# Global Change Impacts on Freshwater Ecosystem Services of the Sacramento Watershed, California USA

Final Report to the Environmental Projection Agency's- Office of Research and Development
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## Contents

# 1. Introduction and Project Background

This study examined the combined effects of climate change, land-use, and other stressors on the ability of the Sacramento watershed to continue to support important aquatic ecological resources and supply valued ecosystem services. Our focus was on freshwater habitat for aquatic life associated with the Sacramento River. The broad goal was to assess how global change-related alterations in surface hydrology, subsurface hydrology, water quality, water demand, water quantity, and the seasonality of flow may affect the provision of important freshwater services. Currently, there are three distinct perspectives on the state of water management in the Sacramento Basin. The first is that the balance between water for food and water for the environment has been destructively tipped in favor of irrigated agriculture and that the only possible future is one based on constant efforts to roll back the irrigated area in the basin. The second is that the Sacramento Basin is too valuable as an agricultural resource to be constrained by environmental considerations and that issues of water for the environment should be dealt with in other, less valuable, areas. Both these views are increasingly giving way to a third perspective that seeks to balance the complex tradeoffs and interactions between water for food and water for the environment in the basin. Establishing this balance is a work in progress, and the prospect of climate change offers the real possibility that the emerging balance will be upset and that further adaptation will be required.

Through this project, an investigative framework was developed that can be applied to similar basins elsewhere. The cornerstone of this approach was the advancement of the Water Evaluation and Planning model Version 21 (WEAP21), which provides for a seamless integration of both the physical hydrology of a region and the water management infrastructure that governs the allocation of available water supplies to meet the range of different water demands. The Sacramento Basin was subdivided into more than 100 sub-catchments, groundwater basins, irrigated areas, and urban demand centers in an attempt to completely characterize the forces that act on water in the basin. A 37-year, monthly climate time series from 1962 to 1998 was used to force a distributed hydrologic model, which simultaneously simulates runoff, groundwater-surface water interactions, and consumptive water demands. The water management infrastructure was superimposed across the physical watershed, and consisted of a multitude of reservoirs, canals and diversions, each with their own rules of operation as represented through WEAP21's allocation logic.

A fundamental component of this project was the engagement of a variety of stakeholders who play a role in watershed management decisions in the Sacramento Basin. To date, the project members have infused themselves into decision making processes in a number of arenas, including federal, state, and local interests. At the federal level three key decision making bodies are taking interest in the framework, including the US Bureau of Reclamation for looking at potential water infrastructure investments, most notably the North of Delta Off Stream Storage (NODOS) project; the CALFED ecosystem restoration program for looking at the potential impacts of climate change on ecosystem restoration; and the US Forest Service, interested in the impacts of climate change on forest and water resource management. At the state level, the California Department of Water Resources is interested in applying the framework to address quantitative issues on climate change in their next Bulletin 160 Water Master Plan; and the project framework will be used to look at climate change on state waster resources as part of a new Climate Imitative being spearheaded by Governor Schwarzenegger's office. At the local level, the project has engaged several water and irrigation districts. These include the El Dorado District, one the fastest growing counties in California, who are interested in the framework for their master plan and drought contingency study, the Placer County water district, interested in applying the framework to study the potential impact of climate change on water supply and hydropower production. The Nevada water district, along with Placer and El Dorado, are developing a regional water planning body, and together are interested in using the framework to address planning issue that include how climate change might impact regional water supply and management.

### 1.1. Roadmap of Report

Climate change and increased climate variability may have a profound impact on the availability of water resources in the Sacramento basin and will consequently affect the use of water for domestic use, the environment and irrigation purposes. The importance of understanding the tradeoffs and interactions among competing water uses will only increase with the added potential of climate change. This report first provides an overview of the Sacramento Basin, both the natural resources and the most important water related issues and problems in the Sacramento basin (Section 2). This is followed by a description the stakeholder process undertaken by the study team (Section 3). Next, an innovative water resources modeling environment (the Water Evaluation and Planning V21) developed to address climate change impacts throughout the watershed is described (Section 4) and the validation of this model as a tool for climate impact assessment is presented in Section 5.

Climate change projections are quantitatively modeled at the basin scale, and impacts are assessed both with and without climate change, particularly from the perspective of food and salmon. These final sections deal with how to cope with these impacts by describing and evaluating regional adaptation strategies for water managers. All of this is put together in a climate change impact assessment for the Sacramento Basin, with a focus on agricultural services (Section 6) and Chinook Salmon (Section 7). Finally, we offer some concluding thoughts in Section 8.

## 2. The Sacramento Basin

A shaded relief map of the continental United States (Figure 2.1) reveals a nearly continuous 1600 km expanse of mountainous terrain that stretches to the Pacific Coast. Within this chaotic western landscape, one feature stands out for its uninterrupted uniformity: the long narrow swathe of California's Central Valley. The Central Valley (Figure 2.2) extends roughly 725 kilometers from north to south between the Sierra Nevada Mountains to the east and the Coast Range Mountains to the west, and appears at first glance to be a largely unbroken plain.

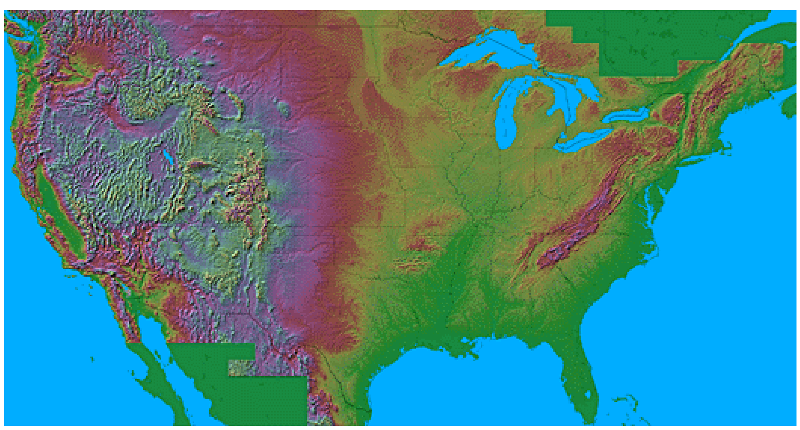

**Figure 2.1: Shaded Relief Map of the Continental United States**

**Figure 2.2: Shaded Relief Map of California**

Adding hydrologic information to the map as illustrated in Figure 2.3A, however, reveals more detail about this expansive valley. The Central Valley is, in fact, comprised of three distinct hydrologic zones: the Sacramento Valley, the San Joaquin Valley, and the Tulare Lake Basin. The Sacramento River, with its headwaters located in the mountains to the north and east of Redding, drains roughly the northern third of the Central Valley. Over its course, the Sacramento River gains its most important tributaries, the Feather and the American Rivers from the Sierra Nevada Mountains to the east. Below the city of Sacramento, the river joins the northward flowing San Joaquin River that drains the middle third of the Central Valley above Fresno. As with the Sacramento, the San Joaquin's most important tributaries also emerge from the Sierra Nevada. The Sacramento and San Joaquin rivers converge in a region known as the Delta prior to flowing from the Central Valley into San Francisco Bay – the combined area is referred to as the San Francisco Bay Watershed (SFBW). Below Fresno, the Central Valley is in fact a closed basin associated with what was once the Tulare Lake, although the lakebed itself has been reclaimed for irrigated agriculture through the impoundment and regulation of the rivers entering that portion of the valley.

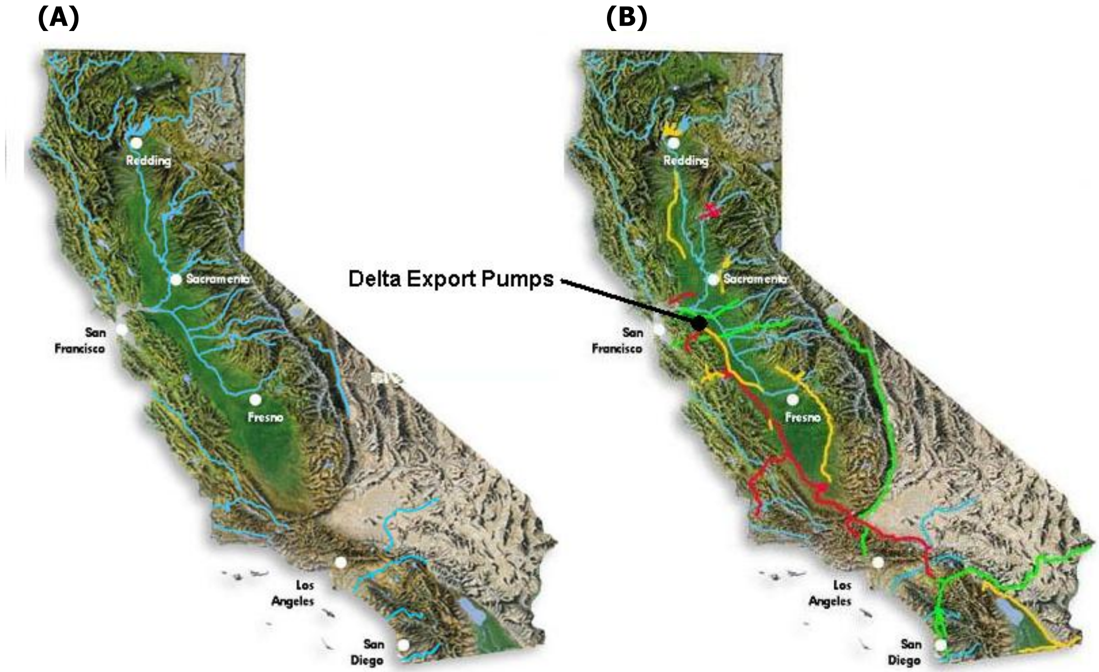


**Figure 2.3: Central Valley Water Resources**

The history of water development in California has substantially blurred the hydrologic distinctions between the Sacramento Basin and the other parts of the state. Figure 3B depicts the primary conveyance infrastructure of the major water projects in California. The scale of water development in the state is among the most substantial in the world, with water often being shifted from one basin to another over distances of hundreds of kilometers in order to satisfy water demands. In fact, much of the water from the Sacramento Basin is exported through pumps in the Delta to satisfy agricultural water demands in the San Joaquin and Tulare Lake Basins, and municipal and industrial demands on the Southern California Coastal Plain between Los Angeles and San Diego. As such, care must be taken when discussing the water resource situation in the Sacramento Basin in isolation from the situation statewide. In fact, to characterize the hydrologic cycle of the Sacramento, it is necessary to extend beyond the hydrologic limits of the Sacramento Basin, into agricultural regions of the San Joaquin and Tulare Lake Basins and the cities of Southern California, in order to place the basin in its proper water management context.

With that caveat, what then are the key distinguishing characteristics of the Sacramento Basin? Approximately 2.9 million of California's 32.7 million inhabitants live in the counties that are either wholly or partially contained within the basin, with the overwhelming majority living in the Sacramento Metropolitan Region. It is anticipated that metropolitan regions in the Central Valley, such as Sacramento, will grow dramatically in the future as the large coastal metropolitan areas, such as the San Francisco Bay Area and Los Angeles, become increasingly crowded. The Sacramento River and its tributaries convey 31 percent of California's average annual runoff, a water resource that has supported the development of over 850 thousand hectares of irrigated agriculture in the basin, as well as expansive irrigation development in other parts of the state. The principal crops grown in the Sacramento Basin include rice, olives, orchard fruits and nuts, corn, alfalfa, tomatoes, and vegetables, and for many of these commodities, the basin is a globally important production center. Not surprisingly, the development of irrigated agriculture has dramatically changed the natural landscape in the basin. As discussed above, only 5 percent of historic wetlands in the Sacramento Basin remain, and only 5 percent of the original riparian forest along the river and its tributaries remains. The health of the aquatic ecosystems throughout the Sacramento and its tributaries is in jeopardy.

## 2.1. Surface and Ground Water Resources

Given the climate conditions common to California, it is not surprising that the surface water hydrology of the Sacramento Basin is dominated by winter snow fall and subsequent spring runoff. Prior to the initiation of large-scale water development in the basin, this climate pattern resulted in flow maxima in the Sacramento River main stem and its principal tributaries — the Feather, Yuba and American Rivers — during the late winter through spring period. Flow minima, which were dramatically reduced relative to peak flows, typically occurred in the late summer and early autumn. Figures 4-5, (A), which are box and whisker plots (showing maximum, high ¼, median, low ¼ and minimum values) of the estimated full natural flow in the Sacramento River at Shasta and the American River tributary, reveal this pattern. Peak runoff in the American system occurs later because these basins include a large percentage of high elevation terrain and therefore are driven more by snowmelt. Water Development in the basin, primarily the construction of major reservoirs on all of the major rivers, has dramatically altered the surface water hydrology in the basin. The operation of these reservoirs generally creates peak flow conditions earlier in the winter as operators manipulate reservoir storage as part of flood control operations in advance of the main runoff season. Spring flows are typically reduced as operators attempt to capture reservoir inflow for later release as part of water supply operations. As a result summer flows are significantly higher than under natural conditions as operators release water downstream to meet summer irrigation demands (Figure 2.4-5, (B)).

