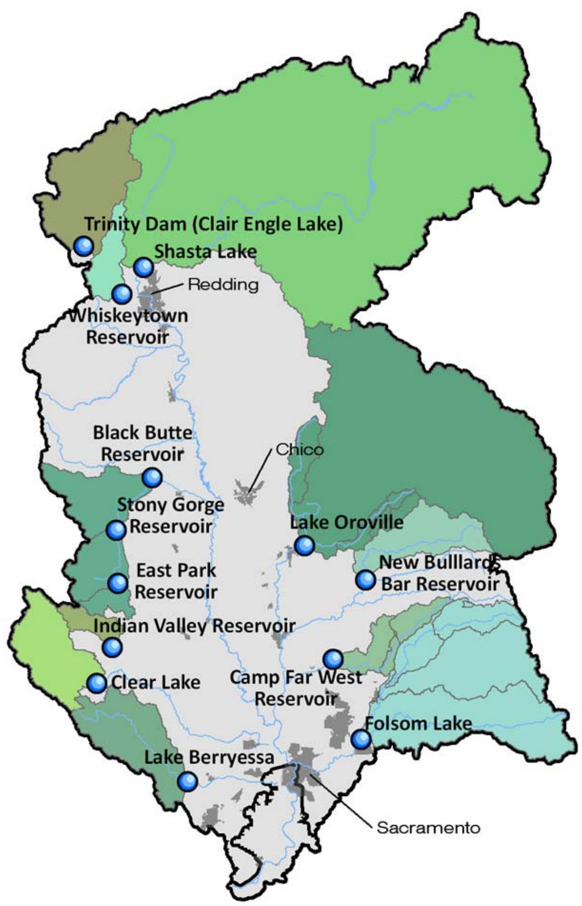


Figure 6-1. Major Reservoirs North of the Delta

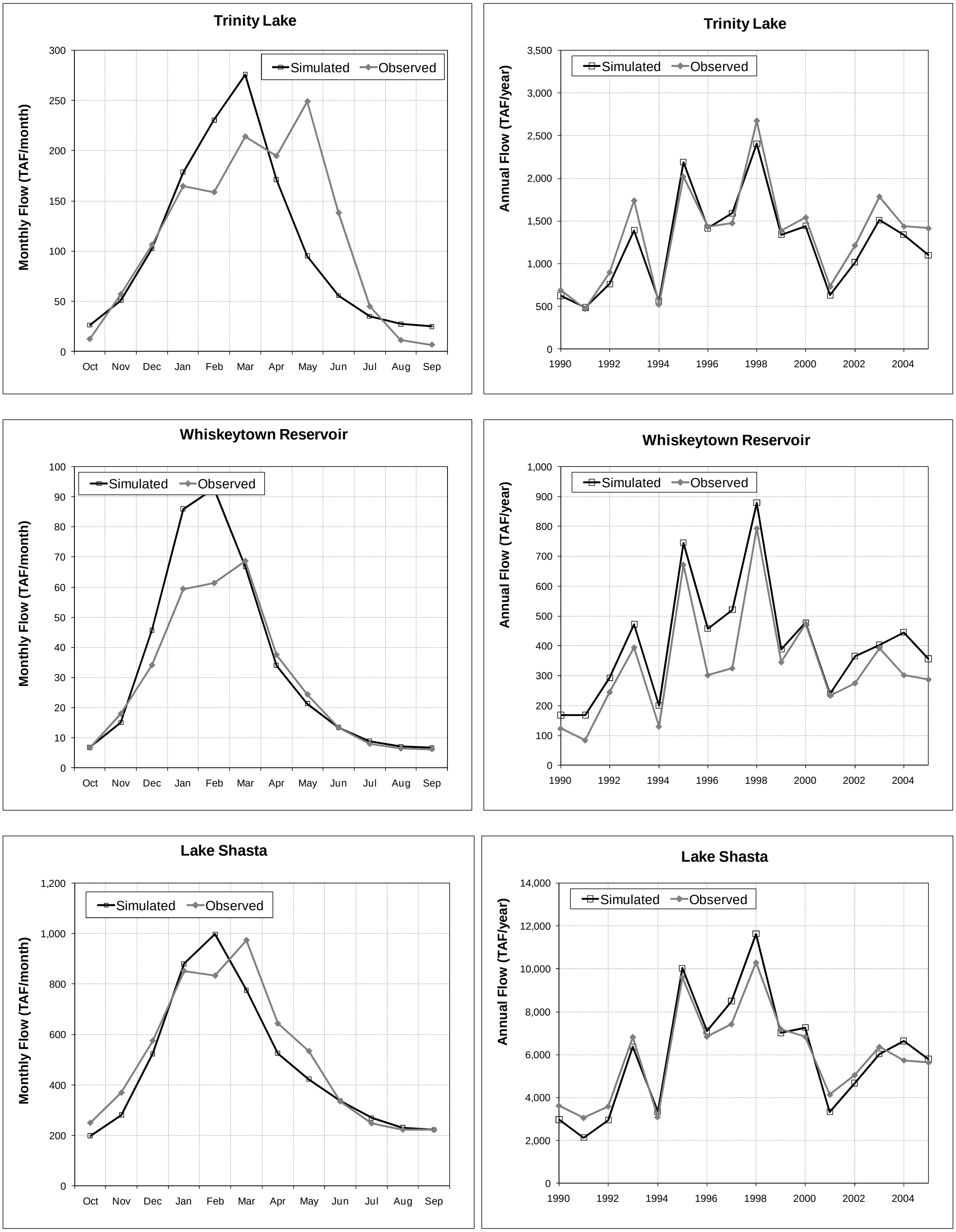


Figure 6-2. Simulated and Observed Reservoir Inflows for the Trinity River and Sacramento River Hydrologic Region

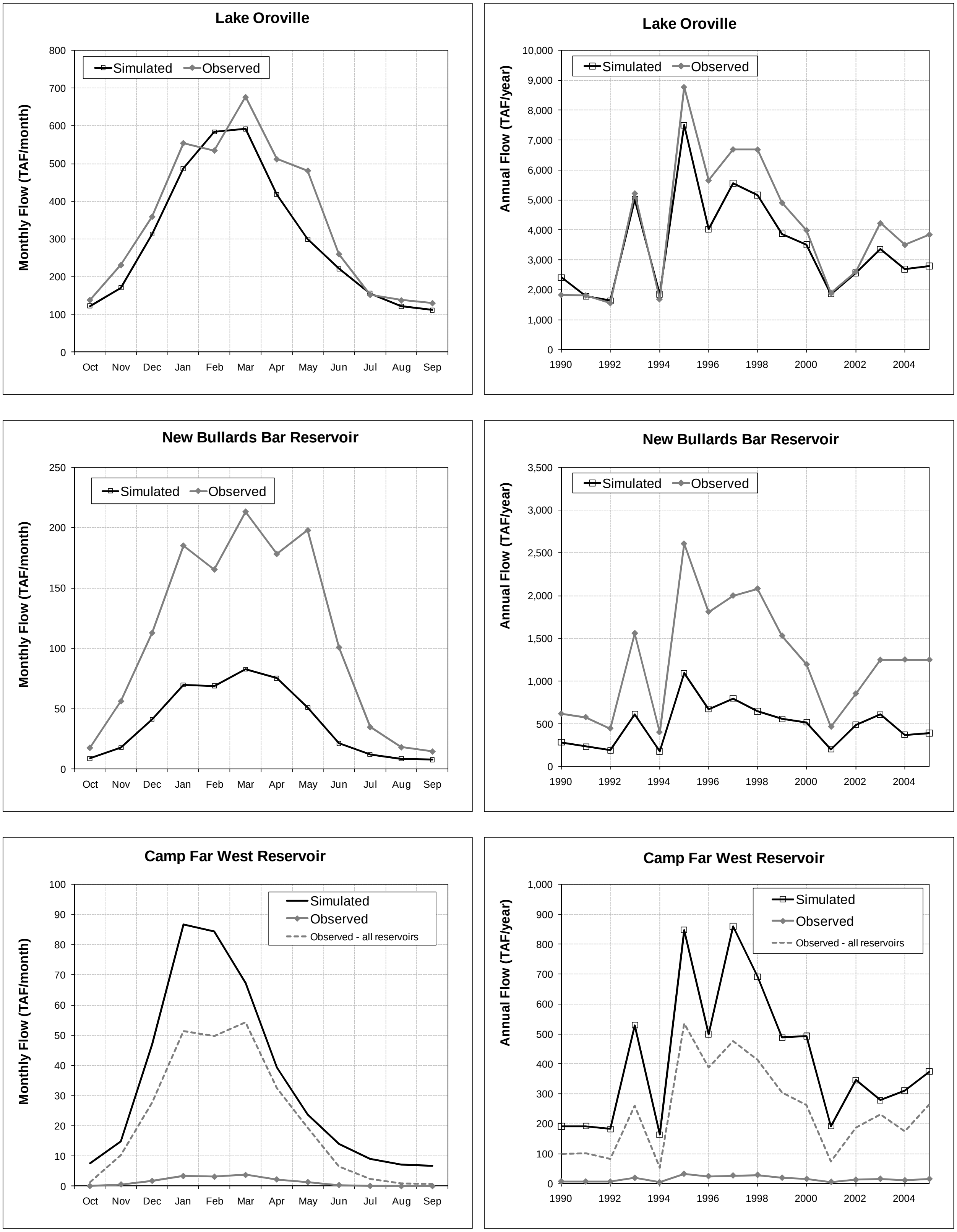


Figure 6-2. Simulated and Observed Reservoir Inflows for the Trinity River and Sacramento River Hydrologic Region (continued)

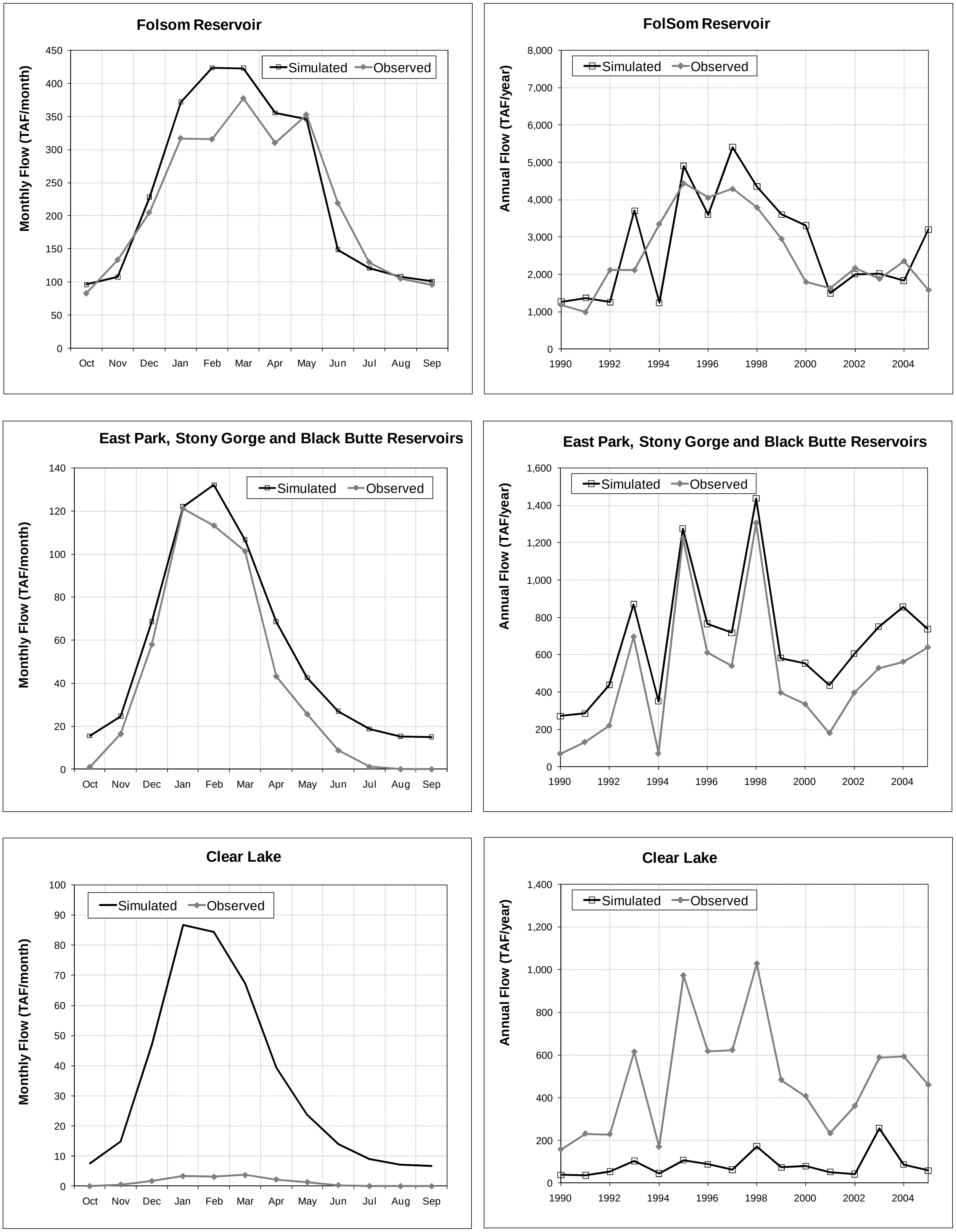


Figure 6-2. Simulated and Observed Reservoir Inflows for the Trinity River and Sacramento River Hydrologic Region (continued)

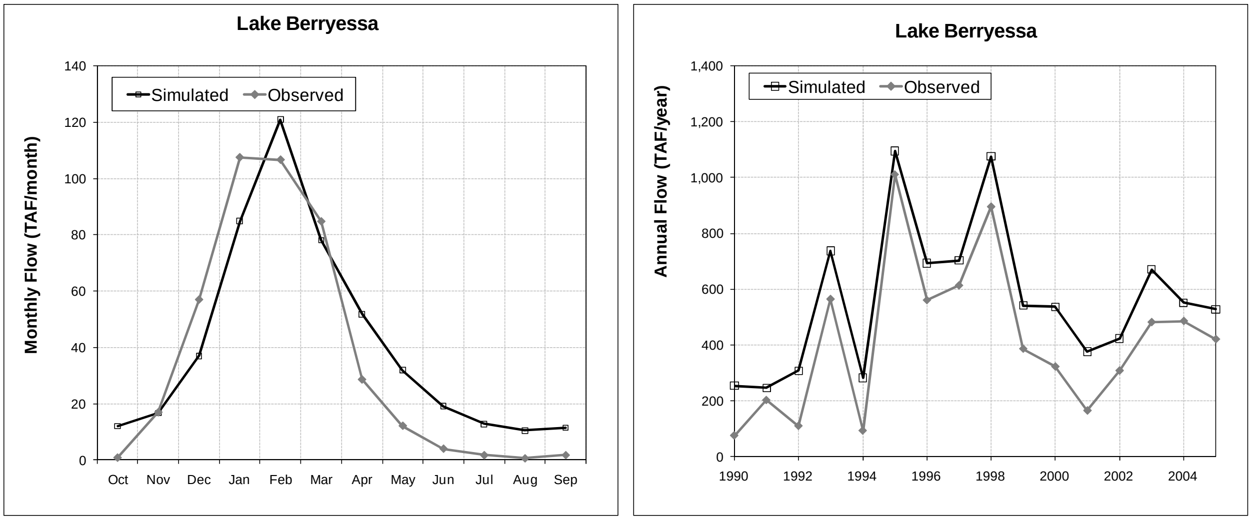


Figure 6-2. Simulated and Observed Reservoir Inflows for the Trinity River and Sacramento River Hydrologic Region (continued)

Following quality assurance checks on the Central Valley PA model, errors were discovered on the inflow calculations to New Bullards Bar Reservoir and Clear Lake. Inflows to these two watersheds need to be recalibrated. Similarly, representation of the Bear River needs to be refined to better simulate water transfers, diversions, return flows and storage regulation upstream of Camp Far West Reservoir.

Figure 6-3 shows the major reservoirs south of the Delta that are represented in the Central Valley PA model. Figure 6-4 presents a comparison of observed and simulated inflows to these reservoirs, including the following:

- Pardee Reservoir on the Mokelumne River
- New Hogan Reservoir on the Calaveras
- New Melones Reservoir on the Stanislaus River
- New Don Pedro on the Tuolumne River
- Lake McClure on the Merced River
- Combined Eastman and Hensley lakes on the Chowchilla and Fresno rivers
- Inflow to Millerton Lake on the San Joaquin River

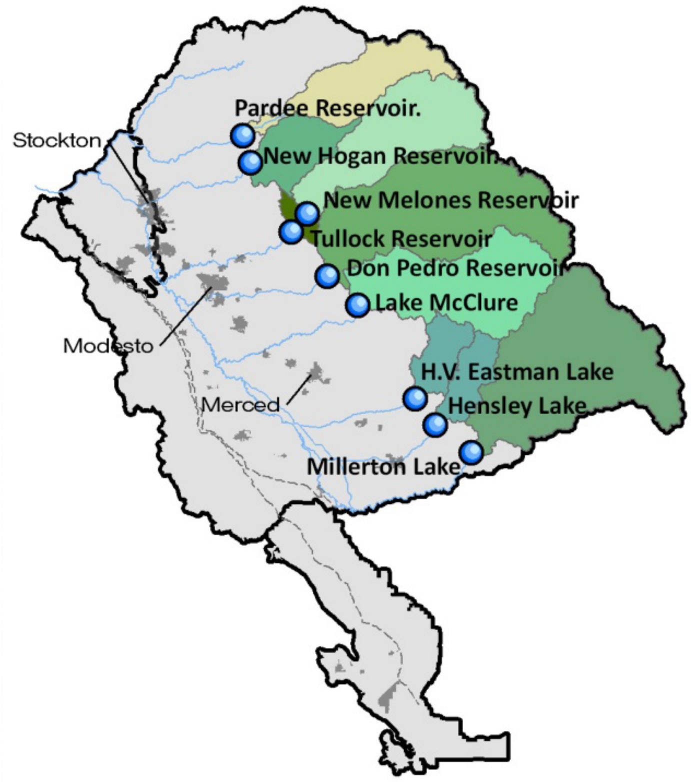


Figure 6-3. Major Reservoirs South of the Delta

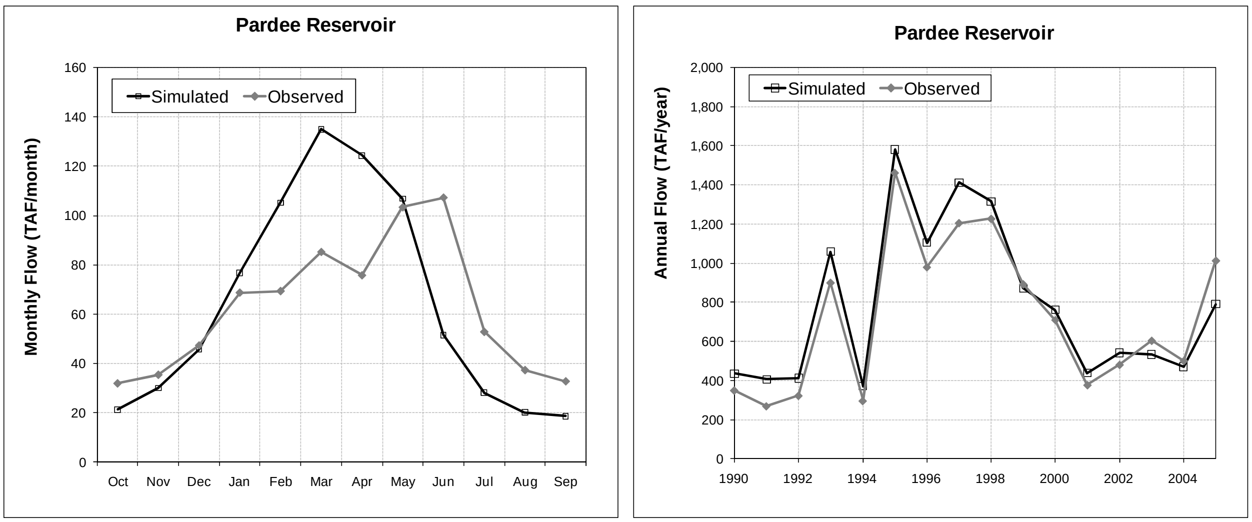


Figure 6-4. Simulated and Observed Reservoir Inflows for the San Joaquin River Hydrologic Region

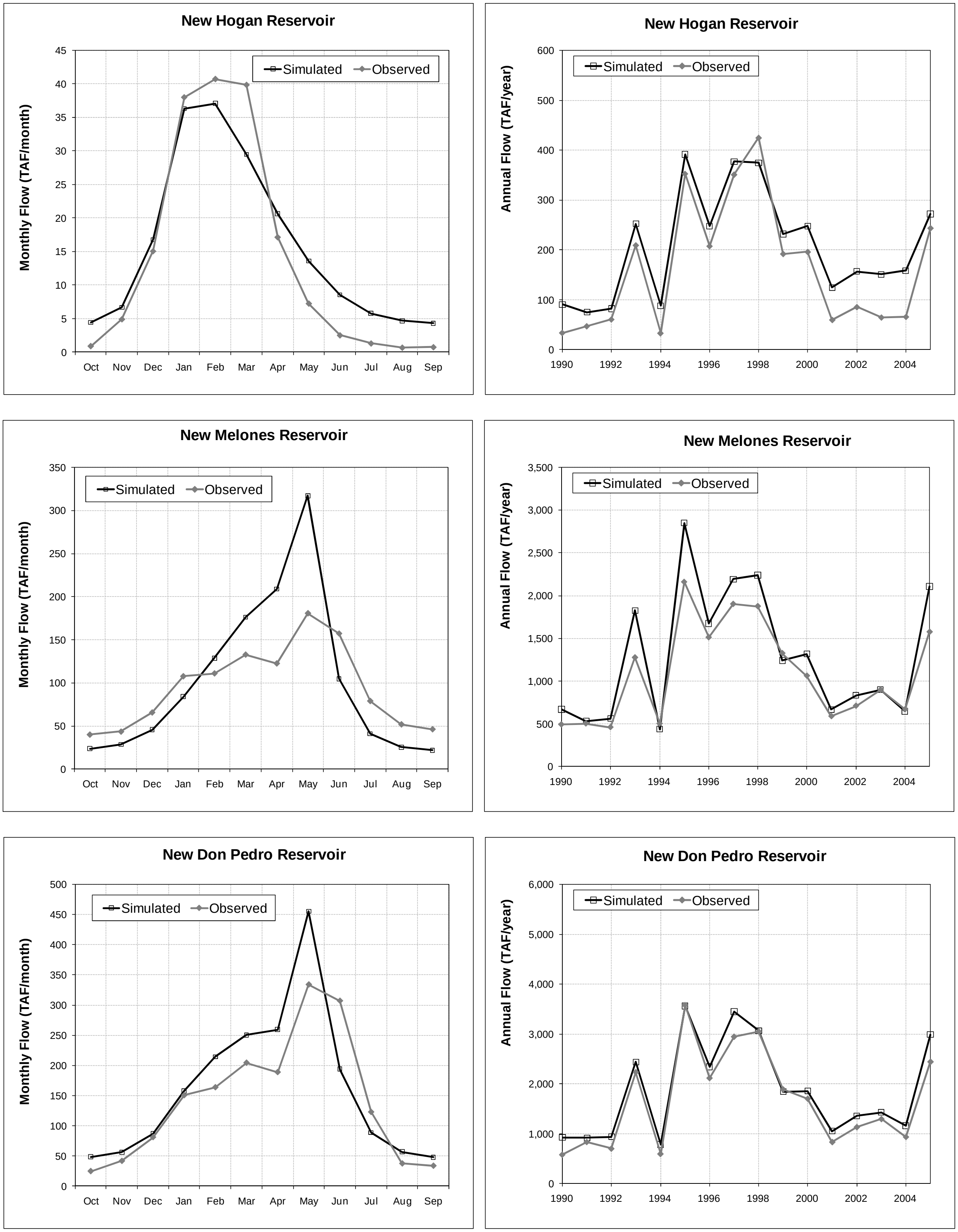


Figure 6-4. Simulated and Observed Reservoir Inflows for the San Joaquin River Hydrologic Region (continued)

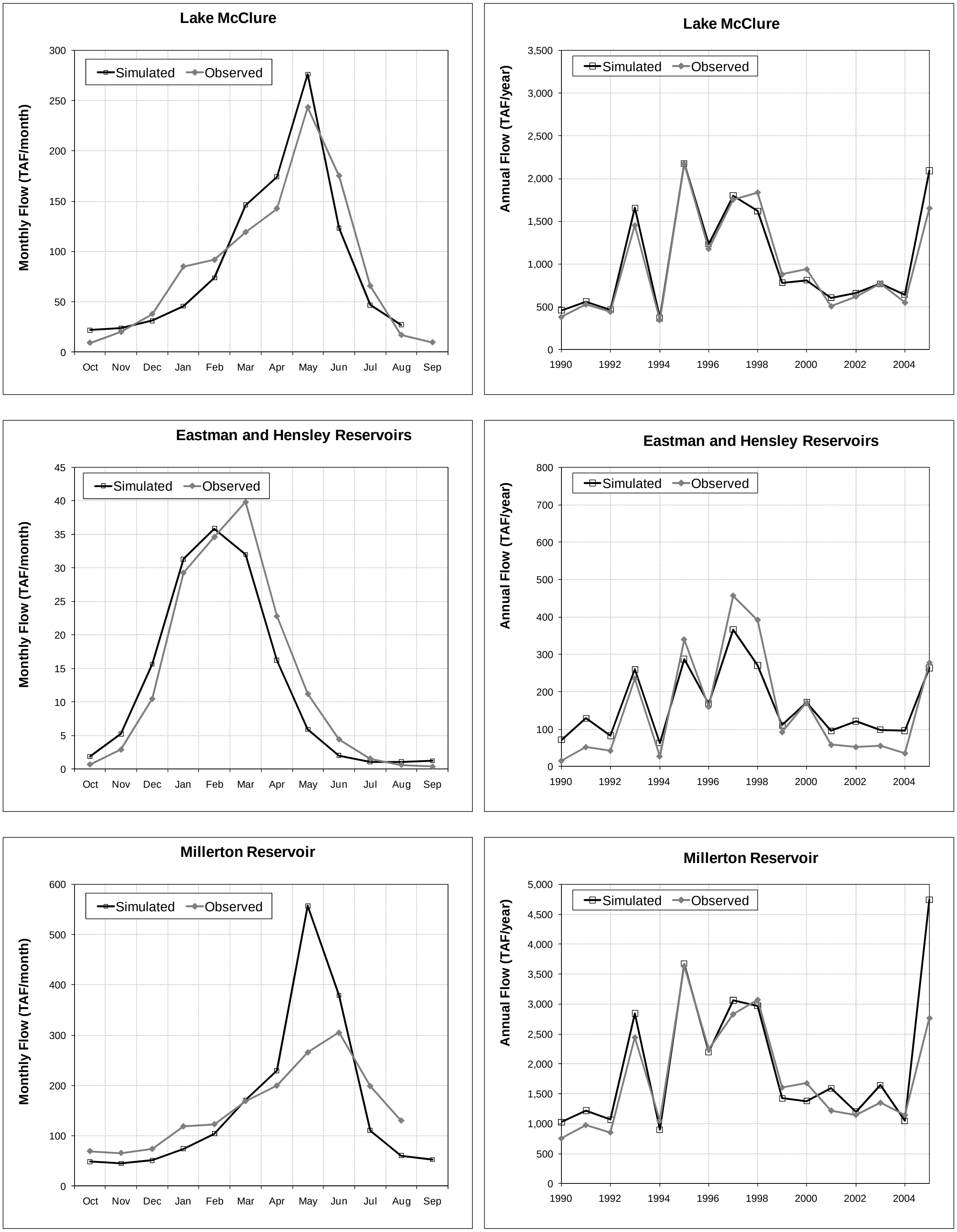


Figure 6-4. Simulated and Observed Reservoir Inflows for the San Joaquin River Hydrologic Region (continued)

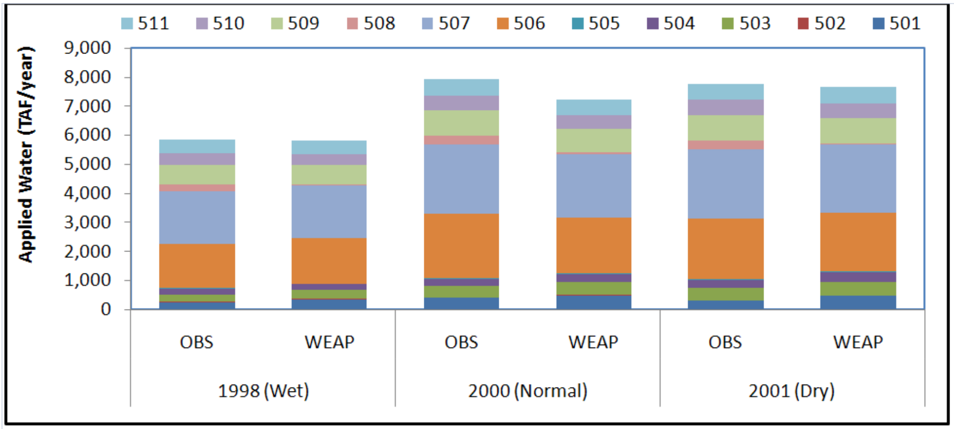
6.2 Water Use

The Central Valley PA model demand was calibrated to estimated demands from DWR's water portfolio data set for water years 1998 to 2005, but with particular focus on water years 1998, 2000, and 2001, as more detailed data have been reported and developed for these years. Water year 1998 was wet, 2000 above normal and 2001 was dry (Sacramento Valley and San Joaquin Valley hydrologic indices). Outdoor urban and agricultural irrigation demands were calibrated by adjusting soil and crop-specific parameters so that simulated annual applied water use and monthly patterns of use more closely matches DWR portfolio data estimates.