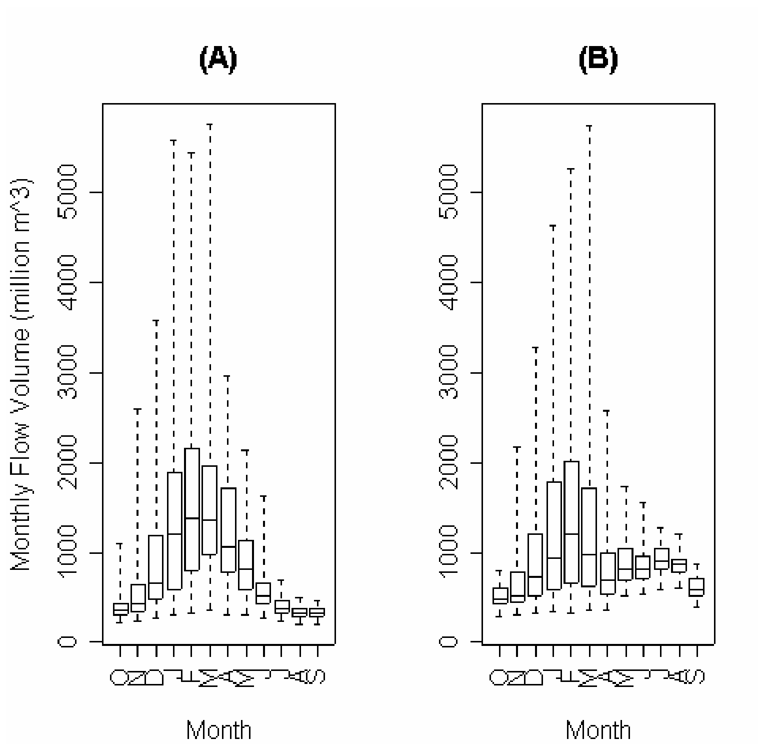


**Figure 2.4: Monthly Flow Volumes in the Sacramento River below Shasta Dam as (A) an Estimate of the Full Natural Flow and (B) the Observed Flow**

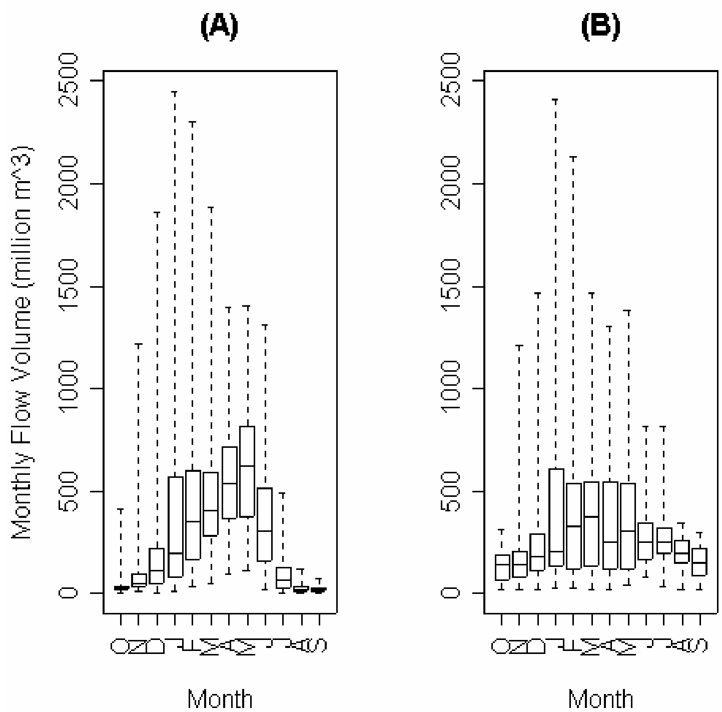


**Figure 2.5: Monthly Flow Volumes in the American River below Folsom Dam as (A) an Estimate of the Full Natural Flow and (B) the Observed Flow**

Operation of the Sacramento Basin's hydraulic infrastructure allows for the allocation of surface water supplies based on average hydrologic conditions and the level of water use associated with the level of development that existed in 1995 (Table 2.1). Of the approximately 27,630 million $m^3$ of average annual runoff in the Sacramento Basin, the vast majority of which flowed into the San Francisco Bay under pre-development conditions, roughly 6877 million $m^3$ is exported to satisfy demand outside of the basin. Roughly 10,819 million $m^3$ is used to meet urban and agricultural demand within the basin. To meet this demand, Sacramento Basin runoff is supplemented with a diversion of 1087 million $m^3$ from the neighboring Trinity River Basin, leaving roughly 11,021 million $m^3$, or 40 percent of the total basin runoff unallocated and available to flow from the Delta to the Bay.

**Table 2.1: Approximate Sacramento Basin Water Budget**

| | | Annual Volume (million $m^3$) |
|---|---|---|
| Sacramento Basin Runoff | A | 27630 |
| Import from Trinity River System | B | 1087 |
| Total Sacramento Basin Supply | C: A+B | 28717 |
| Export to Southern California | D | 1938 |
| Export to Tulare Lake Basin | E | 3020 |
| Export to San Joaquin Valley | F | 1806 |
| Export to San Francisco Bay Area | G | 113 |
| Unexported Sacramento Basin Runoff | H: (A+B)-(D+E+F+G) | 21840 |
| Sacramento Basin Urban Water Use | I | 871 |
| Sacramento Basin Agicultural Water Use | J | 9948 |
| Unallocated Sacramento Basin Runoff | K: H-(I+J) | 11021 |
| As a Percentage of Sacramento Basin Runoff | L: K/A*100 | 40% |

The figures in Table 2.1 are based on average surface water availability conditions. As noted in Figures 2.4 and 2.5, the variability in surface water supplies in the Sacramento Basin is quite dramatic. During dry years, groundwater resources provide a critical water supply buffer that can protect against shortage. While much of the upland portion of the Sacramento Basin is not underlain by productive aquifers, several areas do benefit from the presence of substantial groundwater resources. From a water supply point of view, the most important aquifer is the Sacramento Valley aquifer that lies below the entire Central Valley portion of the Sacramento Basin, and is associated with the Redding and Sacramento groundwater basins, which are themselves comprised of several sub-basins. Groundwater plays a major role in satisfying water demands in the Sacramento Basin. It is also clear that this role varies in importance between sub-basins based both on the physical characteristics of the sub-basin but also as a function of the availability of surface water supplies. While groundwater is used in the Sacramento Basin, the level of use has not generally led to long-term overdraft (not shown).

## 2.2. Water Quality

Prior to the 1960's the main contaminant problems in the freshwater ecosystems of the Sacramento Basin were caused by untreated sewage releases. This resulted in low oxygen concentration and high bacterial concentrations, with subsequent adverse effects on biota. Beginning in the 1950's, however, primary and secondary sewage treatment facilities were installed. Now, despite a five-fold increase in the population of the basin, problems associated with untreated wastes are rare. Currently, the main contaminants of concern are associated with agriculture: organic pesticides and metals have caused impacts on biota. The most notorious instance is that of selenium poisoning of wildlife during the 1980s in the San Joaquin Valley. Agricultural irrigation concentrated naturally occurring selenium from the soil and inserted it into wetland food webs. The result was reproductive failure and increased mortality among a number of bird species (Heinz 1996).

## 2.3. Freshwater Ecosystem Services

In addition to urban and agricultural use, the waters of the Sacramento Basin also support several important ecosystems. Three are of particular note and are presented here, although many other ecosystem services are provided. The first ecosystem component of note is the anadromous fishery, and most notably the Chinook salmon fishery that spends a portion of its life cycle in the Sacramento Basin. The second is the waterfowl migrating along the Pacific Flyway that relies upon wetlands in the Sacramento Basin during their north-south migration. The final ecosystem component of note is the riparian cottonwood and willow forests that shelter many birds and mammals in the Sacramento Basin.

Along the Pacific Coast of the United States, salmon have become the single most important focal point in disputes over water allocation. Prior to their development and regulation, the major rivers in the region literally teemed with fish during the spawning season. Indigenous peoples in the region built both their diets and their cultures largely on the harvest of the silvery fish that can reach weights of up to 20kg. With the arrival of European and American immigrants, fishing communities along the coast quickly emerged to harvest salmon in ocean waters. With the construction of dams that blocked their passage and changes in the flow regime that disrupted the signals fish use to initiate migration from their spawning and rearing grounds in the rivers to the ocean, and back again, the numbers of fish have dramatically declined. While the tradeoff between water development and salmon survival was understood by the planners of the early dam projects, contributing partly to the investment made to construct fish hatcheries in the region, agricultural development was deemed a higher social good.

With time, however, American Indians, commercial fishermen and environmentalists have called into question the logic of this choice. There is a growing feeling that wild salmon, which spawn in the rivers rather than in artificial hatcheries, need to be preserved. The passage of the Endangered Species Act in 1973 provided the legislative mechanism to assure the protection of these fish. In the Sacramento Basin there are four runs of Chinook salmon, named for the time period during which they enter the San Francisco Bay from the Pacific Ocean to begin their migration towards upstream spawning grounds. The Fall Run, Late-Fall Run, Winter Run and Spring Run salmon are each considered to be separate species. In 1992, the U.S. Congress passed an act calling for the sustainable doubling of the average number of Chinook salmon, of all runs, in the system between 1967 and 1991. The actual targets for each of the four Sacramento Basin Chinook salmon runs, detailed by river system, are shown in Table 2.2.

**Table 2.2: Chinook Salmon Restoration Target Numbers by Run and River System**

| | Sacramento R | Clear C | Cow C | Cottonwood C | Battle C | Paynes C | Antelope C | Mill C |
|---|---|---|---|---|---|---|---|---|
| Fall run | 230,000 | 7,100 | 4,600 | 5,900 | 10,000 | 330 | 720 | 5,200 |
| Late-fall run | 44,000 | | | | 550 | | | |
| Winter run | 110,000 | | | | | | | |
| Spring run | 59,000 | | | | | | | 4,400 |
| | Deer C | Butte C | Big Chico C | Feather R | Yuba R | Bear R | American R | |
| Fall run | 1,500 | 1,500 | 800 | 170,000 | 66,000 | 450 | 160,000 | |
| Late-fall run | | | | | | | | |
| Winter run | | | | | | | | |
| Spring run | 6,500 | 2,000 | | | | | | |

Implementation measures designed to help water managers reach these targets included the establishment for minimum flow and temperature standards in the rivers downstream of major dams, the rehabilitation of degraded spawning and rearing habitat, and the construction of fish screens at major river diversions. It is anticipated the combined impact of these efforts will allow for the recovery of Chinook salmon runs. The current commitment of water to meet instream flow objectives is summarized in Table 2.3.

Even with these substantial commitments of water to meet Chinook salmon restoration targets, there is no guarantee that these targets will be met. The case of the Winter-Run is particularly illuminating. The numbers for Winter-Run have fallen so dramatically that they have been afforded special protection and restoration attention by virtue of being listed as endangered under the ESA. The actual number of Winter-Run fish observed at the Red Bluff control point and the restoration target are shown in Figure 2.5. The ambitious nature of this recovery program may indeed create the need to consider augmenting the currently accepted instream flow regime at some point in the future.

**Table 2.3: Instream Flow Requirements to Meet Salmon Targets Relative to Total Annual Flows.**

| River | min (million $m^3$) | low 1/4 (million $m^3$) | median (million $m^3$) | high 1/4 (million $m^3$) | max (million $m^3$) | Typical Instream Flow Requirement (million $m^3$) | As % of median | Dry Year Instream Flow Requirement (million $m^3$) | As % of low 1/4 |
|---|---|---|---|---|---|---|---|---|---|
| Sacramento | 4063 | 6999 | 9437 | 12964 | 21192 | 2399 | 25.4% | 2099 | 30.0% |
| Feather | 1227 | 3296 | 4875 | 7238 | 11617 | 1085 | 22.3% | 725 | 22.0% |
| Yuba | 455 | 1703 | 2737 | 3905 | 6077 | 338 | 12.3% | 242 | 14.2% |
| American | 431 | 1832 | 3201 | 4514 | 7872 | 289 | 9.0% | 289 | 15.8% |

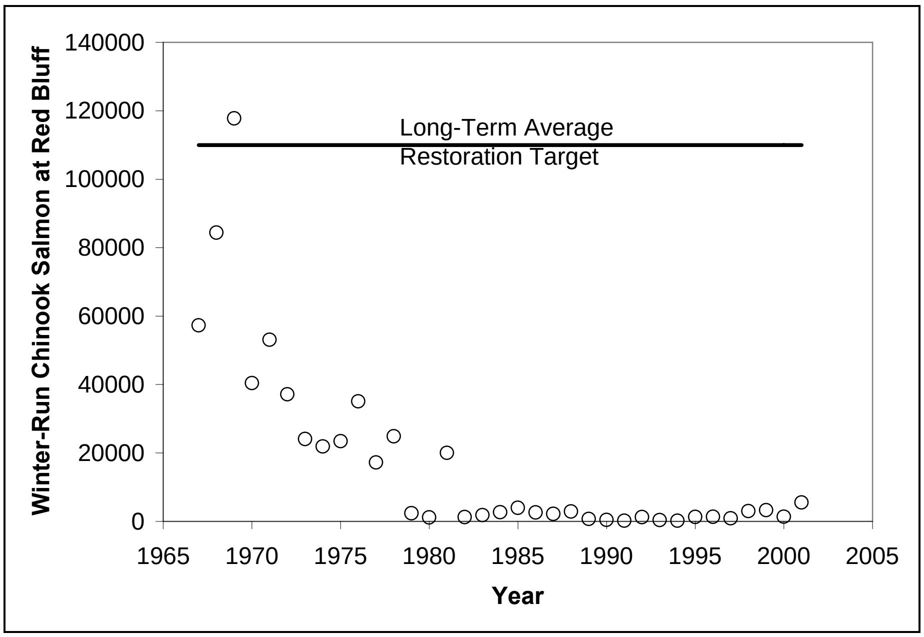


**Figure 2.6: Upper Sacramento River Winter-Run Chinook Salmon**

A second ecosystem component of major importance in the Sacramento Basin is the freshwater wetlands that provide important habitat for migratory water fowl moving along the Pacific Flyway. Prior to irrigation development and urbanization in the region, much of the Central Valley was covered by permanent and seasonal wetlands, and comprised a major portion of the 1.2 to 2.1 million hectares of historic wetlands in California. Over the past century, between 90 to 95 percent of these wetlands have been lost. The remaining area is managed either as part of State and Federal wildlife management units or as private wetland preserves, many of which are owned by hunting clubs. In the Sacramento Basin the U.S. Fish and Wildlife Service operates the Sacramento River National Wildlife Refuge Complex which includes a series of disconnected managed wetland systems with a total surface area of 4540 hectares. As these wetlands are now disconnected from the main river, water must be provided to them in order to maintain permanent wetlands, flood seasonal wetlands, and irrigated areas which provide food for waterfowl.

Until 1992, refuge water managers relied mostly on irrigation drainage and return flows for their water supply. This strategy created both reliability and water quality challenges for the Fish and Wildlife Service. In 1992, however, Congress insisted that refuge water supplies be given a high enough priority to eliminate the need to use irrigation return flows as part of refuge management. Congress further found that even this new supply would not be sufficient to assure optimal long-term management of the refuge complex and instructed that an additional increment of supply be identified. These supplies, referred to as Level 2 and Level 4 supplies, must now be provided to support this ecosystem component. Table 2.4 contains the Level 2 and Level 4 supplies that have been dedicated to the five major components of the Sacramento River National Wildlife Refuge Complex, stated both as absolute requirements and as a percentage of the median annual flow in the Sacramento River system.

**Table 2.4: Managed Wetlands Water Requirements in the Sacramento Basin**

| Wetland | Level 2 Supply (million $m^3$) | Level 4 Supply (million $m^3$) | Total Refuge Supply (million $m^3$) |
|---|---|---|---|
| Sacramento NWR | 57.5 | 61.7 | 119.2 |
| Delevan NWR | 25.8 | 37.0 | 62.8 |
| Colusa NWR | 30.8 | 30.8 | 61.7 |
| Sutter NWR | 29.0 | 37.0 | 66.0 |
| Gray Lodge WMA | 43.7 | 54.3 | 97.9 |
| Total | 186.7 | 220.8 | 407.5 |
| As % of median | 2.0% | 2.3% | 4.3% |

Considering that between approximately 1.5 and 4.8 million individual waterfowl visit the Central Valley between the fall and spring each year, the publicly owned wetlands must be complemented by private wetlands. As previously mentioned, much of the private wetland area is owned by hunting clubs. Increasingly conservancy groups are purchasing land that can either be preserved or restored as wetlands. A final piece of the wetland management puzzle is the extensive rice fields that exist in the Sacramento Basin. Following the harvest in the autumn, the remaining rice stubble was traditionally burned, but air quality impacts associated with this practice have resulted in its severe curtailment. As an alternative, rice farmers would like to re-flood their field in the winter to promote the decomposition of the rice stubble while at the same time providing important resting and feeding habitat for waterfowl species. The farmers would also gain the added benefit of the soil nutrients provided by the accumulation of animal waste. At the current time, work is underway to secure a water supply to allow for the flooding of harvested rice fields in the Sacramento Basin.

The final ecosystem component of interest in the Sacramento Basin with a water supply dimension is the riparian forest community located along the Sacramento River and its tributaries. Historically, 200,000 hectares of riparian forests occupied the Sacramento River flood plain, with valley oak woodland covering the higher river terraces. Use of trees for lumber and fuel, particularly cordwood for steamboats, reduced the extent of the riparian forests in the Sacramento Valley during the late 1800s. Since then, urbanization and agricultural conversion have been the primary factors eliminating riparian habitat. Water development and reclamation projects, including channelization, dam and levee construction, bank protection, and stream flow regulation have altered the riparian system and contributed to vegetation loss. There has been approximately an 89 percent reduction of riparian vegetation along the Sacramento River and its tributaries.

There is now an emerging consensus that the remaining riparian forest should be protected and additional forest reaches restored. Along part of the Sacramento River, the processes of flooding and channel movement continue to sustain a small, viable, remnant riparian community. The plants in the riparian forest of the Sacramento River, which are dominated by cottonwood and willow trees, have many specialized adaptations to life in an environment frequently disturbed by flooding and deposition. The 42 common plant species and diversity of other plants provide food and cover for approximately 11 endangered or threatened species, 126 bird species, many fish species and an array of other wildlife.

While much physical rehabilitation has accompanied the restoration of riparian forest communities, there is also a need to manage flow conditions in the river in ways that mimic the natural fluctuations that typified runoff in the system. Although the exact water supply implications of these flow manipulations are still being assessed, it is likely that restoration of this ecosystem component will influence water supply considerations in the basin.

Through reclamation and modification, the SFBW has lost approximately 86% of its historical wetlands (Frayer et al., 1989). Nevertheless, a large number of goods and services are provided by the remaining aquatic ecosystems (Table 2.5). These services range from extractive uses of water and biota that occur in the aquatic systems (e.g., agricultural irrigation, drinking water, harvestable fish) to *in situ* water use (e.g., for recreation, water quality improvement, or fish and wildlife habitat).

**Table 2.5. Some major services provided by aquatic ecosystems in the Central Valley of California**

| **a). Extractive** | **b). *In situ*** |
|---|---|
| Water for agriculture | Aquatic-based recreation (e.g. boating, fishing ) wildlife viewing) |
| Water for domestic consumption | Flood/drought mitigation |
| Water for industry | Water quality improvement |
| Harvestable fish/wildlife | Water for fish and wildlife habitat |
| | Water for hydro power |
| | Sediment/nutrient transport |

## 3. Stakeholder Involvement

A fundamental component of this project was the engagement of a variety of stakeholders who play a role in watershed management decisions in the Sacramento Basin. Through both formal and informal solicitation, we engaged several stakeholders to aid in the analytic design, analysis, evaluation and interpretation of information. Stakeholders helped guide the selection and prioritization of analytic activities, help establish project goals, share expertise, and provided information in a variety of areas including public values, equity considerations, and relevant decision processes. Their continuous input about their information needs enhanced the relevance and credibility of results.

This project used the concept of "ecosystem services" to articulate specific objectives and project endpoints. The term "ecosystem services" describes both the conditions and the processes through which ecosystems sustain and fulfill human life (Daily 1997). Ecosystem services maintain biodiversity, produce goods, and perform life-support functions. Freshwater aquatic ecosystem services include flood and drought alleviation, waste assimilation and purification capacity, and recreational opportunities. Goods include water for irrigation and domestic use and harvestable aquatic species. The reason for employing the concept of ecosystem services is that it enables individuals from a cross section of society (e.g., ecologists, economists, the general public) to express the values they hold for ecological processes or functions using a common language. Common expressions of value help frame analyses to produce information relevant to decision making. Translating changes in ecological functioning and processes into changes in ecosystem services also enables clearer communication of the effects of global change on aquatic ecosystems. Both social and ecological consequences may be captured and expressed using this concept (CRB, 1997).

### *3.1. Institutional arrangements*

The water management institutional landscape in California is quite complex, and cannot be fully articulated in a couple of paragraphs. Nonetheless, it has important implications in the search for balance between water for food and water for the environment, and as such several key features are described below. The most important characteristic, however, is the fact that no single entity has complete and comprehensive authority over the management of California's water resources.

The organization that most closely approximates the function of water management is the State Water Resources Control Board, commonly referred to as the State Board. The State Board is responsible for implementing the water law of the State of California as articulated by the State Legislature and the Governor (in the United States, the Federal Government has largely ceded responsibility for the administration of water resources to the states). At the current time, the state water code deals primarily with the administration of surface water rights (no regulation of groundwater use is currently mandated in California) and makes several key distinctions with regards to these rights. The most important is that water rights are according to "prior appropriation," whereby the guiding legal doctrine is "first in use, first in right". The State Board then is responsible to assess and assign the priority date to all uses of surface water in the State. They began this exercise in 1914 and assigned all uses of water that existed at that time a "Pre-1914" water right. Since 1914, each new use of surface water approved by the State Board has been assigned a priority date. In times of shortage, the most recent or "junior" water rights holders are cut off completely before the holders of "senior" water rights experience any cutback. The State Board also acts as an administrative court to resolve disputes

Two main types of surface water rights are conferred by the State Board. The first is to divert the waters of the State, and the second is to store the waters of the State. Many of the early water rights cover the right to divert. With the development dams and reservoirs, storage rights were also established. Individuals initially established early water rights, but the most important rights were later established by local government entities that formed to improve water management. For example the Glenn-Colusa Irrigation District has a pre-1914 water right to divert a substantial amount of water from the Sacramento River because this entity very early on built a diversion structure and canal to convey water to irrigated fields. The Modesto Irrigation District has a pre-1914 storage right because in the early 20$^{th}$ century they built a low dam to store the water of the Tuolumne River, a San Joaquin tributary. There are literally hundreds of local public water management organizations similar to these that have been established across California.

In the second half of the 20$^{th}$ Century, the scale of the river diversion and reservoir storage projects undertaken generally exceeded the capacity of local government entities to execute the projects. At this point the Federal Government, through the activity of the United States Bureau of Reclamation and the State of California Department of Water Resources, began to execute large storage and delivery projects. In the Sacramento Basin, the Federal Central Valley Project (CVP) includes Shasta Reservoir on the Sacramento River north of Redding and Folsom Reservoir on the American River upstream of Sacramento. Water from these facilities is used to provide water for irrigation in the Sacramento Basin and for exports from the Delta. The State Water Project (SWP) includes Oroville Reservoir on the Feather River that is used to provide water for export from the Delta. Both projects have been allocated a water right from the State Board to operate their facilities and generally contract with local water management entities to deliver the water to end users.

The role of the Department of Water Resources is complicated because in addition to operating the SWP facilities for the benefit of a limited number of contracting local government entities, DWR is also the primary water planning institution in the State. The California legislature has instructed DWR to issue an updated version of the California Water Plan (Bulletin 160) every five years. This plan is intended to inventory the water supply and demand balance in the State over the coming 20-30 years and to propose any necessary remedial actions should the systems become imbalanced. Obviously the results of this analysis have potential implications in terms of the operation of the SWP.

Superimposed on these complex water rights, water management, and water planning systems are a series of State and Federal laws that can influence the management of water resources. Among these are laws related to the assurance of clean water supplies, the preservation of remaining wetlands, the protection of threatened and endangered species and the designation of important natural features. Historically water interests in the state have sought redress in the courts to resolve water management disputes, often invoking one or several of these legal constructs. These embroilments often created several decades of contentious litigation on a number of fronts, which ultimately convinced all of the water stakeholder communities that the search for consensus would prove more fruitful then continued legal maneuverings. The outgrowth of this realization was the CALFED Bay-Delta Program.

CALFED is a joint state-federal process to develop long-term solutions to problems in the Bay-Delta Estuary related to fish and wildlife, water supply reliability, natural disasters, and water quality. The intent is to develop a comprehensive and balanced plan that addresses all of the resource problems. The public has a central role in the development of a long-term solution. A group of more than 30 citizen-advisors selected from California's agriculture, environmental, urban, business, fishing, and other interests with a stake in finding long-term solutions for the problems of the Bay-Delta Estuary have been chartered under the Federal Advisory Committee Act as the Bay-Delta Advisory Council (BDAC). BDAC advises the CALFED Program on its mission and objectives, the problems to be addressed and proposed actions. BDAC also provides a forum for public participation, and reviews reports and other materials prepared by CALFED staff. The Program is engaged in a three-phase process to achieve broad agreement on long-term solutions.

In the first phase, the CALFED Program developed a range of alternatives consisting of hundreds of actions. The Program conducted meetings and workshops to obtain public input, concluding in September 1996 with the development of a range of alternatives for achieving long-term solutions to the problems of the Bay-Delta estuary. Phase II involved a comprehensive programmatic environmental review process that lead to the identification of three draft alternatives and program plans. These were first released on March 16, 1998, and after lengthy public comment, the final programmatic EIS/EIR was released on July 21, 2000, followed by the Record of Decision (ROD) on August 28, 2000. CALFED is now in Phase III - implementation of the preferred alternative. The first seven years of this phase, referred to as Stage 1, will lay the foundation for the following years. Site-specific, detailed environmental review will occur during this phase prior to the implementation of each proposed action. Implementation of the CALFED Bay-Delta solution is expected to take 30 years.

CALFED is a tenuous institution, in which parties participate voluntarily and from which they can withdraw. Like all consensus-building processes it involves compromises, which are beginning to shape the emerging balance between water for food, water for the environment, and water for urban areas. To date, all parties have determined that this emerging balance is preferable to a return to litigious confrontation, although this sentiment is increasingly tested as CALFED moves from evaluating alternatives to implementing projects. An interesting issue for the is whether this emerging balance can withstand the influence of climate change, or whether additional adaptations will be required in the future. While these larger decision making bodies (DWR and CALFED) are major players in defining water policy for the state, there are also a host of local decision makers such as water utility or irrigation districts that drive water use and planning across the state. To this end, our project attempted to engage both state and local water management entities to bring climate change into their planning process to address their central challenges.

### 3.1.1. Central Challenges for Decision Makers

The two central challenges in California water management are: (1) To overcome the spatial and temporal mismatch between where and when precipitation occurs and where and when needs arise to use water, and (2) To balance the competing needs for water for off-stream uses in agriculture and urban areas and in-stream use for aquatic ecosystems. In California, the mismatch of demand with supply reaches extreme proportions: two thirds of the state's precipitation occurs north of Sacramento, while over two thirds of the state's water use occurs south of Sacramento; and over 80% of the total precipitation occurs between October and March, while about 75% of all water use occurs between April and September. The supreme challenge is, thus, to ensure that water is available in the right place and at the right time.

In light of the emerging consensus that climate change will have an impact on California hydrology and the management of the state's hydraulic infrastructure, it seems prudent that water management decision-making process underway in the state factor these changes into supporting analysis. At present this is not typically the case. There are several reasons for the apparent reluctance to consider the potential implications of climate change on water resource systems. At the most basic level they relate to the legal frameworks used for project planning, typically the National Environmental Protection Act or the California Environmental Quality Act. Climate change is not considered in most water resources planning efforts because there is a general perception that significant changes will not occur within the typical 20 to 30 year planning horizon used in most NEPA and CEQA studies.

While this conclusion may be legitimate within the legal framework used for project planning, it belies the fact that many of the decisions being made have implications that extend beyond this time horizon. A new reservoir, for example, is typically assigned a useful life of 100 years. Investments made to restore damaged ecosystems seek to assure the viability of key, at-risk species in perpetuity, not just for a few decades. Nonetheless, another reason given for discounting climate change in water resource planning and decision making is the uncertainly inherent is future climate predictions. While there is recognition that new infrastructure and ecosystem restoration investments must perform over more that 20 to 30 years, the feeling is that future climate regimes are difficult to define within the limits of the "reasonable and foreseeable" standard used to define future scenarios in NEPA and CEQA studies. As stated previously, the preponderance of analysis seems to be converging on the conclusion that climate change is foreseeable.

Even if change is coming, integrating climate change assessment into water resource decision making processes is hampered by a lack of suitable analytical frameworks for rigorously evaluating the impact of a range of future climate scenarios. In California, most analysis conducted in support of water resource planning responds to the question of how the systems might perform differently should (1) a project be implemented and (2) the past 70 plus years of hydrology repeat itself in the future. Decision-makers are very used to evaluating future projects based on how well they would perform during the 1928-1934, 1976-1978, and 1987-1992 droughts. This analytical time warp has lead to the development of a number of analytical packages that are tightly bound to the historic hydrology and which complicate analysis under different climate and hydrologic futures.