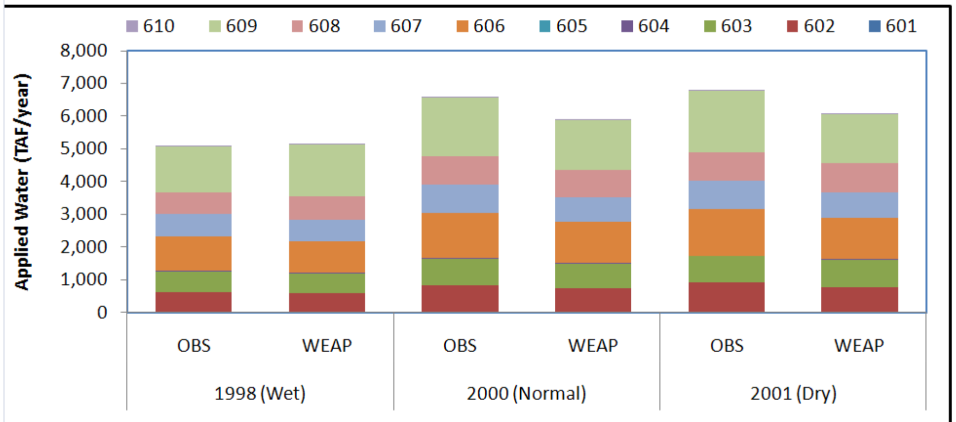
The Central Valley PA model considers 3 general categories of water use: irrigated agriculture, urban, and environmental. Urban applied water includes both indoor and outdoor water use, while environmental uses include managed wetlands, instream flows, and Delta outflow. Water demands for agricultural, outdoor urban and managed wetlands are climate driven in the Central Valley PA model by making use of WEAP's catchment object. Figures 6-5 through 6-8 compare estimated applied water use as reported in DWR portfolio data, and the Central Valley PA model simulated water use disaggregated by hydrologic region and planning area. Generally, the Central Valley PA model captures total applied water use, with slight under-prediction in the dry years.

The Central Valley PA model uses static land use and cropping patterns for the period of calibration; therefore, the urban footprint and crops planted and irrigated in 1998 are the same as in 2000 and 2001. Simulated changes in water demand are driven primarily by climate fluctuations. The impact of this variability, however, is masked somewhat by delivery variability because of supply limitations and operational constraints.

Figure 6-7 presents indoor urban applied water use for 1998, 2000, and 2001. These values reflect indoor urban demands that were fixed at 2000 levels until the year 2000, after which they were interpolated to 2005 levels. Figure 6-8 shows the applied water use of managed wetlands. This use is dominated by planning areas 506, 507, and 606, with total use less than 1.0 MAF.



Planning Area	1998 (Wet) OBS	1998 (Wet) WEAP	2000 (Normal) OBS	2000 (Normal) WEAP	2001 (Dry) OBS	2001 (Dry) WEAP
501	256	363	409	495	318	486
502	8	4	10	6	10	6
503	265	332	397	449	416	472
504	173	170	237	282	257	307
505	45	26	47	34	51	38
506	1,503	1,558	2,195	1,892	2,083	2,025
507	1,820	1,836	2,391	2,201	2,384	2,339
508	243	31	310	45	283	48
509	656	648	872	817	876	868
510	405	388	506	473	549	511
511	469	456	555	525	554	553
Total Sacramento River HR	5,841	5,811	7,927	7,217	7,782	7,654



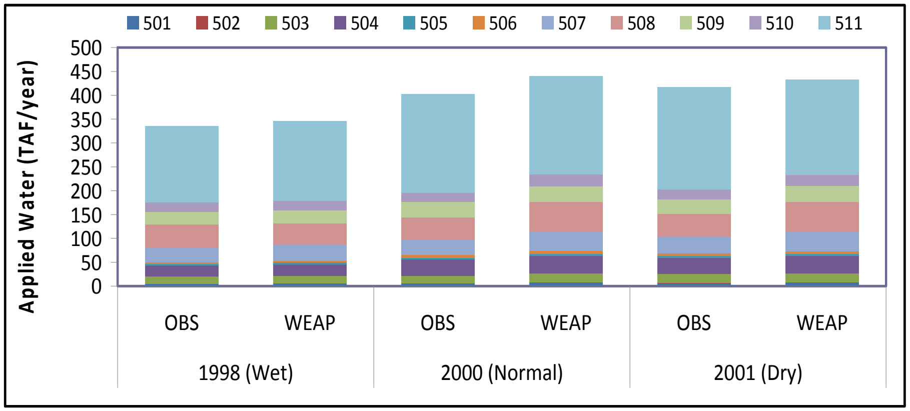
Planning Area	1998 (Wet) OBS	1998 (Wet) WEAP	2000 (Normal) OBS	2000 (Normal) WEAP	2001 (Dry) OBS	2001 (Dry) WEAP
601	28	20	34	22	36	22
602	594	561	810	707	878	760
603	634	621	795	765	805	835
604	14	7	17	10	20	11
605	-	-	-	-	-	-
606	1,042	981	1,384	1,282	1,417	1,275
607	698	630	865	723	881	781
608	650	730	863	852	862	868
609	1,417	1,573	1,784	1,529	1,891	1,517
610	4	2	3	1	3	1
Total San Joaquin River HR	5,079	5,125	6,556	5,891	6,794	6,069

Figure 6-5. Irrigated Agricultural Applied Water Use for 1998, 2000, and 2001

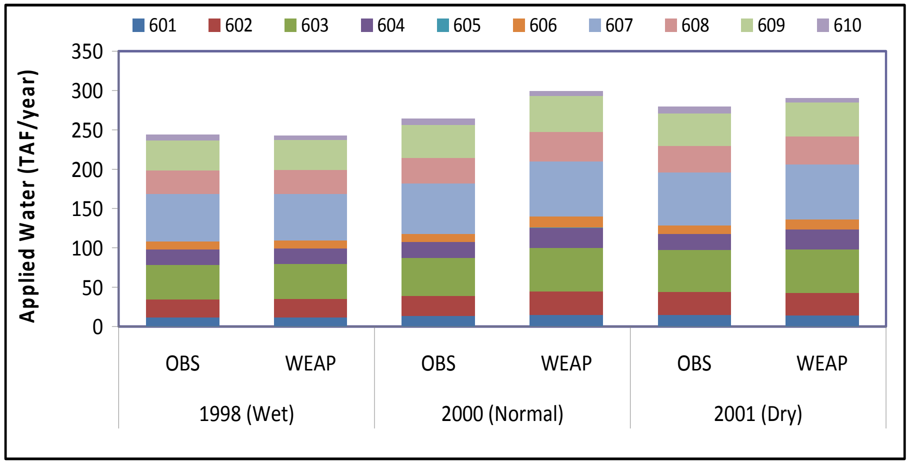
Notes:

1. There is to significant irrigated agriculture in planning area 606
2. Year types refer to the Sacramento Valley and San Joaquin Valley indices as defined by the State Water Resources Control Board 1995 Water Quality Control Plan.

Key: HR = hydrologic region, OBS = observed, TAF = thousand acre-feet, WEAP = Water Evaluation and Planning (Framework)



Planning Area	1998 (Wet)		2000 (Normal)		2001 (Dry)	
	OBS	WEAP	OBS	WEAP	OBS	WEAP
501	5	5	5	7	6	7
502	0	1	0	1	0	1
503	15	15	16	19	19	20
504	23	25	35	38	34	37
505	3	3	4	4	5	4
506	4	4	5	5	5	5
507	31	33	32	42	34	42
508	48	45	46	61	49	62
509	27	27	33	34	31	32
510	19	20	19	24	21	24
511	160	167	207	206	215	200
Total Sacramento River HR	336	345	403	440	417	434



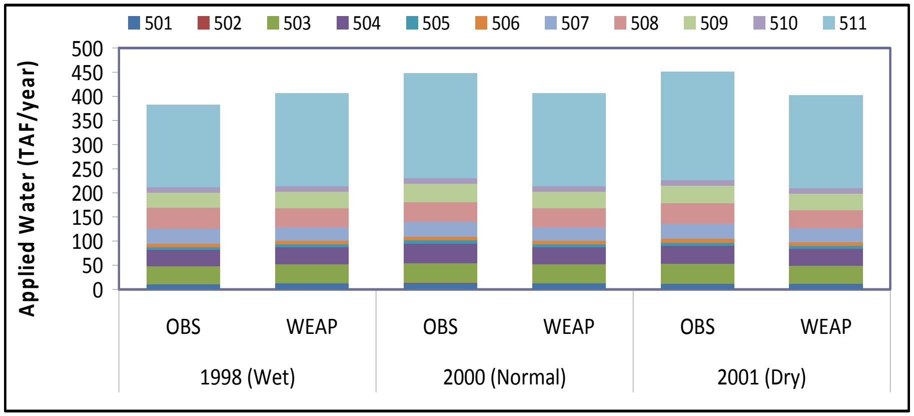
Planning Area	1998 (Wet)		2000 (Normal)		2001 (Dry)	
	OBS	WEAP	OBS	WEAP	OBS	WEAP
601	12	12	14	15	15	15
602	23	23	25	29	30	28
603	44	44	49	56	53	55
604	20	19	20	26	21	25
605	-	0	-	1	-	1
606	10	10	10	14	10	13
607	60	59	64	70	68	70
608	30	31	33	38	34	35
609	38	38	41	46	41	44
610	7	6	8	6	8	6
Total San Joaquin River HR	244	243	264	300	279	291

Figure 6-6. Outdoor Urban Applied Water Use for 1998, 2000, and 2001

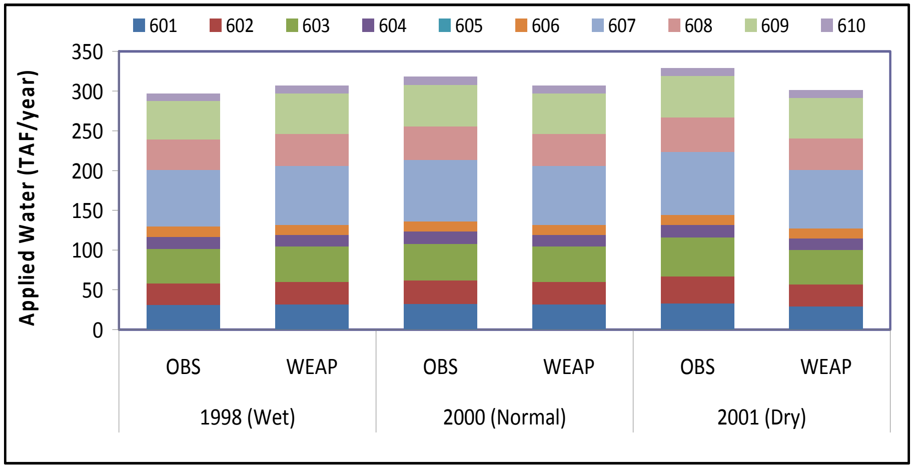
Notes:

1. There is to significant urban demand in planning area 605.
2. Year types refer to the Sacramento Valley and San Joaquin Valley indices as defined by the State Water Resources Control Board 1995 Water Quality Control Plan.
3. Simulated indoor water use is based on results from the Statewide HR model for the year 2000, which leads to much lower 2005 water use estimates because the number of employees has changed dramatically.

Key: HR = hydrologic region, OBS = observed, TAF = thousand acre-feet, WEAP = Water Evaluation and Planning (Framework)



Planning Area	1998 (Wet)		2000 (Normal)		2001 (Dry)	
	OBS	WEAP	OBS	WEAP	OBS	WEAP
501	11	13	13	13	12	12
502	0	0	1	0	1	0
503	37	39	41	39	41	37
504	34	35	41	35	37	36
505	6	6	7	6	6	6
506	7	8	8	8	8	7
507	31	28	30	28	31	28
508	43	39	41	39	43	38
509	32	35	39	35	36	34
510	11	11	11	11	11	11
511	170	193	217	193	225	192
Total Sacramento River HR	382	406	448	406	451	402



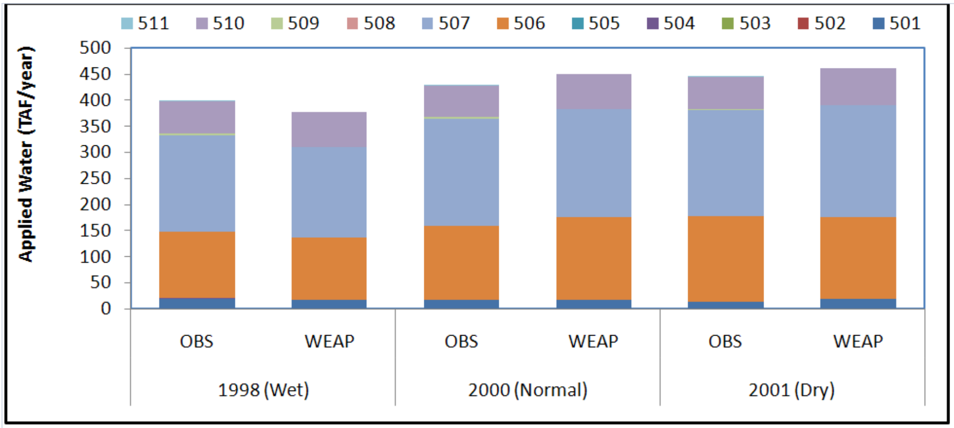
Planning Area	1998 (Wet)		2000 (Normal)		2001 (Dry)	
	OBS	WEAP	OBS	WEAP	OBS	WEAP
601	31	32	32	32	33	29
602	27	28	30	28	35	28
603	44	45	46	45	49	43
604	15	15	15	15	16	15
605	-	0	-	0	-	0
606	13	12	13	12	13	12
607	72	74	77	74	79	74
608	38	40	42	40	43	40
609	49	51	53	51	52	50
610	9	10	10	10	10	10
Total San Joaquin River HR	297	307	319	307	329	301

Figure 6-7. Indoor Urban Water Use for the Years 1998, 2000, and 2001

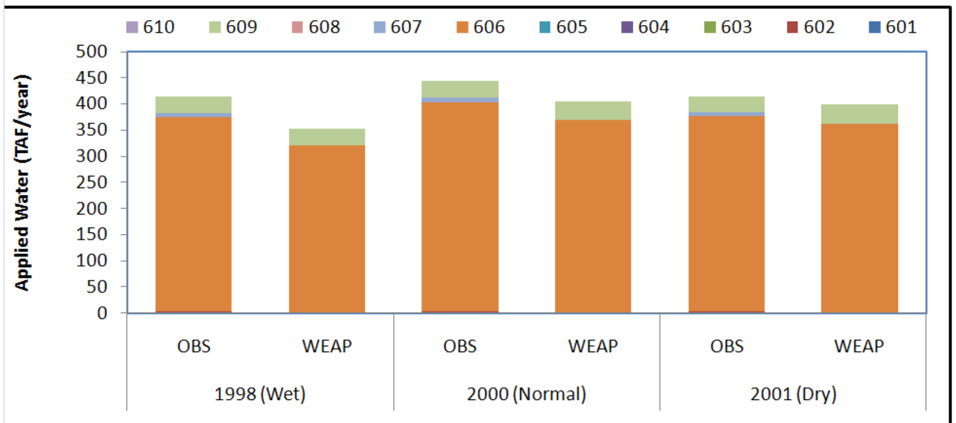
Notes:

1. There is to significant urban demand in planning area 605.
2. Year types refer to the Sacramento Valley and San Joaquin Valley indices as defined by the State Water Resources Control Board 1995 Water Quality Control Plan.