### 3.1.2. An Inventory of California Water Management Decision Making Processes

Through a series of interviews with informed individuals in the stakeholder community, the authors developed a list of environmental decision making processes currently underway in the California water system that are potentially sensitive to climate change. From this a list a reasonable number of decision-making processes amenable to a climate change assessment using the integrated framework was distilled. A decision making process was considered to be a promising candidate if:

- The success of the project would be strongly influenced by hydrologic variability;
- The resources committed to a project were substantial enough to merit a climate change assessment; and

- Some segment of the stakeholder community had expressed a concern about the potential impact of climate change on the project.

The combined threshold of suitability then was one of Sensitivity, Significance and Stakeholder support, or the 3S standard.

Applying the Sensitivity standard eliminated several decision making-processes identified during the interviews. One example was a decision-making process related to defining a remedy to the financial exposure to flood damage risk that was assigned to the State of California by a recent court decision concerning a significant Central Valley flood event in 1986. In this flood a levee on the Yuba River failed releasing a 1.2 m high wall of water into nearby communities. The levee that failed was approximately 80 years old in 1986 and was constructed by a local entity using scrappers to borrow nearby mining debris that was piled up to form the levee without any compaction. It was also aligned on top of porous remnant channels of the Yuba River without constructing a foundation. In the 1920's the Federal and State governments created the Sacramento River Flood Control Project (SRFCP) that included numerous existing levees, including the failed levee, into the SRFCP, often with limited modifications.

After the failure, a group of flood victims sought damages from the State of California and after 18 years of litigation the court assigned liability for damage caused by the levee failure to the state, even though the levee was constructed by another entity. While the legal justifications for the decision are somewhat arcane, the fact is that the State of California has been exposed to future liability for the failure of many miles of poorly constructed levees that it acquired during the creation of the SRFCP. Policy-makers are now developing a response to this new financial exposure. This decision-making process fails to meet the sensitivity standard because the flood risk is real and significant based on the magnitude of current flood events, even without considering climate change. The primary determinant of the appropriate response is the values of property constructed in floodplains protected by old levees rather than any flood frequency analysis. This process will lead to a plan to indemnify the state against the damage caused by future levee failures which may not look significantly different is climate change were to be factored into the discussion.

Several decision making-processes were eliminated by applying the Significance standard. One class of examples is the decision making process leading to the approval of new residential, commercial, industrial and mixed-use real estate developments. Historically land-use decisions in California have been made by cities and counties that were not necessarily the perspective water supplier with the assumption being that a local water supplier would expand its service area to include the new development. This changed in 1992 when Contra Costa County approved the residential development project and identified the East Bay Municipal Utility District as the water provider. East Bay MUD objected claiming that is had insufficient supplies to meet projected demand within its existing service area. In response, the California Legislature enacted laws in 1995 (SB 901) and 2002 (SB 610 and SB 221) that sought to build an assurance of sufficient water supply into land-use decision-making in California.

The combined implication of these laws is that cities and counties must include a "Water Supply Assessment" in the documents considered in the approval of real estate development projects. The basic premise is to assure that sufficient water supply exists over a 20-year planning horizon, even in the case of "multiple dry years". While the details of what constitutes an acceptable WSA are being worked out, frequently through litigation, they are being prepared for projects currently under consideration. In reality climate change is probably not a significant factor in the approval of these projects as other planning considerations such as transportation and educational infrastructure dominate the discussion. Further no single project can likely be assigned the responsibility for a potential failure of the statewide water delivery system under a dramatically different climate and hydrologic future. This is a discussion better suited to higher level water planning dialogues.

Several decision making-processes were eliminated by applying the Stakeholder support standard. One example is Integrated Energy Policy Report called for on a biennial basis by the California Legislature. The report seeks to: identify historic and current energy trends; forecast and analyze potential future energy developments; and recommend new policies for current and pressing energy issues facing the state. The most recent version was published in 2003 and work is underway to prepare the 2005 edition. One mandated component of the Integrated Energy Policy Report is the Electricity and Natural Gas Assessment Report, which among other objectives seeks to assess trends in electricity and natural gas supply, demand, and wholesale and retail prices for electricity and natural gas and assess the adequacy of electricity and natural gas supplies to meet forecasted demand growth. This study helps to inform generation and demand decisions that could be made within the next two years by analyzing their possible intended and unintended consequences through the coming decade.

While there is a recognition that climate change may have a long-term impact on both the overall demand for electricity and the supply generated by installed hydroelectric capacity, this process is geared towards relatively short-term adjustments in the California energy sector. The stakeholders involved with the preparation of the report have many complex considerations to balance in planning these short-term adjustments which limits potential enthusiasm for climate change assessment. The stakeholders involve with this planning dialogue do not necessarily see the value in adding additional complications to the process.

Four examples of decision making processes that meet the 3S standard are the process of updating the California Water Plan, the Integrated Storage Investigation that seeks to define the next generation of water storage projects, the ongoing public investments in ecosystem restoration project in the Central Valley, and a regional water planning process called the Cosumnes, American Bear, Yuba regional planning consortium (CABY). Each of these processes is presented in further detail in the following sections.

**State Water Plan Update**

The California Department of Water Resources is mandated by the Legislature to update the California Water Plan (Bulletin 160) once every five years. This document serves as the foundational statewide analysis upon which a myriad of local water management decisions are tiered (Significance). The last update was published in 1998 and the next edition was scheduled for release in 2003. To date, it has not been released owing to the fact that the approach taken in developing the document has undergone major reform since Bulletin 160-98 was published. Historically the approach taken in preparing Bulletin 160 was to develop projections of future demand and to compare these to the yield provided by currently installed water infrastructure under average and dry conditions (Sensitivity). The analysis typically lead to an assessment of how much additional supply development was required to meet anticipated demand. Further, Bulletin 160 was historically developed by DWR staff with only limited input form the public.

This has changed with Bulletin 160-2003 which has adopted a new portfolio approach to water planning which has its origins in financial planning. Much like an investor would analyze the potential value of a financial portfolio by making different assumptions about the performance of individual assets, the new Bulletin 160 will consider the future, and by nature uncertain, role that a range of factors will play in determining "future" balances between water supply and demand in California. DWR has been guided in this transformation by an advisory panel comprised of over 70 stakeholders. For the first time, one of the potential factors that may influence these futures, climate change, has been recognized and considered (Stakeholder Support).

According to information released by the Department of Water Resoure, in addressing global climate change in the current update of Bulletin 160, rather than focus on causes of global climate change, the update will look at the potential impacts of climate change on water resources in California and potential strategies for adapting to these changes. The word commonly used to describe this approach is "qualitative". The department suggests, however, that future updates of the Water Plan will contain more intensive evaluations of climate change as more data become available, modeling techniques are improved, and management strategies implemented. The intention is to develop a more quantitative assessment of climate change in future editions of Bulletin 160.

The qualitative assessment of climate change in the current version of the Bulletin 160 will be contained primarily in a two papers included in a chapter on climate change in the document refereed to as the Reference Guide. The first of these papers is a survey of the literature documenting the current understanding of global climate change and its potential impact on California. The second paper is a compilation of data for California that attempts to describe the extent to which the climate shifts may already be underway and to lay out important markers that can be used to monitor future changes in climate and hydrology. The decision was made, however, not to include climate scenarios in the analysis of various future portfolios included in this edition of the document but instead to spend some time evaluating various analytical platforms for potentially including this analysis in the next version of the document.

The DWR staff responsible for selecting an analytical platform for future analysis is considering the integrated hydrology/allocation climate change assessment tool developed by the authors and understands its unique integration of watershed response and water management. The authors have undertaken a collaboration with DWR to develop a study on water management tradeoffs associated with future climate change. This will be accomplished by running the WEAP-based Sacramento model under a variety of climate scenarios and priority/preference landscapes and the development of a matrix of tradeoffs (see DWR workplan in the Appendix A).

**Integrated Storage Investigations**

The CALFED Bay-Delta Program is an initiative of several Federal and state agencies designed to develop and implement a plan to better balance the off-stream and in-stream uses of water in California. As part of the CALFED Record of Decision published in 1999, a commitment was made to launch the Integrated Storage Investigation (ISI). This program was designed to identify promising surface storage opportunities and to quantify what stand to be both the substantial costs and benefits of new storage projects (Significance). Storage programs are part of the CALFED water management strategy that combines storage with program actions such as conservation, water transfers, and habitat restoration. Together these complementary actions will contribute to meeting CALFED's water supply reliability, water quality, and ecosystem restoration objectives. The analytical test of performance typically applied in this assessment is how CALFED actions will perform during the dry periods that characterize California hydrology (Sensitivity)

Since its inception, the ISI has successively narrowed the field of candidate surface storage projects to a current list of five projects. These include:

- Raise Shasta Dam on the Sacramento River
- Construct an off-stream reservoir in the Sacramento Valley
- Construct an in-Delta storage facility by converting a Delta island to a reservoir
- Construct an off-stream reservoir in the San Joaquin Valley
- Raise or Replace Friant Dam on the San Joaquin River

Studies are currently being conducted to assess the viability of each of these projects with goal of developing draft environmental documentation by the end of 2006.

The potential off-stream storage facility in the Sacramento Valley is located sparsely populated valley in the Coast Range Mountains. The name of the single community in the valley, Sites, is used to describe the Sites Reservoir project. This facility, which could have a capacity of up to 2500 million m3, will be operated by diverting water from the Sacramento River. Water will be returned to the system from storage either by delivering it to water users on the west side of the Sacramento River in exchange for their normal Sacramento River diversions or through the construction of new conveyance works from the propose reservoir back to the Sacramento River. One issue of concern is the impact that the potential diversions and returns will have on the flow regime in the Sacramento River and on the important in-stream benefits supported by this flow regime. A group of stakeholders has spent over two years designing a required flow regime that could be used to guide the operation of Sites Reservoir. This group recognizes that climate change could significantly impact the components of this flow regime (Stakeholder Support).

The benefits associated with a major water storage project such as Sites Reservoir will depend on the characteristics of future climatic and hydrologic regimes. Using the next phase of support from the U.S. EPA the authors will use the integrated hydrology/allocation climate change assessment framework to simulate the operation of Sites Reservoir under a variety of climate future climate scenarios. The results of this analysis will be provided to interested stakeholders.

**Ecosystem Restoration Investments**

The Ecosystem Restoration Program (ERP) of the California Bay-Delta Authority (formally CALFED) has been created to meet several important objectives. These can be summarized as improving habitat and ecological function in the Bay-Delta system and the recovery and support of important at-risk species. Since its inception seven years ago the ERP has invested tens of millions of dollars (Significance) in a variety of ecosystem restoration projects designed to help assure regulatory compliance for other aspects of the CALFED program, such as water supply and flood control. These projects fall into six broad categories related to the ERP goals that include at-risk species, ecological processes, harverstable species, habitat restoration, non-native invasive species, and environmental water and sediment quality. On critical issue in assessing the utility of these investments is whether over the decades-long time scale anticipated for the realization of a return on ecosystem restoration investment, climate change will have an impact on the design and ultimate success of a particular investment (Sensitivity).

The Yuba River offers an excellent example of this issue. The Yuba drains a watershed of approximately 3500 km2 from the crest of the Sierra Nevada to the confluence of the Feather River near Marysville and Yuba City in the northern Central Valley. The north fork of the Yuba River flows into Bullards Bar Reservoir above the confluence of the north and middle forks. Further downstream, the middle and south forks of the Yuba River flow into Englebright Lake, which provides water-based recreational benefits; 55 million m3 of stored water-right capacity; and hydroelectric generation to meet the annual energy needs for 50,000 homes. The height of Englebright Dam effectively blocks fish migration although biological data suggests that the Yuba River above Englebright historically had habitat that supported anadromous fish species. The Upper Yuba River may present an opportunity to improve habitat for native anadromous fish species whose populations are in decline, while developing a comprehensive plan that will restore ecological health, improve water management and provide positive benefits to the public.

In 1998, the ERP recommended a studies program to determine if returning steelhead trout and spring-run salmon to the Yuba River was feasible by changing Englebright Dam. Through active public involvement and collaborative efforts, stakeholders agreed on key issues and concerns to be addressed in the studies, including upstream and downstream habitat, water quality, sediment, flood risk management, water supply and hydropower, and economics (Stakeholder Support). Study plans were develop for each issue and consultants were engaged to implement the plans. The implication is that if the studies reveal that the restoration of anadromous fish to the Upper Yuba is feasible, then additional funds will be invested to make the necessary structural and operational changes in the system.

As the Yuba River is a classic smowmelt driven Sierra Nevada watershed, there is a strong possibility that climate change will have and influence on the hydrologic conditions in the basin, and that these conditions may have a bearing on the viability of any proposed anadromous fish recovery strategy. Under the second phase of support from the U.S. EPA the authors will refine the current formulation of the Yuba River watershed in the hydrology/allocation climate change assessment tool and to add climate change considerations to the ERP analysis. This information will be provided to stakeholders.

**Integrated Regional Water Management Plan (IRWMP) - Consumes, American, Bear and Yuba Watersheds (CABY)**

In the above Ecosystem Restoration process, the authors have had the opportunity to infuse themselves into a timely regional planning process called the CABY. This IRWMP effort was initiated by a group of water suppliers and watershed and conservation groups with interests in all or some of these four Sierra watersheds outside of Sacramento. The group began initial discussions regarding each entities' respective water issues, and soon realized many shared objectives for the entire region. The group understands the complicated nature and interdependence of the CABY watersheds, and all support the need for an integrated planning effort to develop solutions that support the common and individual objectives for the region.

In support of this action, the study team has undertaken a series of actions to provide modeling support for the CABY IRWMP process (see Appendix B). It has been structured in recognition of the fact that the deadline for the preparation CABY Plan is December 31, 2006 and by the reality that modeling support will certainly be needed as efforts move from regional planning towards the implementation of projects that are consistent with the plan over the coming years. This process was particularly compelling to the study team the CABY member entities wan to evaluate the potential impact of climate change on specific projects that may emerge from the regional planning effort. The project team is developing a WEAP model of the CABY region that can become an analytical engine for evaluating these projects. Activities to Support of the development of the CABY Plan include:

1. Review the final version of the management strategies developed by the three planning workgroups (Water Supply, Water Quality, and Ecosystem and Habitat Protection) in order to assess the potential utility of the WEAP tool in evaluating the effectiveness of each. This assessment will divide the strategies into those that can be directly evaluated using WEAP, those that are not suited to evaluation using WEAP, and those that lie somewhere between these two extremes.
2. Use the existing American River model, developed in collaboration with the El Dorado Irrigation District, to demonstrate how WEAP can be used to test the effectiveness of strategies suited to evaluation using the model. Prepare a technical annex that summarizes this demonstration that can be included in the CABY Plan.
3. Work collaboratively with partners in the CABY process to develop a WEAP model of a similar level of refinement as the existing American River model that represents the entire CABY planning region. This activity will be accomplished through implementation of the following steps
   a. Assemble all appropriate and available data for the CABY region.
   b. Define appropriate sub-watershed boundaries.
   c. Build and parameterized the hydrology portion of the model.
   d. Calibrate the model for sub-watersheds where there is a record of the natural hydrology.
   e. Add physical infrastructure, along with the appropriate representation of operating logic, to the model.
   f. Test the model to determine if it can reproduce observed conditions in the managed portions of the system.
4. Develop a technical appendix that describes the development of the regional model and propose a plan for its use during a later implementation phase of the CABY Plan, that includes considerations of future climatic change.

### *3.2. Project Purpose and Approach*

The two central challenges in California water management are: (1) To overcome the spatial and temporal mismatch between where and when precipitation occurs and where and when needs arise to use water, and (2) To balance the competing needs for water for off-stream uses in agriculture and urban areas and in-stream use for aquatic ecosystems. In California, the mismatch of demand with supply reaches extreme proportions: two thirds of the state's precipitation occurs north of Sacramento, while over two thirds of the state's water use occurs south of Sacramento; and over 80% of the total precipitation occurs between October and March, while about 75% of all water use occurs between April and September. The supreme challenge is, thus, to ensure that water is available in the right place and at the right time.

Since work by Gleick (1987), Lettenmaier et al. (1991) and others, it has been recognized that climate change in California could exacerbate both of these problems. Climate change is likely to cause more winter precipitation in the High Sierra Nevada Mountains along the state's eastern spine to fall as rain rather than snow and to lower the water content of the snow on the ground, leading to an increase in winter runoff as a fraction of total runoff, an increase in the frequency of winter floods, and an earlier start of spring snowmelt. In the absence of additional storage facilities, these changes would have the effect of reducing the state's effective water supply. A large volume of subsequent research has generally reinforced these conclusions, including recent work Dettinger and Cayan, (1995), Glieck and Chalecki (1999), Miller et al (2003)), Lund et al. (2003), Brekke et al. (2004), Dettinger et al. (2004), Stewart et al. (2004), and VanRheenen et al. (2004). Moreover, there is evidence that some of these changes are already under way, with clear signs of a warming trend in California over the past two decades (Dettinger et al., 2004) and the peak snowmelt runoff now occurring one to three weeks earlier in various watersheds of the Sierra Nevada.

Most analyses of the effects of climate change on the California water system are based on simulations of global climate change prepared for use in the 2001 report of the Intergovernmental Panel on Climate Change (IPCC). The latest results from two of the major General Circulation Models, the Hadley model and PCM, became available at the end of 2003, and these were downscaled to California and analyzed (Hayhoe et al 2004). Of the two models, Hadley is considered a medium climate sensitivity model and PCM a low climate sensitivity model. Both models show sharply different climate impacts for California in their new versions than what they had shown in their previous versions.

While the details differ among the models (and depend on the specific emissions scenario being considered), both models now predict an increase in temperatures in California. Previous versions of these models had shown a warming of about 1-4$^{o}$C in the winter by the end of the century, and a similar degree of warming in the summer. The new versions suggest a slightly higher level of warming in the winter (about 2-4.5 $^{o}$C), but a substantially warming in the summer, amounting to 2.5-4.5 $^{o}$C under a low emissions scenario (B1) and a dramatic increase of 4.5-9.5 $^{o}$C under a high emissions scenario (A1fi). A consequence of the temperature increase is a sharp decline in the Sierra Nevada snowpack.

By the beginning of April in a "good" water year, the total amount of water stored in the Sierra snowpack roughly equals the total amount stored in major reservoirs; thus, the snowpack effectively doubles the ability to store water for warm-season uses. By mid-century, the snowpack is projected to decline by about 25-40%. Toward the end of the century, the loss of snowpack could reach 30-70% (4300-11,100 million $m^3$ of storage) under the low emissions scenario, and a stunning 70 – 90% (11,000-13,500 million $m^3$) under the high emissions scenario (Hayhoe et al., 2004).

It remains to be seen whether the new versions of the other major GCMs will show similar changes when downscaled to California. However, it is clear that climate change has the potential to cause some major disruptions to the California water system, starting within the next two or three decades and continuing over the rest of the century, by which time the population of California is likely to double. Climate change is likely to exacerbate the mismatch in the timing and location of precipitation and demand to sharpen the competition between off-stream and in-stream water uses. The predicted reduction in the snowpack and the earlier timing of snowmelt will greatly complicate the task of managing California's reservoirs, and make for a more difficult tradeoff between filling reservoirs to capture runoff for warm-season uses versus leaving empty space for flood control in the event of a possible late winter storm. Any future adjustment of the current reservoir operations regime in response to this tradeoff has implications for meeting ecosystem objectives in the system.

In light of the emerging consensus that climate change will have an impact on California hydrology and the management of the state's hydraulic infrastructure, it seems prudent that water management decision-making process underway in the state factor these changes into supporting analysis. At present this is not typically the case. There are several reasons for the apparent reluctance to consider the potential implications of climate change on water resource systems. At the most basic level they relate to the legal frameworks used for project planning, typically the National Environmental Protection Act or the California Environmental Quality Act. Climate change is not considered in most water resources planning efforts because there is a general perception that significant changes will not occur within the typical 20 to 30 year planning horizon used in most NEPA and CEQA studies.

While this conclusion may be legitimate within the legal framework used for project planning, it belies the fact that many of the decisions being made have implications that extend beyond this time horizon. A new reservoir, for example, is typically assigned a useful life of 100 years. Investments made to restore damaged ecosystems seek to assure the viability of key, at-risk species in perpetuity, not just for a few decades. Nonetheless, another reason given for discounting climate change in water resource planning and decision making is the uncertainly inherent is future climate predictions. While there is recognition that new infrastructure and ecosystem restoration investments must perform over more that 20 to 30 years, the feeling is that future climate regimes are difficult to define within the limits of the "reasonable and foreseeable" standard used to define future scenarios in NEPA and CEQA studies. As stated previously, the preponderance of analysis seems to be converging on the conclusion that climate change is foreseeable.

Even if change is coming, integrating climate change assessment into water resource decision making processes is hampered by a lack of suitable analytical frameworks for rigorously evaluating the impact of a range of future climate scenarios. In California, most analysis conducted in support of water resource planning responds to the question of how the systems might perform differently should (1) a project be implemented and (2) the past 70 plus years of hydrology repeat itself in the future. Decision-makers are very used to evaluating future projects based on how well they would perform during the 1928-1934, 1976-1978, and 1987-1992 droughts. This analytical time warp has lead to the development of a number of analytical packages that are tightly bound to the historic hydrology and which complicate analysis under different climate and hydrologic futures.

With the support of the U.S. Environmental Protection Agency, the authors developed an integrated hydrology/water management climate change assessment framework (hereafter the integrated framework) for the Sacramento Valley (Figure 1), which apart from being calibrated against historic conditions is unbound from the historic hydrologic record. While this framework responds to the third challenge, and the emerging consensus about the likelihood of future climate change reduces the uncertainty associated with future climate scenarios, the first reason given for discounting climate change, namely the relatively short planning horizon of most planning studies, remains. After presenting a summary of the integrated framework, this paper identifies specific decision-making processes that are well suited for climate change analysis in the face of this claim and describes the role that the new analytical framework could play in arriving at a water management decision.

## 4. Hydrologic Modeling and Future Projections

In light of the emerging consensus that climate change will have an impact on California hydrology and the management of the state's hydraulic infrastructure, it seems prudent that water management decision-making process underway in the state factor these changes into supporting analysis. At present this is not typically the case. There are several reasons for the apparent reluctance to consider the potential implications of climate change on water resource systems. At the most basic level they relate to the legal frameworks used for project planning, typically the National Environmental Protection Act or the

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Even if change is coming, integrating climate change assessment into water resource decision making processes is hampered by a lack of suitable analytical frameworks for rigorously evaluating the impact of a range of future climate scenarios. In California, most analysis conducted in support of water resource planning responds to the question of how the systems might perform differently should (1) a project be implemented and (2) the past 70 plus years of hydrology repeat itself in the future. Decision-makers are very used to evaluating future projects based on how well they would perform during the 1928-1934, 1976-1978, and 1987-1992 droughts. This analytical time warp has lead to the development of a number of analytical packages that are tightly bound to the historic hydrology and which complicate analysis under different climate and hydrologic futures.

With the support of the U.S. Environmental Protection Agency, the authors developed an integrated hydrology/water management climate change assessment framework (hereafter the integrated framework) for the Sacramento Valley (Figure 4.1), which apart from being calibrated against historic conditions is unbound from the historic hydrologic record. While this framework responds to the third challenge, and the emerging consensus about the likelihood of future climate change reduces the uncertainty associated with future climate scenarios, the first reason given for discounting climate change, namely the relatively short planning horizon of most planning studies, remains. After presenting a summary of the integrated framework, this paper identifies specific decision-making processes that are well suited for climate change analysis in the face of this claim and describes the role that the new analytical framework could play in arriving at a water management decision.

## *4.1.* WEAP's Integrated Hydrology/Water Allocation Framework

At the most basic level, the integrated framework (Yates et al. 2005a, b), which has been constructed on the WEAP platform (Raskin 1992), recognizes that water supply is defined by the amount of precipitation that falls on a watershed. Further this basic supply is progressively depleted through natural watershed processes, where the watershed itself is the first significant point of depletion through evapotranspiration (Mahmood and Hubbard, 2002). The residual supply, after the satisfaction of evaporative demands throughout the watershed, is the water available to the water management system. Thus, as in the physical realm there is a seamless link in the WEAP framework between climate, land use/land cover conditions, and the management of the water system.

Specifically the natural watershed process component of WEAP accounts for two different hydrologic realities (Figure 4.2). The first is the concept that precipitation in upstream watersheds, with complex topography, steep slopes, and abrupt hills and valleys, contributes to gaining streams, with a relatively short time lag (Burness et al. 2004; Eckhardt and Ulbrich 2003; Winter et al. 1998; and Winter 2001). Conversely, downstream watersheds with flatter terrain tend to overlie alluvial aquifers linked to river systems to which they can contribute flow and from which they can receive seepage, depending on hydrologic conditions. These groundwater systems also provide storage that can be used to satisfy demands. As shown in Figure 4.2, the WEAP framework also allows for the use of surface water supplies to satisfy demand in these downstream watersheds, supplies which are generated by watershed processes and managed by the installed hydraulic infrastructure.

An application of this integrated framework was developed for the Sacramento Valley, which includes three of the primary surface water storage facilities in the California water system, Lake Shasta, Lake Oroville and Folsom Lake. The current operation of these facilities is based on the assumption that a large portion of the available water supply in the spring months is stored in the higher elevation snow pack. Figures 3-4 show the degree to which the calibrated version of the integrated framework was capable of capturing the hydrology and management of the system in terms of Storage in Lake Shasta and the total surface water outflow from the Sacramento Valley. The successful calibration of the integrated framework allow for it to be confidently deployed in the context of ongoing water management decision making processes in California in order to introduce a consideration of climate change into these dialogues. The following section describes a process that was used to identify suitable decision making processes.

## *4.2.* The Water Evaluation and Planning Model (WEAP21)

The Water Evaluation and Planning (WEAP) model has a long history of development and use in the water planning arena. Raskin et al. (1992) first applied it to a study on the Aral Sea, but that version of WEAP had several limitations, including an allocation scheme that treated rivers independently, gave priority to demands on upstream sites over downstream sites, and assured demand sites that preferred groundwater to surface water were last in line in getting surface water allocations. Given these deficiencies, WEAP21 introduces major advances including a modern Graphic User Interface (GUI), a robust solution algorithm to solve the water allocation problem and the integration of hydrologic sub-modules that include a conceptual rainfall runoff and an alluvial groundwater model and a stream water quality model.

WEAP21 data objects and the model framework are graphically oriented, with the software built using the Delphi Studio® programming language (Borland Software Corporation), and also utilizing MapObjects® software libraries from the Environmental Systems Research Institute (ESRI) to allow for spatial referencing of watershed attributes (e.g. river and groundwater systems, demand sites, wastewater treatment plants, watershed and political boundaries, and river reach lengths). WEAP21 model simulations are constructed as a set of scenarios, where simulation time steps can be as short as one day, to weekly, to monthly, or even seasonally with a time horizon from as short as a single year to more than 100 years.

The Current Accounts provide a snapshot of actual water demand, pollution loads, resources and supplies for the system for the current or a baseline year. Scenarios are alternative sets of assumptions such as different operating policies, costs and factors that affect demand such as demand management strategies, alternative supply sources and hydrologic assumptions, with changes in these data able to grow or decline at varying rates over the planning horizon of the study. Among others, the scenarios are evaluated with regards to supply sufficiency, cost and average cost of delivered water, the meeting of in stream flow requirements, hydropower production, and sensitivity of results based on uncertainty of key variables. These could include reductions in water demand due to demand side management, assumptions of rates of growth, incorporation of technical innovation, changes in supply, etc.

The advancements of WEAP21 in this project have been based on the premise that at the most basic level, water supply is defined by the amount of precipitation that falls on a watershed or a series of watersheds with this supply progressively depleted through natural watershed processes, human demands and interventions, or enhanced through watershed accretions. Thus, WEAP21 adopts a broad definition of water demand, where the watershed itself is the first point of depletion through evapotranspiration via surface-atmosphere interactions (Mahmood and Hubbard, 2002). The residual supply, after the satisfaction of evaporative demands throughout the watershed, is the water available to the management system, which is typically the head flow boundary condition of a water planning or operations model. In addition to streamflow generated via hydrologic simulation, the user is free to prescribe time series of head flows for the surface water system and groundwater recharge for focusing solely on water management.