Key: HR = hydrologic region, OBS = observed, TAF = thousand acre-feet, WEAP = Water Evaluation and Planning (Framework)



Planning Area	1998 (Wet) OBS	1998 (Wet) WEAP	2000 (Normal) OBS	2000 (Normal) WEAP	2001 (Dry) OBS	2001 (Dry) WEAP
501	19	17	17	18	13	19
502	-	-	-	-	-	-
503	0	-	0	-	0	-
504	1	-	1	-	1	-
505	-	-	-	-	-	-
506	128	120	142	158	163	156
507	185	173	205	206	203	215
508	-	-	-	-	-	-
509	3	-	3	-	3	-
510	61	68	61	68	61	70
511	1	-	1	-	1	-
Total Sacramento River HR	398	378	430	451	446	461



Planning Area	1998 (Wet) OBS	1998 (Wet) WEAP	2000 (Normal) OBS	2000 (Normal) WEAP	2001 (Dry) OBS	2001 (Dry) WEAP
601	-	-	-	-	-	-
602	3	-	3	-	3	-
603	0	-	0	-	-	-
604	-	-	-	-	-	-
605	-	-	-	-	-	-
606	372	320	400	369	373	362
607	7	-	9	-	8	-
608	-	-	-	-	-	-
609	33	33	33	37	31	38
610	-	-	-	-	-	-
Total San Joaquin River HR	415	353	445	406	415	399

Figure 6-8. Managed Wetlands Applied Water Use for 1998, 2000, and 2001

Notes:

1. There are no significant managed wetlands in many of the planning areas.
2. Year types refer to the Sacramento Valley and San Joaquin Valley indices as defined by the State Water Resources Control Board 1995 Water Quality Control Plan.

Key: HR = hydrologic region, OBS = observed, TAF = thousand acre-feet, WEAP = Water Evaluation and Planning (Framework)

6.3 Reservoir Storages

Figures 6-9 to 6-12 compare the monthly simulated and observed storage volumes for major reservoirs on the Trinity River and in the Sacramento River and San Joaquin River hydrologic regions for the calibration period of 1990 to 2005. These figures also compare the end-of-September (carryover) storage for the same period. The Central Valley PA model shows generally good agreement with historical storage, including continued drawdown during the drought of the early 1990s.

The Central Valley PA model represents San Luis Reservoir operations using a 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 fall and winter (October through March), and to release the stored preferentially in 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. Currently, the model does not consider DMC capacity constraints upstream from O'Neil Pumping Plant. Monthly releases during the summer drawdown season are limited to one-sixth of the storage available at the beginning of April. These simple rules suffice to operate San Luis Reservoir in a manner consistent with observed records (Figure 6-12).

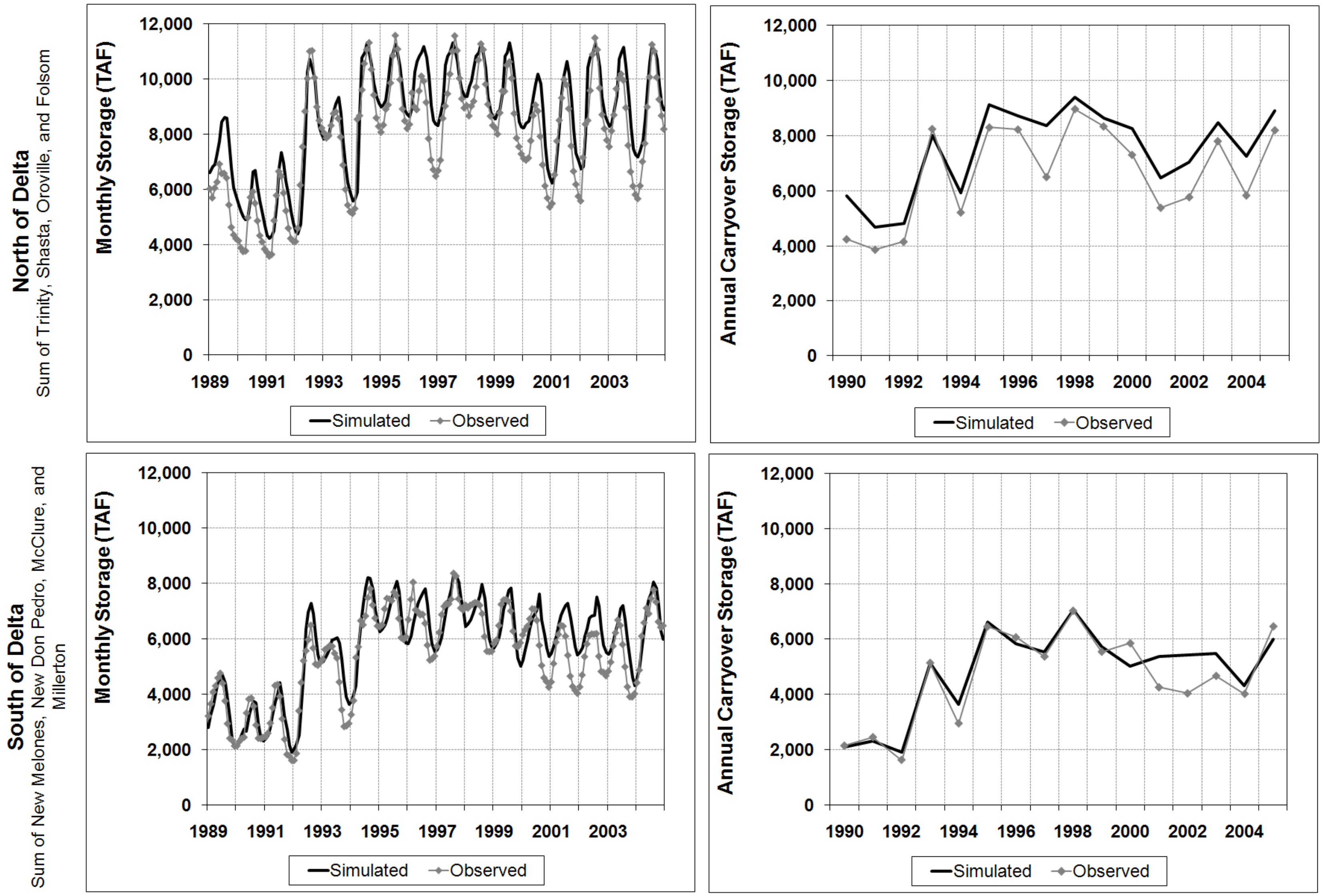


Figure 6-9. Observed and Simulated Reservoir Storage North and South of the Delta

Integrated Scenario Analysis for the 2009 California Water Plan Update

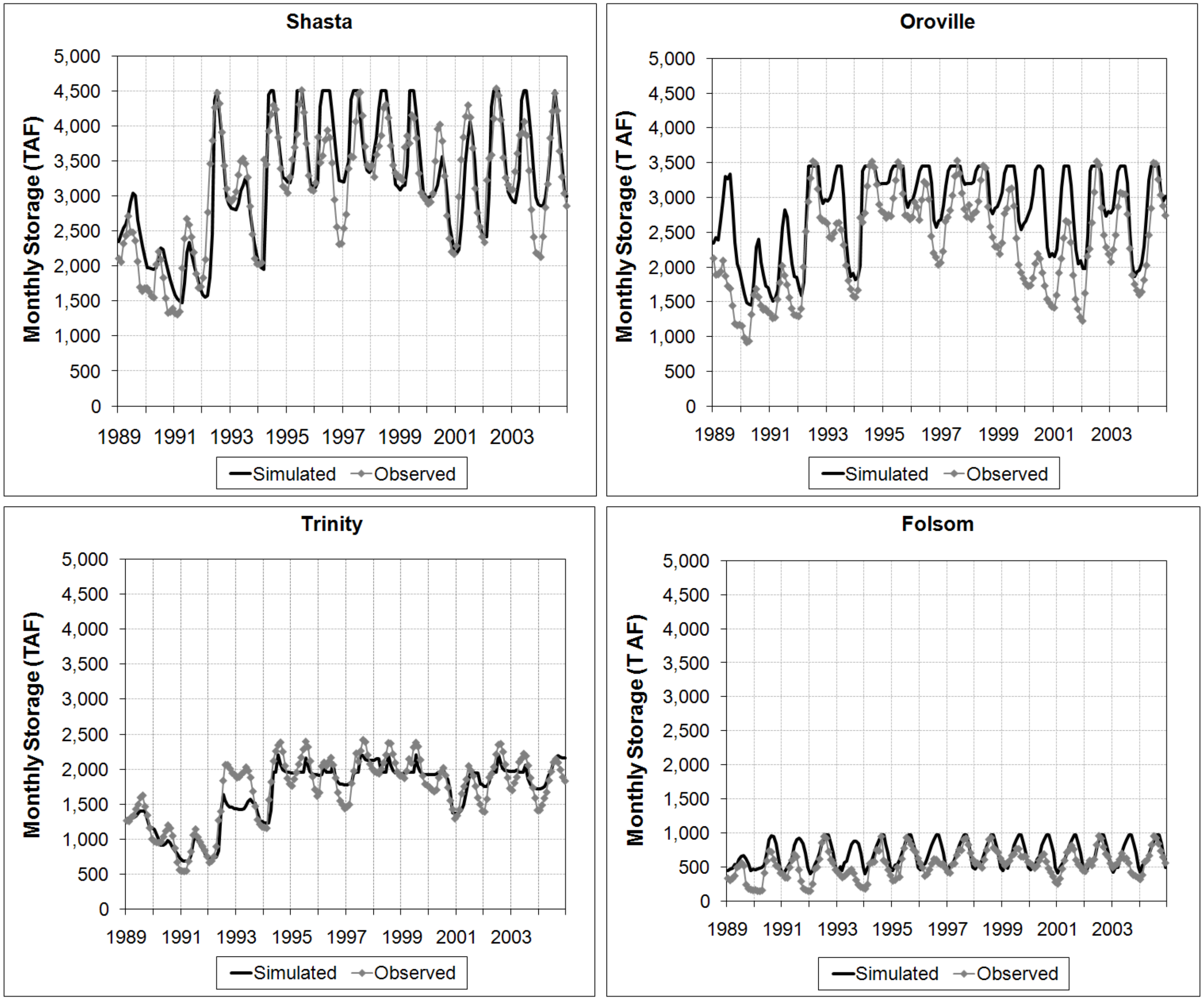


Figure 6-10. Observed and Simulated Monthly Storage for Major Reservoirs North of the Delta

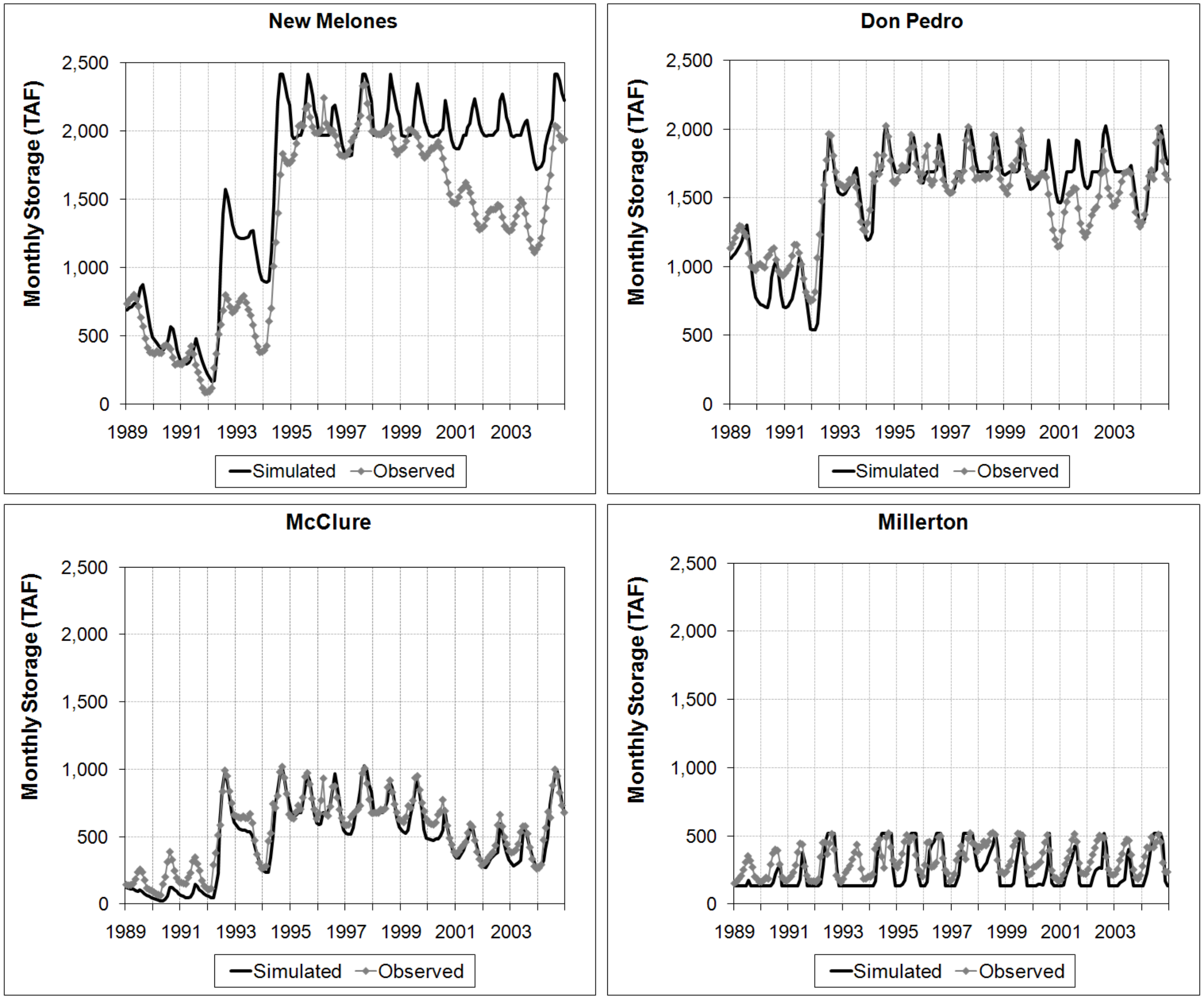
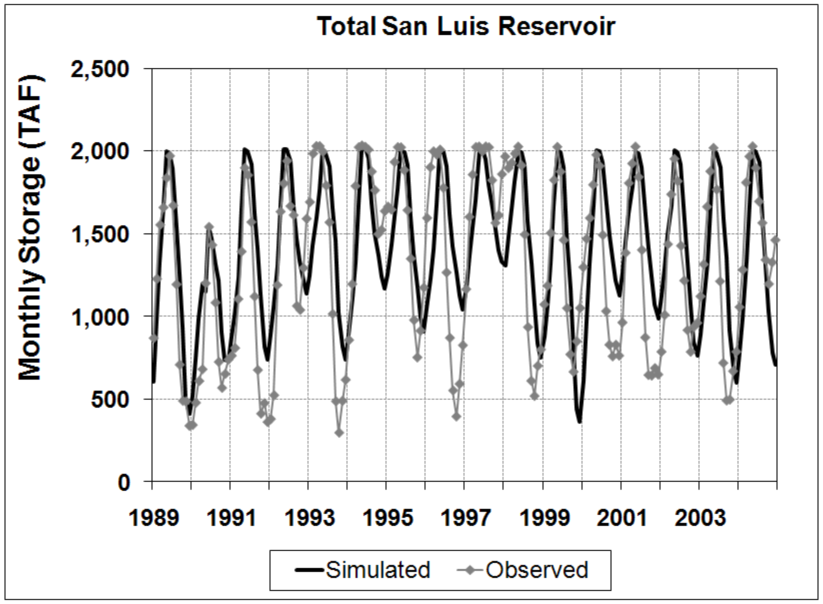


Figure 6-11. Observed and Simulated Monthly Storage for Major Reservoirs South of the Delta



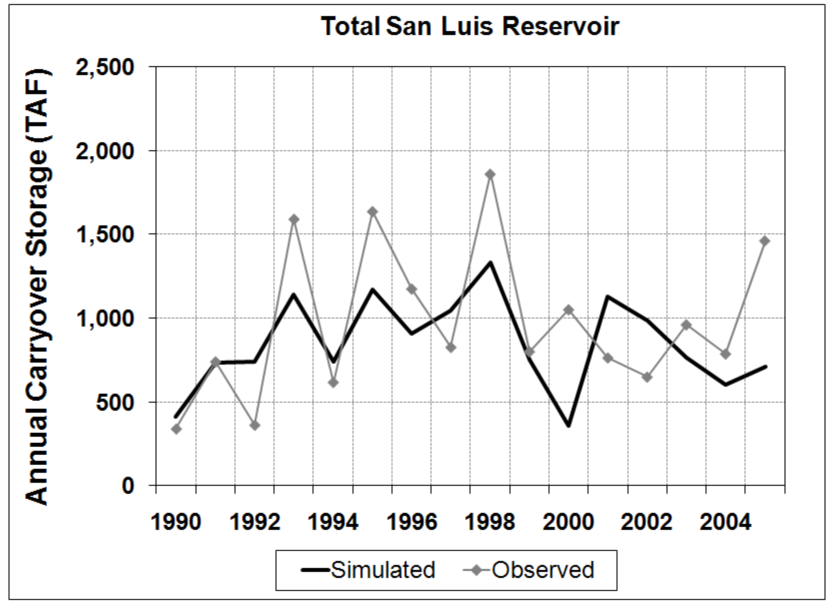


Figure 6-12. Observed and Simulated CVP/SWP Monthly Storage in San Luis Reservoir

6.4 Delta Inflows, Outflows and Exports

Figures 6-13 to 6-19 compare simulated and observed annual and average monthly Delta inflows, outflows and exports for water years 1990 to 2005. Before 1995, Delta operations were governed by the 1978 SWRCB Water Quality Control Plan (WQCP). Between 1990 and 2005, the period of comparison, CVP and SWP operations were affected by the following regulatory actions (DWR, 2003):

- **1991:** U.S. Department of Interior Secretarial Decision (May 8) specifies minimum annual flow releases to the Trinity River of 340,000 acre-feet for water years 1992 to 1996.
- **1991**: DWR expands capacity at Banks Pumping plant to 10,300 cfs. Drought Water Bank Program created and activated to alleviate major cutbacks to contractors.
- **1992:** CVPIA, passed by Congress, addresses several issues for improving water quality and ecosystem health, sets new guidelines for contracts and transfers, and dedicates 800,000 acre-feet per year for fish and wildlife purposes in addition to Reclamation refuge water supplies.
- **1992:** Drought water bank program re-activated to alleviate major cutbacks to contractors.
- **1992:** A one-year Biological Opinion (BO) issued by the National Marine Fisheries Service (NMFS) (February 14) on winter-run Chinook salmon specifies minimum flows below Keswick Dam to provide temperature control, and requires Red Bluff Diversion Dam gates to remain open for a longer period.
- **1992:** Salinity standards at Emmaton relaxed in June to maintain sufficient cool water supplies in north-of-Delta reservoirs for salmon spawning; Contra Costa Canal Intake chloride standard relaxed in November and December (with restrictions on CVP and SWP exports).
- **1993:** Long-term BO released by NMFS (February 12) for the Sacramento River winter-run Chinook salmon. Requirements include 1.9 MAF carryover storage in Lake Shasta, Sacramento River minimum flow requirement downstream from Keswick Dam, Qwest requirements to eliminate reverse flow, and constraints on the Delta cross-channel operations. BO limits incidental take to less than one percent of the out-migration population.
- **1993:** Delta smelt declared a federally threatened species. U.S. Fish and Wildlife (USFWS) issues one-year BO (May 26). Incidental take requirements limit combined project exports to 4,000 cfs in May and 5,000 cfs in June. Additional Qwest standard specified.
- **1994:** Drought water bank re-activated to alleviate major cutbacks to contractors.
- **1994:** Second one-year Delta smelt BO released by USFWS (February 4). CVP-SWP operations found likely to jeopardize continued existence of Delta smelt. Reasonable and prudent alternative defines X2 estuarine habitat standard, adds additional net Delta outflow criteria and minimum flows for the San Joaquin River at Airport Way Bridge near Vernalis (San Joaquin River at Vernalis).

- **1994:** Monterey Agreement between DWR and SWP contractors (signed December 1) provides for greater flexibility in water operations. Provisions include permanent water transfers, creation of a turn-back pool, storage of water outside of SWP service area, and use of SWP facilities for transfer of non-SWP water. During shortages, water is to be allocated in proportion to contractors' Table A amounts.
- **1994:** Bay-Delta Accord signed (December 15) by federal and state agencies. Agreement contains a set of standards that include export: inflow (E:I) restrictions on project pumping, X2, periods of closure for the Delta cross channel gate, minimum flows in the San Joaquin River at Vernalis, and export limits during the April/May 30-day pulse-flow period. Compliance with take provisions of BOs to be achieved at no additional water cost to projects through adjustment of export pumping limits.
- **1994:** Draft 1994 WQCP issued by SWRCB, developed concurrently with the Bay-Delta Accord.
- **1995:** SWRCB WQCP defines new water quality objectives for the Delta. The WQCP contains revised electrical conductivity (EC) and chloride standards and Delta outflow requirements. X2 standard specified. E:I ratio limits total project pumping. Exports during the April 15 – May 15 San Joaquin River pulse flow period limited to the greater of 1,500 cfs or the San Joaquin River flow at Vernalis.
- **1995:** SWRCB Order WRO 95-6 grants temporary 3-year approval of CVP/SWP joint point of diversion.
- **1995:** USFWS issues (March 6) long-term BO for Delta smelt, revising take limits at project export pumps.
- **1995:** NMFS issues amendments (May 17) to 1993 BO to conform to Bay-Delta Accord, revising operation of the Delta Cross Channel, Qwest requirements, and take limits at CVP/SWP export pumps.
- **1998:** SWRCB Order WRO 98-9 extends temporary conditional approval of CVP/SWP joint point of diversion.
- **1999:** SWRCB D-1641implements objectives of the 1995 WQCP. Replaces D-1485 as modified by WRO 98-9. Amends CVP and SWP permits. Adopts the Vernalis Adaptive Management Program (VAMP). Conditional approval of joint point of diversion.
- **2000:** SWRCB Order WR 2000-02 denies petitions for reconsideration of D-1641. Amends several conditions of D-1641.
- **2000:** Record of Decision (ROD) for Trinity River Environmental Impact Statement/Environmental Impact Report (EIS/EIR) signed. Preferred alternative specifies annual minimum flow releases of 369,000-815,000 acre-feet per year, depending on water year classification, and a minimum carryover of 600,000 acre-feet.
- **2000:** Framework for Action for proposed CalFed Bay-Delta Program (CalFed) long-term plans signed. Release of final Programmatic EIS/EIR for the Bay-Delta Program. ROD signed implementing proposals listed in the Framework. ROD establishes the EWA.

6.4.1 Delta Inflows

Standard water planning models rely on historical streamflow records to estimate surface water inflows into a managed system. These model inputs include estimates of inflows to major reservoirs, unregulated inflows from upper watersheds, and incremental flows (or accretions) that come from local sources of surface water and groundwater and discharge into rivers and streams. As many of these sources are ungaged, it is usually necessary to derive these inputs from volumetric flow balance calculations conducted at a regional scale.

These data inputs are not required for Central Valley PA model, because it uses climatic data to drive both the water supply and demands of the system. This obviates the need to rely on historical streamflow records to estimate surface water inflows to the managed system. However, it is still necessary to confirm that the model agrees with the overall water balance of the historical baseline. To this end, Central Valley PA model simulations were compared with historical streamflow records at two key locations within the model – the Sacramento River at Freeport (USGS gage 11447650) and San Joaquin River near Vernalis (USGS gage 11303500) – that reflect the hydrology and water management (i.e., inflows, diversions, consumption, return flows, and storage) for both the Sacramento River and San Joaquin River hydrologic regions. These data are presented in Figures 6-13, 6-14 and 6-15. The total outflow from the Sacramento Valley is better measured as the sum of the flow in the Sacramento River at Freeport and outflow from the Yolo Bypass. The Yolo Bypass conveys Sacramento River flood water spilled over the Freemont and Sacramento weirs, outflow from Cache Creek and Putah Creek, and minor irrigation return flows during the summer months. Unfortunately, measurement of historical flows in Yolo Bypass is relatively poor. The USGS gage near Woodland (11453000) is located upstream of Putah Creek and does not measure low flows. Consequently, Figure 6-14 compares simulated and observed flows for the Sacramento River at Freeport, combined with Freemont and Sacramento weir spills.

For the 1990 to 2005 calibration period, the Central Valley PA model recreates the variability in total annual and monthly streamflows for the Sacramento River. Simulated flows in the Sacramento River at Freeport average 16.4 MAF per year, compared to historical average flows of 16.9 MAF per year. When weir spills are included, simulated flows average 18.2 MAF per year compared to average historical flows of 19.5 MAF per year. The Central Valley PA model under-estimates the summertime river flows.

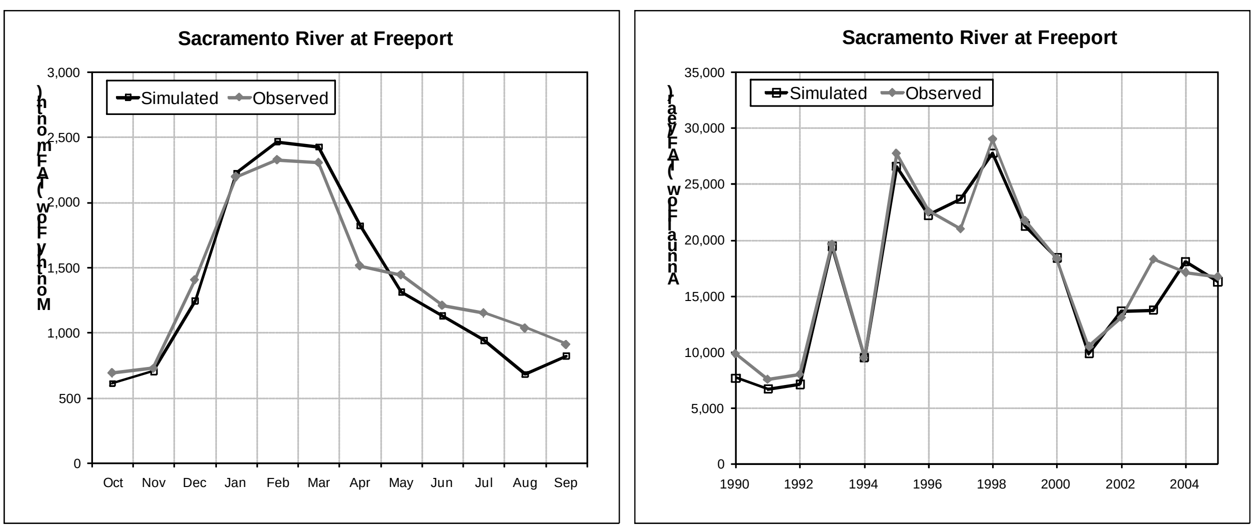


Figure 6-13. Sacramento River at Freeport
For Water Years 1990 – 2005

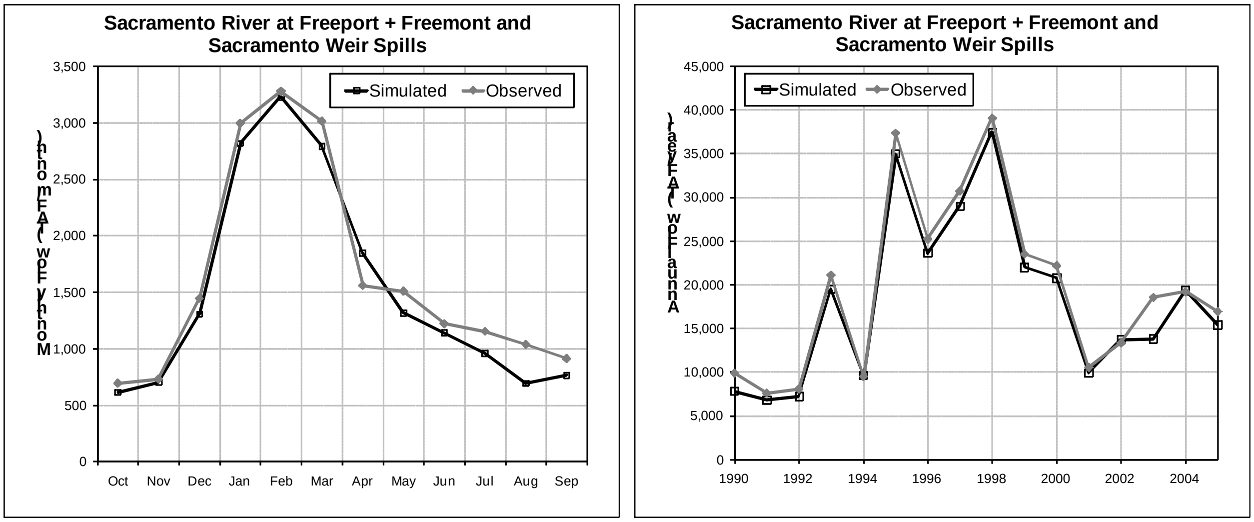


Figure 6-14. Sacramento River at Freeport plus Freemont and Sacramento Weir Spills
For Water Years 1990 – 2005