Figure 4.2 is a screenshot from the WEAP21 interface of a stylized water resource system, showing the drag-and-drop template from which demands and water resource objects can be created (demands, sub-catchments, rivers, reservoirs, transmission links, instream flow requirements, etc.) and placed on the interactive workspace. A WEAP21 study begins by dividing the watershed into a number of irregular sub-catchments (SC's) based on watershed boundaries, climatological regions, land use categories or combinations thereof. When combined, the sub-catchments account for the total study area of the encompassing watershed. This hypothetical watershed has been divided into four sub-catchments, where each is fractionally subdivided into several land cover classes, which combine to account for a total catchment area of 1250 km2 (Table).

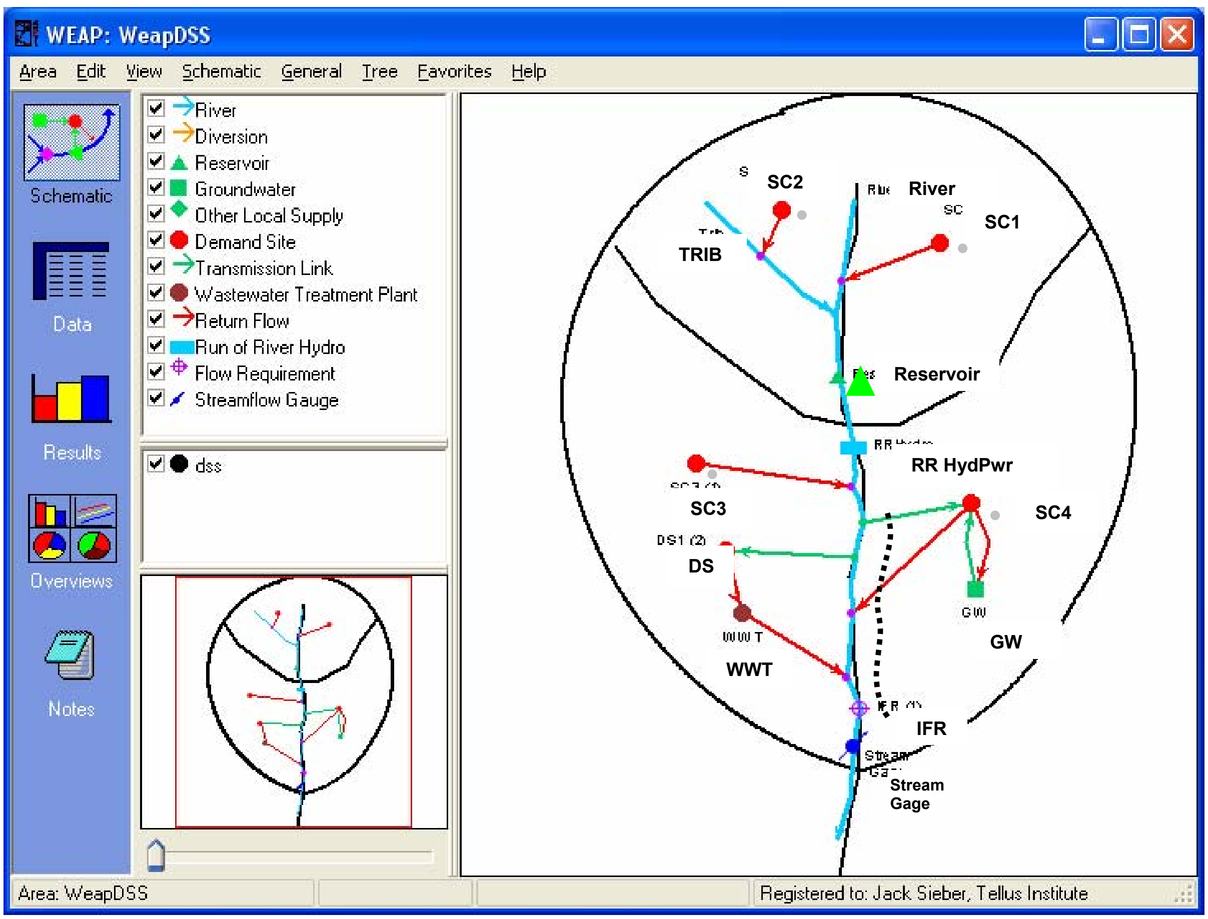



**Figure 4.2. An example of a simple watershed, sub-divided into four catchments (SC's) using the WEAP21 graphical user interface model building tools. The dark, dashed line segment on the lower portion of the river indicates the river length that is hydraulically connected to the local groundwater aquifer, GW. DS is a conventional demand site, WWT is a wastewater treatment plant, IFR is an instream flow requirement, RR HydPwr is a run-of-the-river hydropower object.**

A conceptual model of the hydrologic cycle is defined for each sub-catchment using a semi-distributed water balance approach that yields streamflow and groundwater recharge throughout the watershed (Yates 1996; Yates and Strzepek 1998). Each sub-catchment is represented by the dark circles with gray insets, with arrows originating from each of the SC's that link its hydrologic output to a stream or a groundwater aquifer. So in the case of SC1, generated runoff goes to the river while for SC2, the flow goes to the tributary. Watershed demand in these sub-catchments is estimated by the hydrologic model as evapotranspiration by trees, grasslands, and shrubs.

Table. Description of the base-year land use categories for the four SC's, given as a percentage of their total area, where only SC4 has irrigated land cover types.

| Base-Year 2000 | Irrigated | SC1 | SC2 | SC3 | **SC4** |
|---|---|---|---|---|---|
| Total Area (km2) | | 250 | 330 | 350 | 320 |
| Deciduous | No | 35 | 40 | 15 | |
| Evergreen | No | 25 | 20 | 20 | |
| Grassland | No | 20 | 30 | 55 | 35 |
| Shrub | No | 20 | 10 | 10 | 20 |
| Pasture | Yes | | | | 10 |
| Grains | Yes | | | | 10 |
| Orchards | Yes | | | | 5 |
| Vegetables | Yes | | | | 10 |
| Rice | Yes | | | | 10 |
| TOTAL | | 100% | 100% | 100% | 100% |

The SC4 sub-catchment also applies the surface hydrology model, but is linked to an alluvial groundwater aquifer, represented by the small rectangle and the fact that a return flow arrow is drawn from SC4 to the groundwater object. SC4 can draw water from either the surface supply or from the groundwater aquifer. Note that the surface supply is labeled with a "1", which indicates it is the preferred source to meet SC4's demand, while groundwater has a value of "2" indicating it is a secondary supply. The Watershed's demand in SC4 is both through evapotranspiration by grasslands and the irrigated demand for pasture, grains, orchards, vegetables, and rice (Table). In addition, the node DS1 (represented by a single dark circle) is a municipal center that draws water from the river, returns it to a waste water treatment plant, and then to the river. The river's mainstem includes a reservoir object, a run-of-the-river hydropower object, an instream flow requirement, and a stream gage.

### 4.2.1. The Bio-Physical System: the Physical Hydrology Module

The WEAP21 model includes an irregular grid water balance model that can account for hydrologic processes within a watershed system and can capture the propagating and non-linear effects of water withdrawals for different uses. Our approach is informed by Beven's (2002) article, Towards and alternative blueprint for a physically based digitally simulated hydrologic response modeling system, where he challenges the trend towards physically-based modeling systems. He argues that watershed scientists increasingly attempt to apply first-principle fluid dynamics models in a manner similar to atmospheric scientists and oceanographers without achieving marked improvement over reduced form representations of the hydrologic cycle. Beven points out that in hydrology the small-scale flows are largely dominated by the local geometry and local boundary resistances of the individual flow paths rather than the dynamics of the fluid itself and that these geometries cannot be known in significant detail. Beven concludes with a call to differentiate between physically based in the sense of being based on defined assumptions and theory, and physically based in the sense of being consistent with observations.

The physical hydrology component of WEAP21 has been developed to account for two different hydrologic realities. The first is the notion that precipitation in sub-catchments located in the upstream portions of watersheds, with complex topography, steep slopes, and abrupt hills and valleys, contributes to groundwater baseflows that serve a gaining stream year-round, with a relatively short time lag (Burness et al. 2004; Eckhardt and Ulbrich 2003; Winter et al. 1998; and Winter 2001). Conversely, sub-catchments located in lower portions of watersheds with flatter terrain tend to contribute to alluvial aquifers that are directly linked to the river system to which they can contribute flow (gaining streams) and from which they can receive seepage (losing streams), depending on hydrologic conditions. These groundwater systems can also provide storage from which users can draw water to satisfy demands (Figure 4.3).

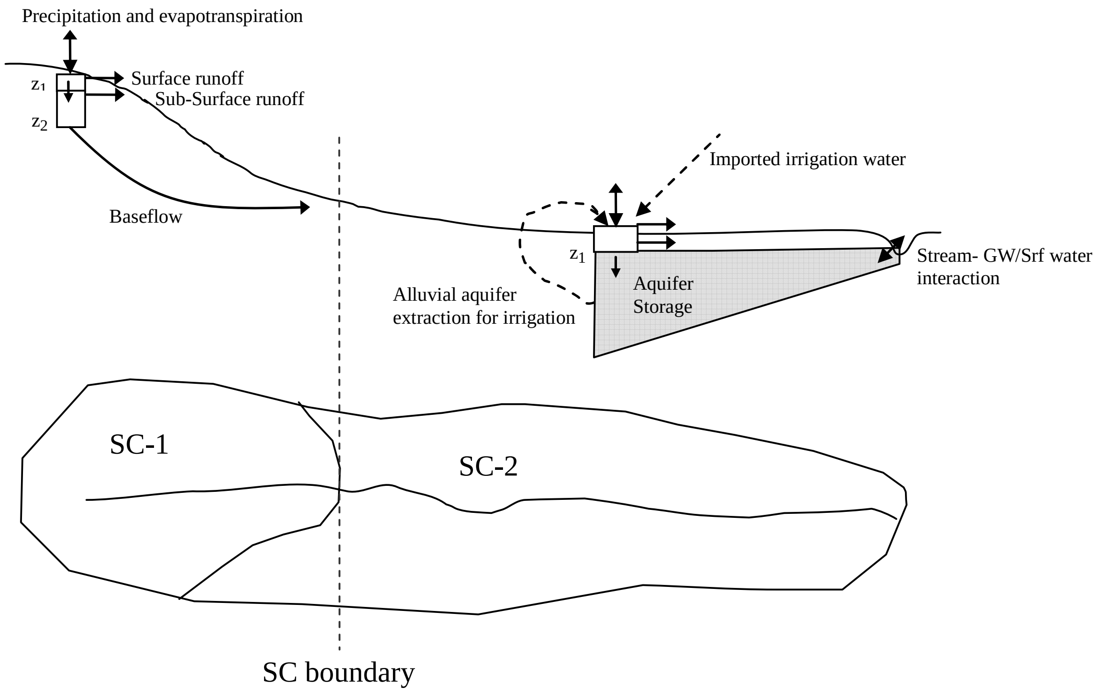



**Figure 4.3. This schematic shows a watershed broken into two sub-catchments. SC-1 is a headwater catchment, without surface-groundwater interaction and applies the two "bucket" water balance model. SC-2 is characterized as being in a valley area, where the surface hydrology applies the single bucket water balance with recharge to an underlying alluvial aquifer which as groundwater-surface water interaction.**

### 4.2.2. Surface water hydrology

The physical hydrology model consists of several conceptually simple components that are combined to be computationally efficient, but with enough specificity to capture important hydrologic process and address key water resource issues. For a given time step, the hydrology module is first run to update the hydrologic state of the watershed, and thus provides mass balance constants used in the linear allocation problem in a second procedure within the same time step.

A one dimensional, 2-storage soil water accounting scheme uses empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff or interflow, and deep percolation (Yates 1996). Figure 4.4 shows the components of this conceptual model that allow for the characterization of land use and/or soil type specific impacts on runoff and groundwater recharge. A watershed is first divided into sub-catchment (SC's) and then further divided into N fractional areas, where a water balance is computed for each fractional area, j of N. Climate is assumed uniform over each fractional area where a continuous mass balance equation is written as,

$$Sw_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{\frac{LAI_j}{2}} - f_j k_j z_{1,j}^2 - (1 - f_j)k_j z_{1,j}^2 \quad \text{Eq. 1}$$

with the relative soil water storage, z1,j given as a fraction of the total effective storage and varies between 0 and 1, where 0 represents the permanent wilting point and 1 field capacity. The total effective storage of the upper layer is approximated by an estimate of the soil water holding capacity (Swj in mm) prescribed for each land cover fraction, j.

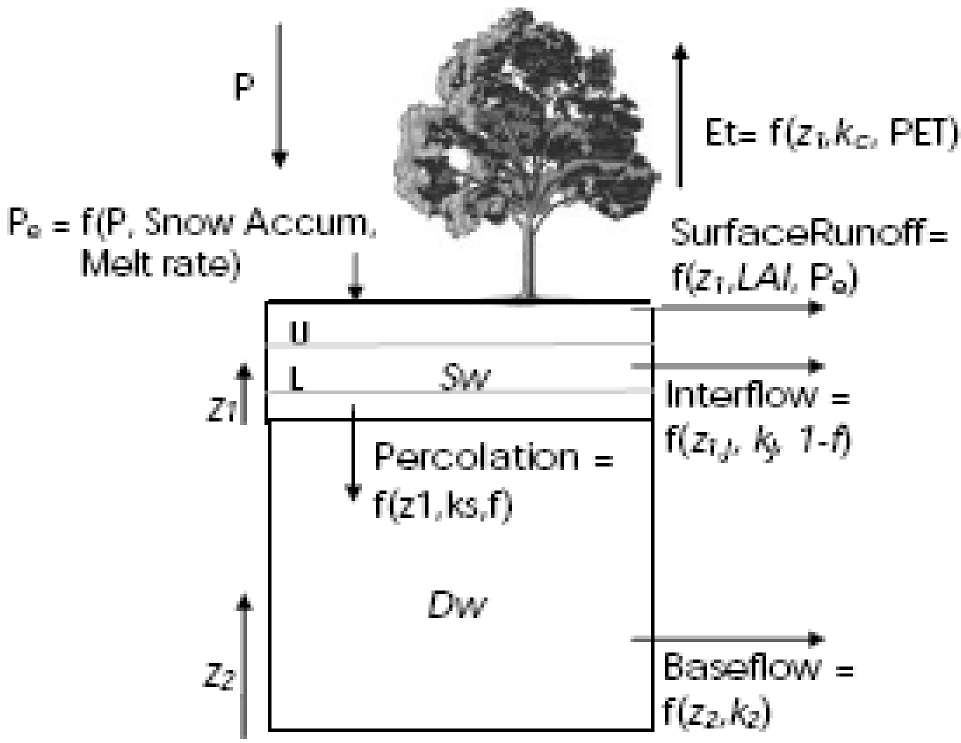



**Figure 4.4. Schematic of the two-layer soil moisture store, showing the different hydrologic inputs and outputs for a given land cover or crop type, j**

WEAP21 includes a simple temperature-index snowmelt model which computes an effective precipitation Pe. The model estimates snow water equivalent and snowmelt from an accumulated snowpack in the sub-catchment, where mc is the melt coefficient given as,

$$m_c = \begin{cases} 0 & T_i < T_s \\ 1 & T_i > T_l \\ \dfrac{T_i - T_s}{T_l - T_s} & \text{if} \quad T_s \le T_i \le T_l \end{cases} \quad \text{Eq. 2}$$

with Ti the observed temperature for period i, and Tl and Ts are melting and freezing temperature thresholds, with the melt rate is given as,

$$m_i = \min(Ac_i m_c, Em) \quad \text{Eq. 3}$$

Snow accumulation, Aci is a function of mc and the observed total precipitation, Pi

$$Ac_i = Ac_{i-1} + (1 - m_c)P_i - m_{i-1} \quad \text{Eq. 4}$$

where Em is the available melt energy converted to an equivalent water depth/time. The effective precipitation, Pe is then computed as

$$P_e = P_i m_c + m_i \quad \text{Eq. 5}$$

The second term in Eq.1 is evapotranspiration from the fractional area, j where PET is the Penman-Montieth reference crop potential evapotranspiration given in mm/day and kcj is the crop/plant coefficient for each fractional land cover. When the model is run with longer time steps, PET is scaled to an appropriate depth/time (Allen et al. 1998). The third term represents surface runoff, where LAI is the Leaf and Stem Area Index (LAI), with the lowest LAIj values assigned to the land cover class that yields the highest surface runoff response, such as bare soils. The third and fourth term are the interflow and deep percolation terms, respectively, where the parameter kj ,is an estimate of the upper storage conductivity (mm/time) and fj is a quasi-physical tuning parameter related to soil, land cover type, and topography that fractionally partitions water either horizontally, fj or vertically (1- fj). The surface and interflow runoff contributions from the upper store, Ro from each sub-catchment at time t is,

$$Ro(t) = \sum_{j=1}^{N} A_j \left( P_e(t) z_{1,j}^{\frac{LAI_j}{2}} + f_j k_j z_{1,j}^2 \right) \quad \text{Eq. 6}$$

where Aj is the contributing area of each land cover class, j. For sub-basins without a modeled aquifer (Figure 4.3), a mass balance for the second store is given as,

$$Dw \frac{dz_{2,j}}{dt} = (1 - f_j) k_j z_{1,j}^2 - k_2 \, z_{2,j}^2 \quad \text{Eq. 7}$$

where the inflow to this deep storage is the deep percolation from the upper storage given in Eq. 1, and k2 is the conductivity rate of the lower storage (mm/time) which is given as a single value for the catchment, and Dw is the deep water storage capacity (mm). Equations 1 and 7 are solved using a fourth-order runge kutta algorithm (Chapra and Canale 1998). Baseflow is simply,

$$Bf(t) = \sum_{j=1}^{N} A_j (k_2 \, z_{2,j}^2) \quad \text{Eq. 8}$$

When an alluvial aquifer is introduced into the model (Figure 4.3), the second storage term is dropped and recharge from the sub-catchment is the percolation term from the top store to the aquifer, P (Vol/time)

$$P = \sum_{j=1}^{N} A_j (f_j k_j z_{1,j}^2) \quad \text{Eq. 9}$$

### 4.2.3. Groundwater-surface water interaction

Surface water and groundwater are dynamically linked, for when groundwater is depleted, a stream contributes to aquifer recharge (a losing stream), while a stream is considered to be gaining when there is substantial recharge to the aquifer across the watershed and flow is from the aquifer to the stream. Irrigated agriculture can complicate the picture even further, since water can be drawn from the stream, pumped from the local aquifer, or even imported from outside the basin, and thus both depletes and recharges the aquifer (Liang et al. 2003 and Winter 2001).

Capturing these dynamics is important, and the groundwater module implemented in WEAP21 allows for the dynamic transfer of water between the stream and the aquifer (Figure 4.5). In WEAP21, the aquifer is a stylized wedge that is assumed symmetric about the river, with total aquifer storage estimated under the assumption that the groundwater table is in equilibrium with the river. Thus the equilibrium storage for one side of the wedge, GSe is given as,

$$GS_e = h_d * l_w * A_d * S_y \qquad \text{Eq. 10}$$

where, hd (m) represents the distance normal from the aquifer to the stream, lw (m) is the wetted length of the aquifer in contact with the stream, Sy is the specific yield of the aquifer, and Ad is the aquifer depth at equilibrium. An estimate of the height which the aquifer lies above or is drawn below the equilibrium storage height is given by yd, so the initial storage GS in the aquifer at t=0, is given as,

$$GS(0) = GS_e + (y_d * h_d * l_w * S_y) \qquad \text{Eq. 11}$$

The vertical height of the aquifer above or below the equilibrium position is given as,

$$y_d = \frac{GS - GS_e}{(h_d * l_w * S_y)} \qquad \text{Eq. 12}$$

and the more the aquifer rises relative to the stream channel, the greater the seepage back to the stream and vice versa, where total seepage, S from a side of the river (m3/time) is defined by,

$$S = (K_s * \frac{y_d}{h_d}) * l_w * d_w \qquad \text{Eq. 13}$$

where Ks (m/time) is an estimate of the saturated hydraulic conductivity of the aquifer, and dw (m) is an estimate of the wetted depth of the stream, which is assumed time invariant. The wetted depth, together with the wetted length, approximates the area through which river-groundwater exchanges can take place, and the saturated hydraulic conductivity controls the rate at which water moves towards or away from this area. Once seepage is estimated, then half of the aquifer's total storage for the current time step is given as,

$$GS(i) = GS(i-1) + (1/2\,P - 1/2\,Ex - S) \qquad \text{Eq. 14}$$

where Ex is the extracted water withdrawn from the aquifer to meet demands, and *P* is the watershed's contributing recharge (Equ. 8), and total aquifer storage is simply *2GS(i)*.

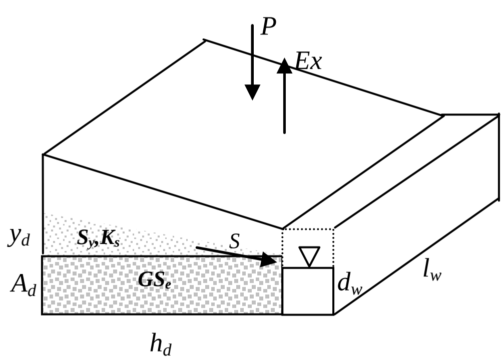



**Figure 4.5. Schematic of the stylized groundwater system, and its associated variables.**

### 4.2.4. Irrigated Agriculture

Demand associated with irrigated agriculture shares the same surface hydrologic model as the watershed demand associated with evapotranspiration from natural land cover. A sub-catchment can be designated as containing irrigated land cover fractions, which are then assigned upper and lower irrigation thresholds, Uj and Lj for crop j (Figure 4.4). These thresholds dictate both the timing and quantity of water for irrigation, as crop evapotranspiration and percolation deplete the available water from the upper zone storage, z1,j. These thresholds are designated by the dashed lines of the top soil moisture storage prescribed for each agricultural type as shown in Figure 4.4. When the relative soil moisture, z1,j drops below Lj, this triggers an irrigation demand for the fractional area, $ID_j = Cp_j * A_j \lfloor (UT_j - z1_{1,j}) * Rd_j \rfloor$, where $Cp_j$ is an time-varying, integer variable, used to prescribe the cropping pattern for each crop j, using a WEAP21 GUI tool. The total irrigation demand for each sub-catchment is simply, $TID = \sum_{j=1}^{N} ID_j$. Sub-catchments with irrigation require a water source to meet that demand and these sources are identified in WEAP21 by using the drag-and-drop capability to link the water sources to the appropriate irrigation demand location. In the example given in Figure 4.2, both surface and groundwater sources are available to meet the irrigation water requirements of SC4. The surface hydrology of SC4 is linked to the river via the return flow arrow from SC4 to the river. Also, the SC4 sub-catchment includes an alluvial groundwater system that is recharged from SC4 and dynamically linked to the lower river reaches, the extent of which is expressed through the wetted length variable, lw.

### 4.2.5. Surface Water Quality

The WEAP21 model includes descriptive models of point source pollutant loadings that can address the impact of wastewater on receiving waters. The water quality parameters are currently limited to conservative constituents that decay according to an exponential decay function, dissolved oxygen (DO), Biological Oxygen Demand (BOD) from point sources, and instream water temperature. The water quality of reservoirs is currently not modeled. The first-order DO and temperature models are patterned after Chapra (1997), where water quality is simulated for select rivers, chosen via the WEAP21 user interface. Mass balance equations are written for each stream segment of the selected rivers, with hydrologic inflows from rivers and groundwater sources automatically input to simulate the water balance and mixing of DO and BOD concentrations and temperature along each reach. The river network is the same for the water resources and the water quality simulation, and assumes complete mixing.

A heat balance equation is written for each node on the river, and the reach control volume is defined by its length, a constant cross-section, and the assumption of constant volume and steady state within a time step. The water quality equations are solved from upstream to downstream, by first computing the mixing from all tributaries, return flows, and groundwater sources, j and for each constituent (T, DO and BOD), x at node i, as follows:

$$x_i = \frac{\sum_{j=1}^{n} Q_j x_j}{\sum_{j=1}^{n} Q_j} \qquad \text{Eq. 15}$$

A heat budget is then computed for each control volume (Chapra 1997, pg. 451), given by:

$$\frac{dT}{dt} = \frac{Q_i}{V}T_i + \frac{Rn}{\rho C_p H} + \left( \frac{\sigma (T_{air} + 273)^4 a \sqrt{e_{air}}}{\rho C_p H} \right) - \frac{Q_i}{V}T_{i+1}$$
$$- \frac{\varepsilon \sigma (T_{i+1} + 273)^4}{\rho C_p H} - \frac{f(u)(T_{i+1} - T_{air})}{\rho C_p H} - \frac{g(u)D}{\rho C_p H} \qquad \text{Eq. 16}$$

where the first term on the right-hand side is the upstream heat input to the stream segment with constant volume, V (m3) expressed as a relationship of flow, Qi (m3/time) and temperature, Ti at the upstream node. The second term is the net radiation input, Rn to the control volume with the density, ρ and the specific heat of water, Cp and the mean water depth of the stream segment, H (m). The third term is the atmospheric longwave radiation into the control volume, with the steffan-boltzman constant, σ, the air temperature Tair, and a, a coefficient to account for atmospheric attenuation and reflection (Chapra 1997). The fourth term is the heat leaving the control volume, while the fifth term is the longwave radiation of the water that leaves the control. The sixth and seventh terms are the conduction of heat to the air and the removal of heat from the river due to evaporation. The terms f(u) and g(u) are wind functions, and D is the vapor pressure deficit. The temperature, Ti+1 is solved for the downstream node with a fourth-order Runga-Kutta and is the boundary condition temperature for the next reach after mixing is considered (Eq. 13).

With Ti computed for each reach segment, the BOD-DO model is then solved from upstream to downstream. First, the oxygen saturation OSi for each segment is estimated as a function of water temperature, $OS_i = 14.54 - (0.39T_i) + (0.01T_i^2)$ and an analytical solution of the classic Streeter-Phelps model is used to compute oxygen concentrations from point source loads of BOD (Tchobanoglous and Schroeder, pg. 338)

$$O_i = OS_i - (\frac{k_d}{k_a - k_r}) \exp^{-kr(L_i / v_i)} - \exp^{-ka(L_i / v_i)} BOD_i - \left( (OS_i - O_i) \exp^{-ka(L_i / v_i)} \right) \qquad \text{Eq. 17}$$

where kd=0.4; ka = 0.95; and kr = 0.4 are the decomposition, the reaction, and the re-aeration rates, respectively (1/day). Li is the reach length (m), vi the velocity of the water in the reach given as vi=Qi/Ai (m/s), with Ai is an assumed constant cross sectional wetted area of the reach (m2). Oi is the oxygen concentration (mg/l) and BODi is the concentration of the pollutant loading (mg/l). Chapra (1997) describes stream bed and settling velocity effects on the reaction rate coefficients of BOD. If the depth of the water, H < 2.4 m then krbod = 0.3 * (H / 2.4) –0.434 else it is given as krbod = 0.3 /day. The total removal rate of BOD is affected by the depth of the river and the water temperature, so krbod = krbod + (0.25 / H) and then krbod = krbod * 1.047(Ti – 20). The BOD removal is given as,

$$BOD_i = BOD_i * \exp^{kr_{bod}(L/v)} \qquad \text{Eq. 18}$$

### 4.2.6. The Management System: the Allocation Module

The starting point in a WEAP21 water management analysis is the development of watershed demands. Each demand is assigned a user-defined priority given as an integer from 1 (highest priority) to 99 (lowest priority). Each demand is then linked to its available supply sources, with each supply source preference set for each demand site (e.g. does the site prefer to get its water from a groundwater or surface water source?). The supply-demand network is constructed and an optimization routine allocates available supplies to all demands. Demands are defined by the user, but typically include municipal and industrial demand, irrigation demands from portions of the watershed, and instream flow requirements.

**Water Demands**

Demand analysis in WEAP21 that is not covered by the evapotransipation-based, physical hydrology module is based on a disaggregated, end-use approach that determines water requirements at each demand node. Demographic and water-use information is used to construct scenarios that examine how total and disaggregated consumption of water evolve over time. These demands scenarios are computed in WEAP21 and applied deterministically to the Linear Program (LP) allocation algorithm. Demand analysis is central to integrated water planning analysis with WEAP21, since all supply and resource calculations are driven by the allocation routine which determines the final delivery to each demand node, based on the priorities specified by the user.

WEAP21 provides flexibility in how data are structured and can range from highly disaggregated end-use oriented structures to highly aggregated analyses. Typically a demand scenario comprises several sectors including households, industry, ecosystems and agriculture; and each can be broken down into different subsectors, end-uses, and water-using devices. However, if the physical hydrology module is used, agricultural and urban turf watering demands are not included in the disaggregated demand analysis but are derived from soil moisture fluctuations.