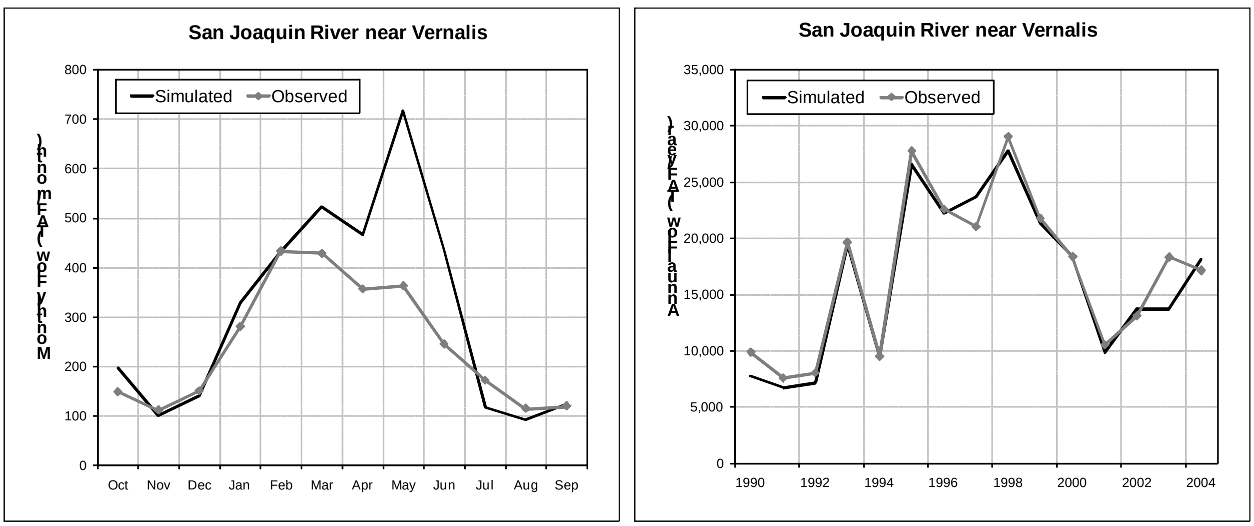


Figure 6-15. San Joaquin River at Airport Way Bridge near Vernalis
For Water Years 1990 – 2005

6.4.1 Delta Outflows

For the 1990 to 2005 calibration period, Central Valley PA model recreates the variability in total annual and monthly net Delta outflow. In general, the model tends to overestimate Delta outflow in wet years over this period, although the model also tends to be correspondingly dry in the early period of the historical simulation (1970 through 1990). This suggests climate forcing bias. These results, together with the other performance metrics, give reasonable confidence that the model is accurately reflecting the overall water balance of the two hydrologic regions.

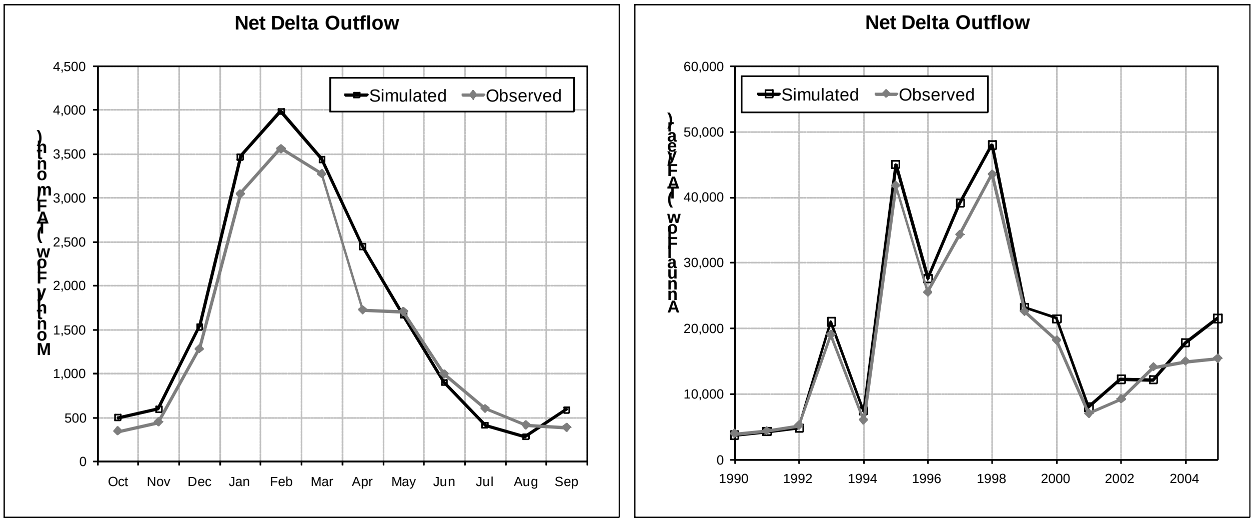


Figure 6-16. Annual Net Delta Outflow
For Water Years 1990 – 2005

6.4.1 Delta Exports

Before water year 2000, the Central Valley PA model approximately matches the annual exports at Banks Pumping Plant. However, for water years 2000 through 2005 simulated export amounts are significantly less than observed. The simulated monthly pattern of pumping at Banks Pumping Plant is less in the fall and greater in the spring and summer compared to observed pumping rates. Since 1995, simulated exports at Jones Pumping Plant are consistently less than observed rates. The monthly pattern of pumping at Jones Pumping Plant matches the observed pattern reasonably well, except for significantly less pumping in March. In general, Central Valley PA model cannot duplicate with a uniform set of operating rules the many discretionary actions and regulatory changes that affected CVP/SWP Delta exports over the 1990 to 2005 period. Simulated exports average 4.6 MAF per year, compared to historical average exports of 5.0 MAF per year. Additional work is required to identify the cause(s) of this 8 percent discrepancy.

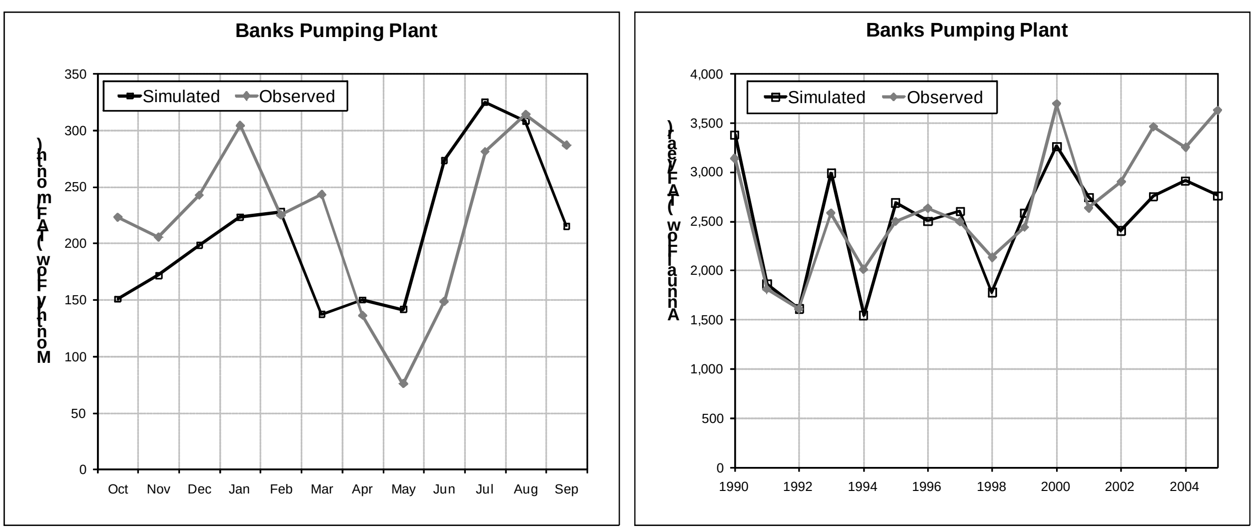


Figure 6-17. Delta Exports – Banks Pumping Plant
For Water Years 1990 – 2005

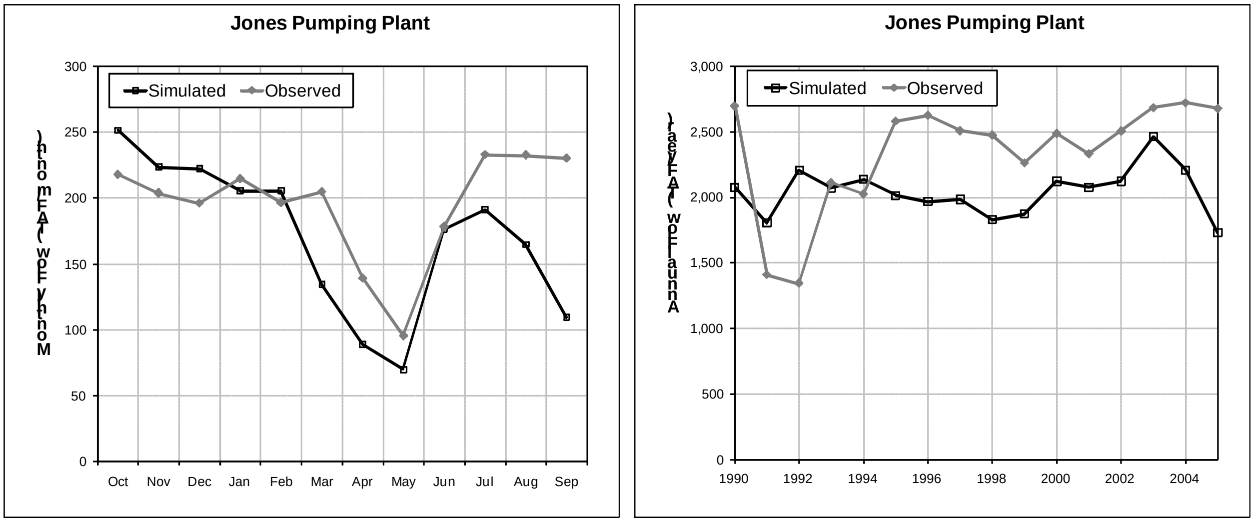


Figure 6-18. Delta Exports – Jones Pumping Plant
For Water Years 1990 – 2005

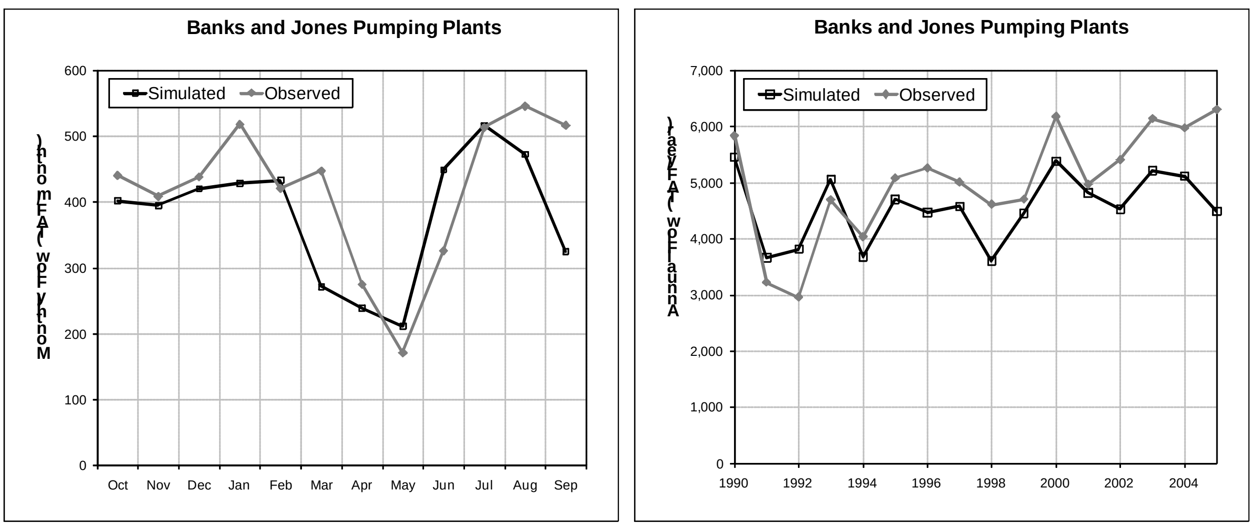


Figure 6-19. Combined Delta Exports – Banks and Jones Pumping Plants
For Water Years 1990 – 2005

6.5 Groundwater and Surface Water Use and Groundwater Elevations

The Central Valley PA model represents the major alluvial groundwater systems within the valley floor of the Sacramento River and San Joaquin River hydrologic regions. These aquifers are a major source of water supply. The groundwater basins within the Central Valley PA model were calibrated to match groundwater pumping estimates under average and drought conditions, as well as regional groundwater table fluctuations.

The physical hydrology module of WEAP has been developed to account for two different hydrologic assumptions. The first assumption is that precipitation in catchments located in the upstream portions of watersheds, with complex topography, steep slopes, and abrupt hills and valleys, contributes to a groundwater system that returns water quickly to the stream as baseflow, with a relatively short time lag. Groundwater in these upland watersheds is not extensively used as a source of supply, nor do the related aquifers receive water from seepage from a stream channel. In contrast, catchments located in lower portions of watersheds with flatter terrain tend to contribute to groundwater aquifers that are directly linked to the river system to which they can contribute flow, and from which they can receive seepage. These aquifers are a source of water to meet urban and agricultural demands.

For the Sacramento and San Joaquin valleys, the Central Valley PA model was configured to simulate groundwater using this active groundwater method, allowing groundwater to be an independent supply source that interacts with the adjacent surface water system. If groundwater is overdrafted, and the groundwater elevation drops below that of an adjacent stream, the river loses water to the groundwater system. In contrast, if the groundwater elevation is positive relative to the river, the groundwater flows to the river, and the river becomes a gaining stream.

6.5.1 Characterization of Groundwater Basins

For each of the planning areas located in the valley floor of the Sacramento River and San Joaquin River hydrologic regions, a local groundwater basin was defined that receives recharge from the overlying catchment and is physically connected to the adjacent riverine system. In all, 15 groundwater basins were implemented, from the northern-most Redding Basin in the Sacramento Valley to the southern-most Chowchilla-Madera basin in the San Joaquin Valley. Published data of total groundwater storage capacity reported in Bulletin 118 (DWR, 2003) were used to define total available storage in these aquifers. Generally, Bulletin 118 reports total available storage to a depth of between 200 and 300 feet. Using this assumption, and the information from Bulletin 118, the initial total available groundwater storage for the Sacramento and San Joaquin valleys was set at 50 MAF and 75 MAF, respectively. This storage was distributed among the 15 groundwater basins.

In addition to initial total storage, broad parameter estimates were made for each of the 15 stylized groundwater basins. For example, the representative horizontal distance, h_d , the farthest edge of an aquifer to a river, were as short as 40 miles for the Redding basin and more than 100 miles for the Eastern San Joaquin basin. The river reach length, l_w , represents the hydraulic connection between the aquifer and the river and ranged from 20 miles for the lower Butte basin and as long as 70 miles for the Yolo-Solano basin. Aquifer hydrologic properties include specific yield, S_y; saturated conductivity, *Ks*; and the wetted depth d_w of the stream through which the stream and aquifer exchange water. Parameter values for specific yield (0.1), saturated conductivity (30 to 50 feet/month), and wetted depth (30 to 50 feet) were prescribed for each stream-aquifer pair. These values were derived through a trial-and-error process that attempted to broadly track observed variations found in groundwater well elevation data available electronically from DWR's water data library (DWR, 2009). Groundwater basin parameters h_d and S_y were adjusted so as to better match simulated to observed groundwater elevations.

6.5.2 Groundwater Pumping

Total water use (at a regional scale) was extracted from DWR portfolio data for each of the planning areas, for 1998, 2000, and 2001. Tables 6-3 and 6-4 show the portions of that water supply that is derived from groundwater and surface water for planning areas reporting significant water use. The portion of water supplied as either surface or groundwater for each planning area for all uses (agriculture, municipal and environmental) is given in thousands of acre-feet. The total water use does not include instream flow requirements. DWR portfolio data for PA 510 includes net Delta outflow, which is not included in the data shown. Internal reuse is assumed to be 76 percent surface water supply. Tables 6-3 and 6-4 also depict how the ratio of groundwater use to total water use changes based on water year type. For example, for PA 503 the percentage groundwater use is relatively constant (ratio = 1.02), while for PA 511 the percentage groundwater use is significantly higher in 2001 (ratio = 1.39).

Water years 2000 and 2001 were dry relative to 1998, resulting in greater water demands in these 2 years. DWR portfolio data shows that total annual water use in 2000 and 2001 increased by 28 percent to 30 percent compared to 1998. This compares with a simulated increase in these two years of between 16 percent and 27 percent. This suggests that the Central Valley PA model tends to under estimate the increase in climate-induced demand in drier years, particularly for the Sacramento River hydrologic region. For the San Joaquin River hydrologic region, the Central Valley PA model does not capture the change in demand in drier years and the associated increase in surface water use.

Generally, there is close agreement between water use reported by the DWR portfolio data and that simulated by the Central Valley PA model. Demand is more dependent on surface water than groundwater, although the share between these two sources varies widely. For some planning areas there appears to be an increased reliance on groundwater in drier conditions. In most cases, the Central Valley PA model assumes that the water supply preference is for surface water, but this delivery is constrained as a fraction of the total water supplied. This tends to lead to an underestimation of the change from surface water to groundwater. For example, in PA507, groundwater's share of total delivery increases by roughly 5 percent when comparing the wet year of 1998 and the dry year of 2001, whereas the fraction is mostly constant from year to year in the model simulation.

PA 508 depends heavily on surface water, while PA 507 and PA 511 rely more heavily on groundwater to meet demands when there are surface water shortages. PA 603 is the only planning area that exhibits a major shift in source water supply under different water year types. In the wet year of 1998, more than 70 percent of the water supply was from surface supplies, while in 2001, there was a net increase in water supplied, with a shift to groundwater, which makes up 73 percent of the supply, while surface supplies make up only 27 percent. For this reason, an expression was introduced in the supply preference to PA 603 so that when the San Joaquin River water year index is greater than 6 (wet), the preference is for surface water and vice-versa when the index reports dry conditions. PA 603 in Table 6-4 shows that Central Valley PA model adequately captured this shift from surface water to groundwater.

Table 6-3. Sacramento River Hydrologic Region Observed and Simulated Applied Water

Planning Area		Ratio of GW Use: 2001 to 1998	1998 (wet)			2000 (normal)			2001 (dry)		
			Total (TAF)	SW	GW	Total (TAF)	SW	GW	Total (TAF)	SW	GW
503	Observed	1.02	416	49%	51%	563	46%	54%	592	48%	52%
	Simulated	1.02	450	53%	47%	584	52%	48%	608	52%	48%
506	Observed	1.30	1,700	80%	20%	2,400	75%	25%	2,300	74%	26%
	Simulated	1.00	1,700	76%	24%	2,100	76%	24%	2,200	76%	24%
507	Observed	1.29	2,160	83%	17%	2,800	80%	20%	2,800	78%	22%
	Simulated	1.00	2,000	77%	23%	2,400	77%	23%	2,600	77%	23%
509	Observed	1.16	760	57%	43%	990	53%	47%	990	50%	50%
	Simulated	1.00	830	49%	51%	1,000	49%	51%	1,000	49%	51%
510	Observed	1.00	496	94%	6%	597	93%	7%	642	94%	6%
	Simulated	0.83	500	94%	6%	590	95%	5%	630	95%	5%
511	Observed	1.39	852	72%	28%	1,020	64%	36%	1,020	61%	39%
	Simulated	1.00	780	73%	27%	900	73%	27%	920	73%	27%
Total	Observed	1.21	6,400	76%	24%	8,370	72%	28%	8,300	71%	29%
	Simulated	1.00	6,200	71%	29%	7,400	71%	29%	7,900	71%	29%

Key:
GW = groundwater
SW = surface water
TAF = thousand acre-feet

Table 6-4. San Joaquin River Hydrologic Region Observed and Simulated Applied Water

Planning Area		Ratio of GW Use: 2001 to 1998	1998 (wet)			2000 (normal)			2001 (dry)		
			Total (TAF)	SW	GW	Total (TAF)	SW	GW	Total (TAF)	SW	GW
603	Observed	2.52	680	71%	29%	890	23%	77%	910	27%	73%
	Simulated	3.41	680	78%	22%	820	33%	67%	890	25%	75%
606	Observed	0.93	1,400	72%	28%	1,840	76%	24%	1,800	74%	26%
	Simulated	1.30	1,480	80%	20%	1,710	75%	25%	1,690	74%	26%
607	Observed	0.95	910	81%	19%	1,110	83%	17%	1,130	82%	18%
	Simulated	1.00	840	81%	19%	950	81%	19%	1,000	81%	19%
608	Observed	1.43	790	79%	21%	1,023	73%	27%	1,020	70%	30%
	Simulated	1.00	820	77%	23%	1,050	77%	23%	980	77%	23%
609	Observed	1.33	1,655	57%	43%	2,060	53%	47%	2,140	43%	57%
	Simulated	1.23	1,900	57%	43%	2,100	48%	52%	2,140	47%	53%
Total	Observed	1.37	5,400	70%	30%	6,920	63%	37%	7,000	59%	41%
	Simulated	1.43	5,700	72%	28%	6,630	62%	38%	6,700	60%	40%

Key:
GW = groundwater
SW = surface water
TAF = thousand acre-feet

6.5.3 Groundwater Elevations

Groundwater water surface elevation (WSE) data are collected by the State from thousands of wells throughout the Central Valley to track groundwater conditions, with many measurements made roughly twice yearly, once in March and again in October. The expectation is that if the Central Valley PA model can adequately represent surface water and groundwater use, it should be capable of tracking trends in groundwater well observations.

WSE data were extracted for wells throughout the Central Valley that corresponded to the broad groundwater basins and geographic regions being modeled in Central Valley PA model. A set of representative wells was selected from which to estimate relative fluctuations in WSE for comparison with simulated WSE. Because so many groundwater well records are available, only wells which had mostly complete records for the period of interest (1970 through 2005) were selected. Observed groundwater WSE varies widely from well-to-well, influenced by local geography and cones of depression as a result of pumping, which the Central Valley PA model is incapable of representing. The Central Valley PA model simulation of groundwater elevations is stylized, therefore, a one-to-one comparison of absolute observed versus simulated groundwater WSE was deemed inappropriate. Instead, the standard normal variate of the observed and simulated groundwater WSE were computed as, $z = (x-\mu)/\sigma$, where x is the observed or simulated water surface elevation, μ is the mean, and σ the standard deviation of the WSE for each well. The following sections compare simulated and observed groundwater elevations for 5 of the 15 model groundwater basins represented in the basin.

Colusa Groundwater Basin

The Colusa basin is an area of intensive agriculture water use in the central portion of the Sacramento Valley. The predominant crop is rice. Bulletin 118 provides this account of historical groundwater level trends for the Colusa groundwater basin (DWR, 2003):

> *The long-term comparison of groundwater levels indicates a slight decline associated with the 1976-77 and 1987-94 droughts, followed by recovery to pre-drought conditions of the early 1970's and 1980's. Some wells increased in levels beyond the pre-drought conditions of the 1970's during the wet season of the early 1980's. Generally, groundwater level data show an average seasonal fluctuation of approximate 5-feet for normal and dry years. Overall there does not appear to be any increasing or decreasing trends in groundwater levels.*

Groundwater WSE data from 12 wells were extracted from the DWR water data library and the standard normal variate computed for each well. The data shows that this groundwater basin undergoes dramatic seasonal variability, being heavily influenced by the intensive rice irrigation. The long-term, simulated trend in WSE is slightly upward, and appears to be consistent with what has been observed in the basin over the past 25 years. Figure 6-20 shows the Central Valley PA model simulated groundwater levels for the Colusa groundwater basin in red and the observed levels in gray. The figure shows that the model adequately tracks the general historical trends.

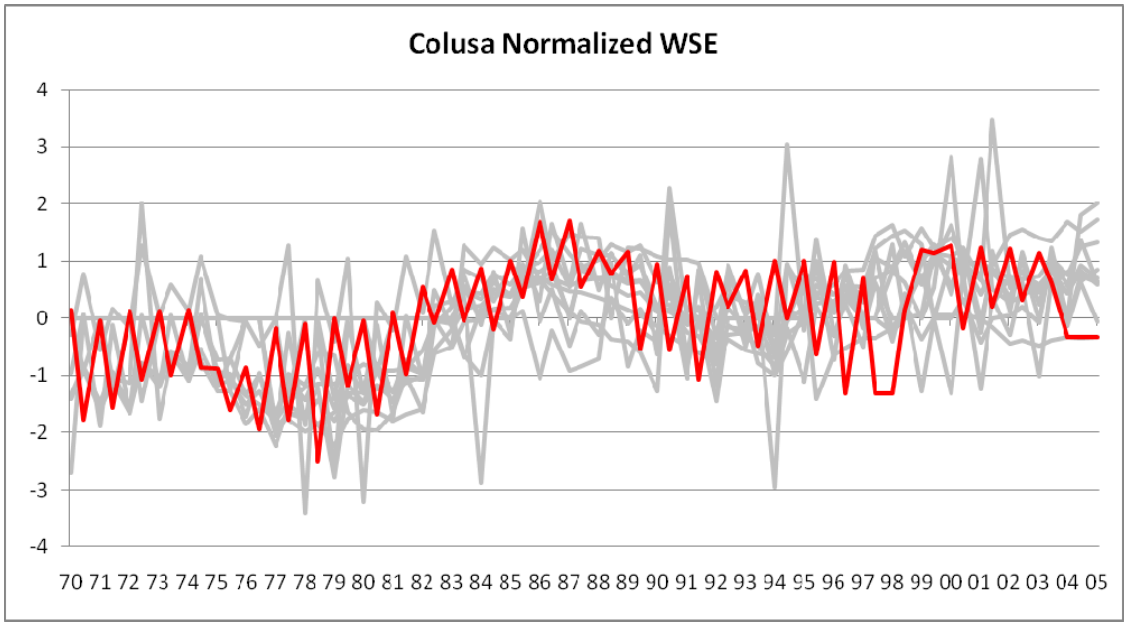


Figure 6-20. Standardized Variation in Groundwater Surface Water Elevation from 11 Wells in the Colusa Basin and Simulated Groundwater Elevations

Chowchilla-Madera Groundwater Basin

The Chowchilla-Madera groundwater basin is of interest because historically it has been subject to major overdraft, and the region relies heavily on groundwater as a source of supply. Bulletin 118 summarizes the groundwater level trends in this basin (DWR, 2003):

> *On average, the subbasin water level has declined nearly 40 feet from 1970 through 2000. The period from 1970 through 1978 showed steep declines totaling about 30 feet. The nine-year period from 1978 to 1987 saw stabilization and rebound of about 25 feet, taking the water levels close to where they were in 1970. 1987 through 1996 again showed steep declines, bottoming out in 1996 at about 45 feet below 1970 levels. Water levels rose about 8 feet from 1996 to 2000. Water level declines have been more severe in the eastern portion of the subbasin from 1980 to the present, but the western basin showed the strongest declines before this time period.*

Figure 6-21 shows the Central Valley PA model simulated groundwater levels for the Chowchilla-Madera groundwater basin in red and the observed levels in gray. The figure shows that the model adequately tracks the general historical trends, but with slightly more dramatic drawdown in the early 1970's. Levels remain low through the mid-decade, but show a strong upward response following the 1976-1977 drought. The model drawdown after 1984 shows an earlier drawdown when compared with the observations, and with a more rapid recovery beginning around 1994.

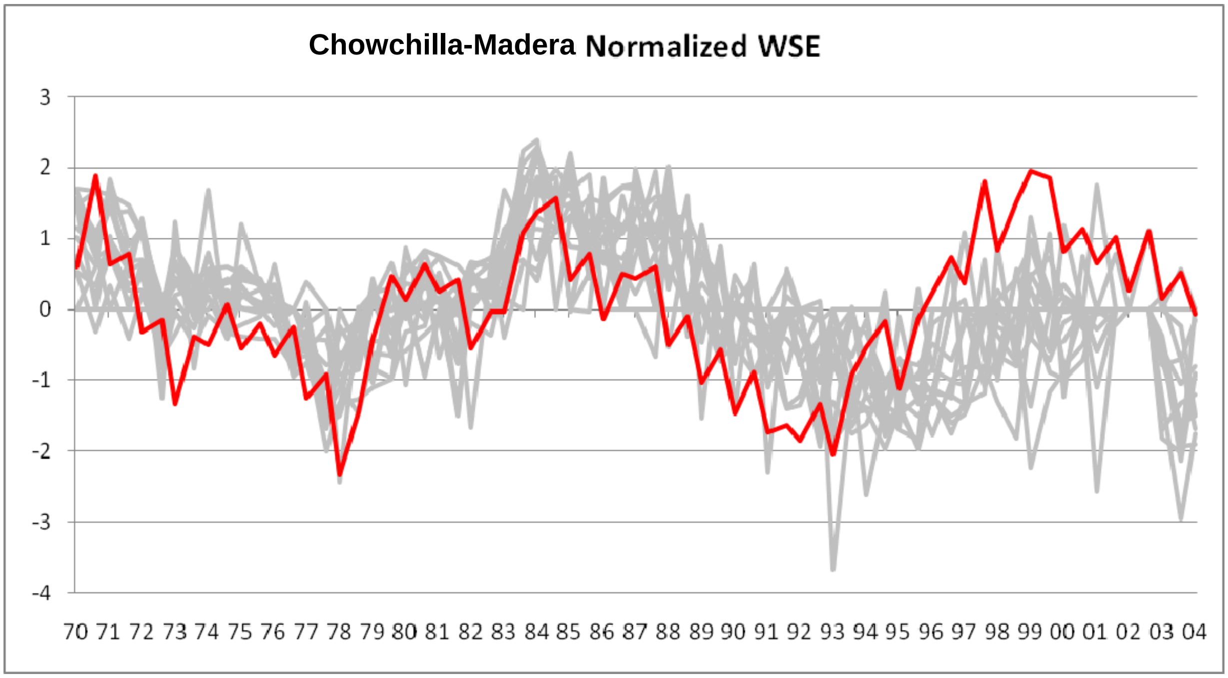


Figure 6-21. Standardized Variation in Groundwater Surface Elevation from 16 Wells in the Chowchilla Basin and Simulated Groundwater Elevations

Other Groundwater Basins

Figure 6-22 and Figure 6-23 show the simulated and observed relative WSE for the Butte and Sacramento-American groundwater basins located in the Sacramento Valley. Generally, the model does reasonable well in reproducing WSE fluctuations. For the Butte basin, there are minimal long-term trends. However, there is dramatic drawdown during the drought, when groundwater supplements surface water to meet irrigation needs.

Figure 6-24 shows the observed and simulated WSE for the Eastern San Joaquin groundwater basin. The Central Valley PA model simulated groundwater level tracks the receding groundwater WSE through the drought of 1977, with recovery to 1985, a decline again to 1994, and then recovery to about 2000.

Together, the simulated traces of groundwater WSE suggest that the Central Valley PA model is generally tracking the overall groundwater mass balance, strengthening its credibility as an effective tool for large-scale water budget analysis.

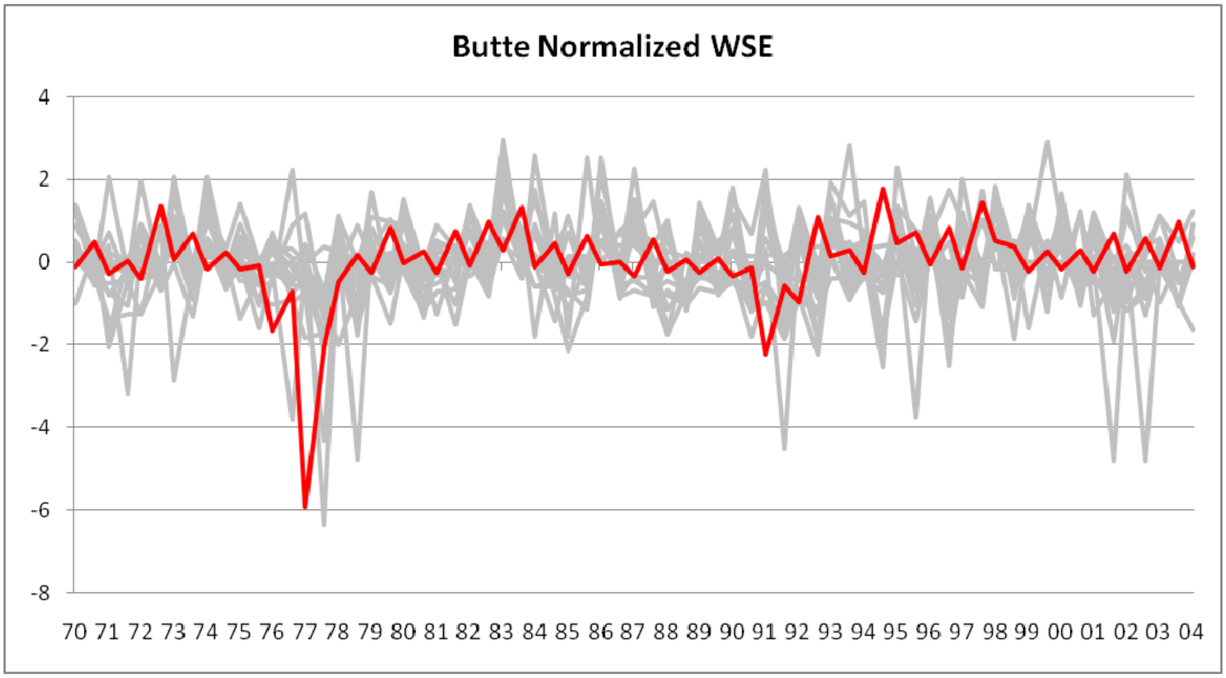


Figure 6-22. Standardized Variation in Groundwater Surface Elevation from 18 Wells in the Butte Basin and Simulated Groundwater Elevations

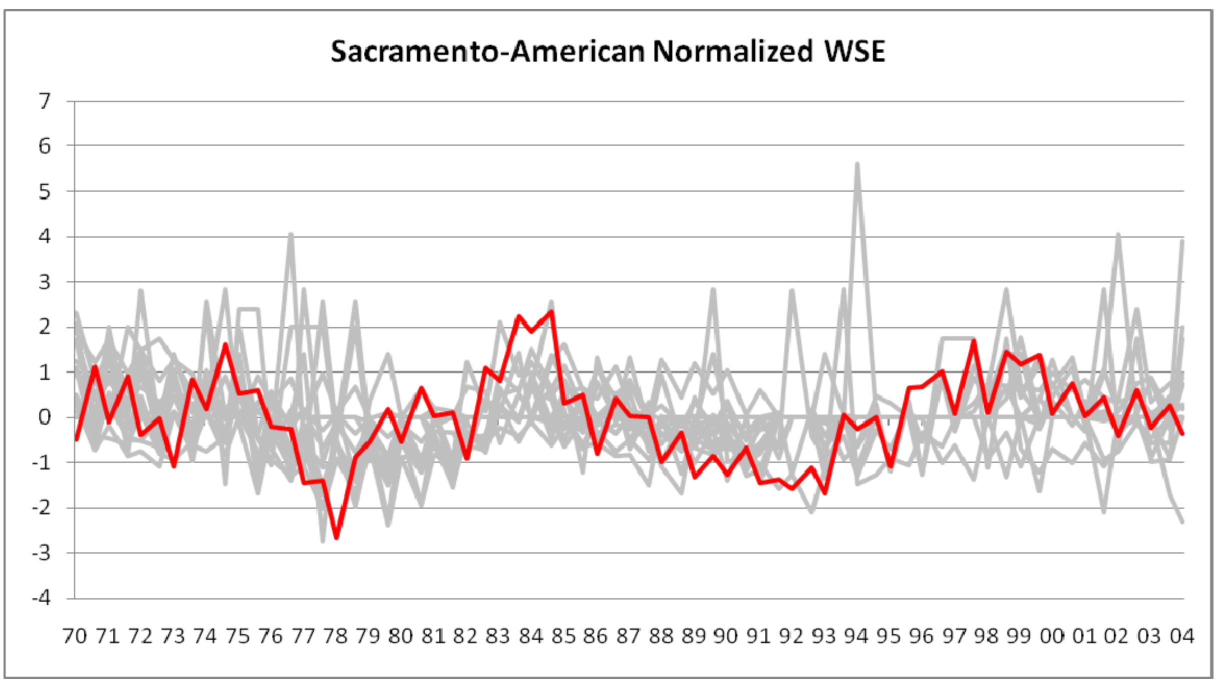


Figure 6-23. Standardized Variation in Groundwater Surface Elevation from 17 Wells in the Sacramento-American Basin and Simulated Groundwater Elevations

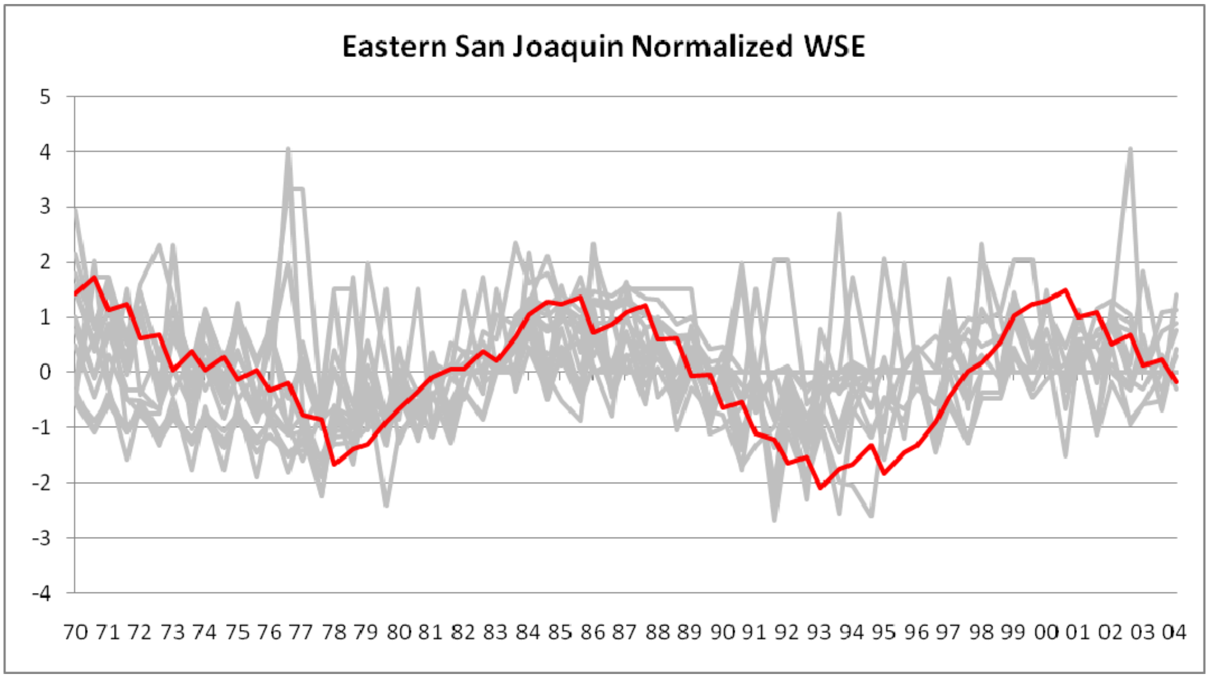


Figure 6-24. Standardized Variation in Groundwater Surface Elevation from 17 Wells in the Eastern San Joaquin Basin and Simulated Groundwater Elevations.

7.0 Conclusions

The WEAP system offers a user-friendly platform for developing hydrologic mass balance accounting tools. WEAP's integrated approach to modeling both the natural and managed components of a 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 historical patterns of observed hydrology. In addition, potential increases in water demand associated with higher temperatures are included in the analysis in a more robust manner than with 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.

The Central Valley PA model is an application of WEAP to the entire Sacramento River and San Joaquin River hydrologic regions. Current representation of the Tulare Lake hydrologic region is limited to the Westlands Water District (though this is being expanded to include the entire region). The spatial scale of the Central Valley PA model broadly corresponds to DWR's planning areas. Additional spatial details have been added, where required, to better simulate specific watersheds or specific groups of water users. Surface water supplies are entirely climate driven. Inflows to the valley floor from upland planning areas are determined using WEAP's internal hydrology module. Snowmelt-dominated watersheds are depicted by model catchment objects, delineated according to elevation. Within the valley floor of the of the Sacramento and San Joaquin hydrologic regions, the Central Valley PA model simulates, at a planning area resolution, agricultural and urban demands, and their supply of water from either surface water or groundwater sources.

The Central Valley PA model includes many management drivers for water operations within the valley floor. User-defined priorities drive the release of stored water to meet many competing objectives, including environmental instream flows and Delta outflow requirements.

7.1 Model Calibration of Upstream Watersheds

The Central Valley PA model has been initially calibrated and validated against a historical set of streamflow, reservoir storage, water demand, water delivery, and groundwater elevation observations.

7.1.1 Calibration of Upstream Watersheds

Model calibration for the upland and mountainous rim watersheds that surround the valley floor has focused on inflows to the major reservoirs on the Trinity River and within the Sacramento River and San Joaquin River hydrologic regions. In general, the Central Valley PA model is able to successfully simulate outflow from watersheds that have no significant upstream storage regulation. In contrast, the model does less well in representing watersheds with significant upstream storage regulation and diversions as model objects for these facilities have not been developed. Examples of this include the watersheds upstream of Camp Far West, Folsom, Pardee and New Don Pedro reservoirs. Additional model development is required to include major upstream diversions and return flows, such as PG&E and Placer County Water Agency's diversions from the Bear River, PG&E canal spills to Lake Folsom, and diversions from Hetch Hetchy Reservoir by the City of San Francisco.

7.1.2 System Operations

The Central Valley PA model is intended to complement the standard set of water planning tools used in California. Given the simplifications made in describing CVP and SWP operations, the model is directed toward 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 existing tools, which can address management issues at a finer scale, or better address conditions in the Delta and constraints on CVP and SWP exports.

Even though there is no explicit representation of individual water right and water contracts, sufficient details of the Central Valley's water system have been captured to generally recreate observed patterns in water supply (i.e., reservoir storage, unimpaired streamflow, groundwater elevation, snow pack), water demand (i.e., crop ET of applied water, urban demand), and system operations. For the 16-year period 1990 to 2005, simulated CVP/SWP exports average 4.6 MAF per year, compared to historical average exports of 5.0 MAF per year. Additional work is required to identify the cause(s) of this 8 percent discrepancy.

7.1.3 Additional Model Testing

Before its use for evaluating growth and land-use scenarios for the next CWP Update, further model validation will be undertaken, focusing on CVP/SWP operations and representation of Delta conditions. This additional validation will be performed through comparison of the Central Valley PA model simulations to CalLite[5]. Additional model refinement is required to account for climate change induced sea-level rise and its effect on Delta salinity.

[5] CalSim is a water resources model jointly developed by DWR and Reclamation for planning and management of the CVP and SWP. CalLite, jointly developed by the same two agencies, serves as a screening model for planning studies relating to the CVP and SWP. While CalLite maintains the hydrologic, operational and institutional integrity as represented in CalSim, the tool is easy to use and reduces run time significantly. Simulation results obtained from a CalLite run are generally within 5 percent of a corresponding CalSim run while CalLite run time is in the order of 5 minutes.

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