The structure of demand data can be adapted to meet specific purposes, based on the availability of data, the types of analyses the user wants to conduct, and their unit preferences. In most cases demand calculations are based on a disaggregated accounting for various measures of social and economic activity (e.g., number of households, water use rates per household, hectares of irrigated agriculture, industrial and commercial activity and water use rates, etc), and are aggregated and applied in the allocation scheme at the demand site level. Activity levels are multiplied by the water use rates of each activity and each can be individually projected into the future using a variety of techniques, ranging from applying simple exponential growth rates and interpolation functions, to using sophisticated modeling techniques that take advantage of WEAP21's built-in modeling capabilities via a spreadsheet-like expression builder.

Figure 4.6 shows an example WEAP21 dialogue box for "South City" which has been broken into single and multi-family residences, with projected growth in each category out to 2008. Here, a growth function has been used with an estimated 3% population growth rate, combined with a technical innovation scenario that shows a declining per-unit use of water per-household due to implementation of water saving devices and a gradual shift from multi-family to single-family housing.

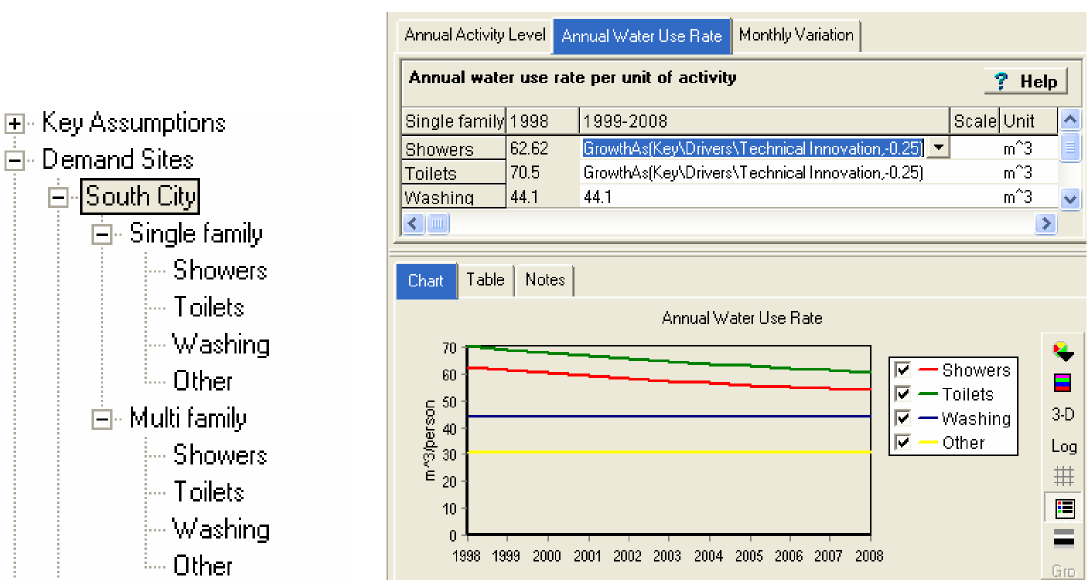



**Figure 4.6. Demand modeling in WEAP21**

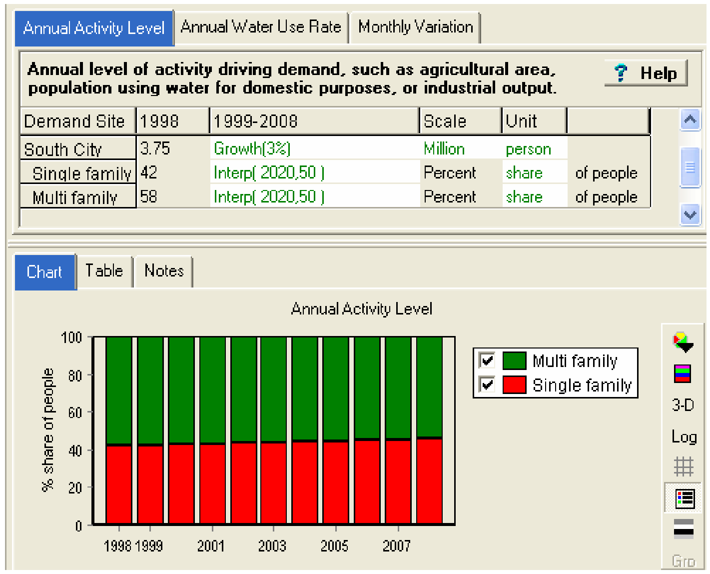


Figure 4.6 Cont. Demand modeling in WEAP21

**Instream Flow Requirements**

Instream flow requirements are used to represent established or new regulatory requirements of minimum flows in a river. These data objects are placed on the river, and are assigned a priority and minimum flow value that must be maintained during a specified period. Instream flow requirements can vary in time, so one can characterize a temporally changing regulatory environment, making it possible to make the instream flow requirements a higher priority and simultaneously raise the minimum standard of flow at any given time in the simulation. Figure 4.7 illustrates this, where the instream flow priority has changed from a 2 (lower priority) to a 1 (highest priority) in 2005, while the minimum instream flow requirement has been raised from 1.0 cubic meters per second (cms) to 2.0 cms in the same year.

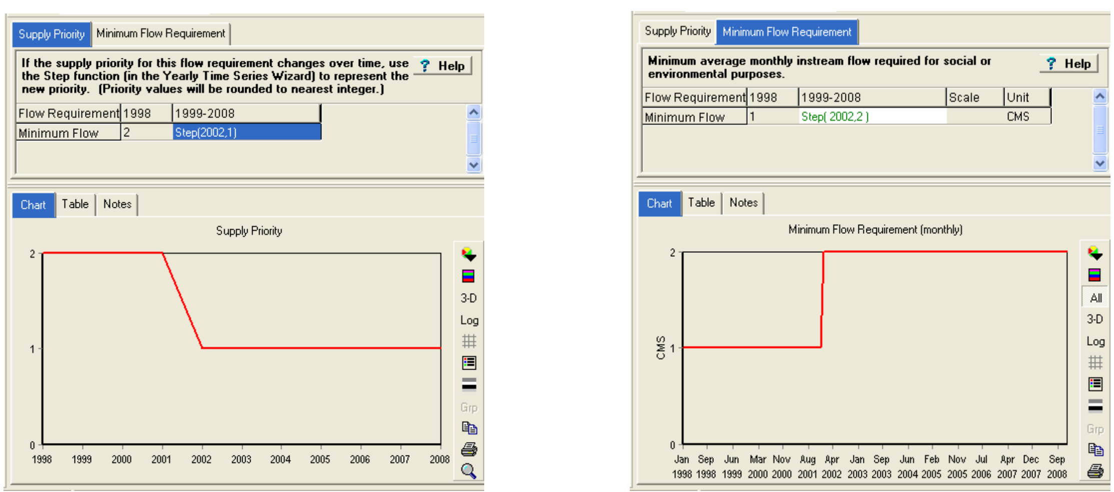


**Figure 4.7. WEAP21's GUI for specifying instream flow requirements. The left panel shows the supply priority of instream flow, while the right panel is the actual instream flow requirement in m$^3$/s. that abruptly change over time as a result of regulatory requirement.**

**Surface Reservoirs**

Reservoirs represent a special object in the WEAP21 model in that they can be configured to store water that becomes available either from the solution of the physical hydrology module or from a user-defined time-series of streamflows. A reservoir's operating criteria determines how much water is available in the current time step for release to satisfy downstream demand and instream flow requirements, hydropower generation, and flood control requirements and how much if any should be carried over until a later time-step. If the priority assigned to storing water in a reservoir is less than downstream demands or instream flow requirements, WEAP21 will release only as much of the available storage as is needed to satisfy demand and instream flow requirements, taking into consideration releases from other reservoirs and withdrawals from rivers and other sources.

In WEAP21, a reservoir is stratified according to water storage volumes as shown in Figure 4.8, where: 1) the flood control storage (Sf) defines the zone that can temporarily hold water but must be released before the end of the time step. In effect, it is always vacant, as additional flows that would lead to reservoir storages above the flood control storage are spilled. 2) the conservation storage (Sc) is the storage available for downstream demands at full capacity, where all water in this zone can be drawn from; 3) the buffer storage (Sb) is a storage that can be controlled to uniquely meet water demands during shortages. When reservoir storage falls within the buffer storage, water withdrawals are effectively conserved via the buffer coefficient, bc, which determines the fraction of storage available for reservoir release; 4) the inactive storage (Si) is the dead storage that cannot be utilized. All these storages parameters can vary in time and can be used to define water conservation and flood storage/release targets. The amount available to be released from the reservoir, Sr is the full amount in the conservation and flood control zones and a fraction (defined by bc) of the amount in the buffer zone, Sr=Sc+Sf+(bc*Sb)..

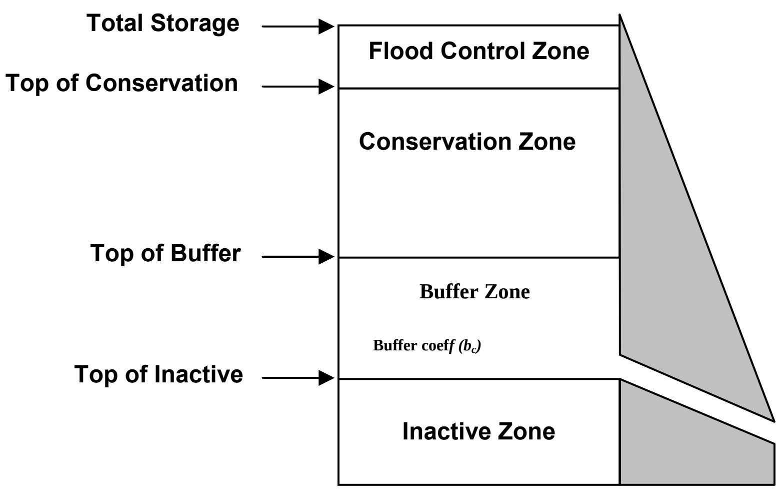



**Figure 4.8. The different reservoir storage volumes used to describe reservoir operating policies.**

### 4.2.7. The LP Allocation Routine

WEAP21 calculates a water and pollution mass balance for every node and link in the system at each time step. Each period is independent of the previous, except for reservoir storage, aquifer storage and soil moisture. Thus, all of the water entering the system in a given time period is either stored in the soil, an aquifer, a river, a tributary, a reservoir, or leaves the system by the end of that period. Point loads of pollution into receiving bodies of water are computed, and in-stream water quality concentrations of conservative and first-order decay constituents, Biological Oxygen Demand (BOD), dissolved oxygen (DO), and water temperature are calculated as above.

All flows are assumed to occur instantaneously and a demand site can withdraw water from the river, consume some, return the remainder to a wastewater treatment plant, which then returns it to the river, all in the same time step. Given there is no routing, the analyst should choose a model time step at least as long as the residence time of water corresponding to the period of lowest flow. Larger watersheds should adopt longer times steps (e.g. one month for example), while smaller watersheds can apply shorter time steps (e.g. 1-day, 5-day, 10-day, etc.) as all demands can be satisfied within the current time step.

### *4.3. Demand Priorities and Supply Preferences*

A standard linear program (Berkelaar et al. 2004) is used to solve the water allocation problem whose objective is to maximize satisfaction of demand, subject to supply priorities, demand site preferences, mass balances, and other constraints. The constraint set is iteratively defined at each time step to sequentially consider the ranking of the demand priorities and supply preferences. The approach has some attributes of a more traditional dynamic programming algorithm, where the model is solved in sequence based on the knowledge of values derived from the previous variables and equations (Loucks et al. 1981; Nandalal and Sakthivadivel 2002).

Individual demand sites, reservoirs, and instream flow requirements are assigned a unique priority number, which are integers that range from 1 (highest priority) to 99 (lowest priority). Those entities with a Priority 1 ranking are members of Equity Group 1, those with a Priority 2 ranking are members of Equity Group 2, and so on. The LP constraint set is written to supply an equal percentage of water to the members of each Equity Group. This is done by adding to the LP for each demand site 1) a percent coverage variable, which is the percent of the total demand satisfied at the given time step; 2) an equity constraint that equally satisfies all demands within each Equity Group in terms of percentage of satisfied demand; and 3) a coverage constraint which ensure the appropriate amount of water supplied to a demand site or the meeting of an instream flow requirement.

The LP is solved at least once for each Equity Group that maximizes coverage to demand sites within that Equity Group. When solving for Priority 1, WEAP21 will suspend (in the LP) allocations to demands with Priority 2 and lower. Then, after Priority 1 allocations have been made that ensure equity among all Priority 1 members, Priority 2 demands are activated (but 3 and lower are still not set).

Similar to demand priorities, supply preferences apply an integer ranking scheme to define which sources will supply a single demand site. Often, irrigation districts and municipalities will rely on multiple sources to meet their demands, so there is a need for a mechanism in the allocation scheme to handle these choices. To achieve this effect in the allocation algorithm, each supply to the same demand site is assigned a preference rank, and within the given priority, the LP algorithm iterates across each supply preference to maximize coverage at each demand site. In addition, the user can constrain the flow through any transmission link to a maximum volume or a percent of demand, to reflect physical (e.g., pipe or pump capacities) or contractual limits, or preferences on mixing of supplies. These constraints, if they exist, are added to the LP. The general form of the allocation algorithm is as follows, For each $p = 1$ to $P$ for each demand priority

For each $f = 1$ to $F \in (D_k^{p,t-n})$ for each supply preference to demand, $k$

maximize (Coverage to all demand sites $k \in N$ with priority $p$)

$Z = C_p$

subject to

$$\sum_{j=1}^{n} x_{j,i}^{p} - \sum_{r=1}^{m} x_{i,r}^{p} + S_i^{t-1} = S_i^t$$ mass balance constraint with storage for node $i$ to node $r$

$$\sum_{j=1}^{F} x_{j,k}^{p} = \mathbf{D}_k^{p,t-n}$$ demand node constraint for demand $k$ from $j$ sources

$$\sum_{j=1}^{F} x_{j,k}^{p} = \mathbf{D}_k^{p,t-n} * c_k^p$$ coverage consraint for demand $k$ from $j$ sources

$$\sum_{j=1}^{m} x_{j,k}^{p} \geq \quad {}_{k}^{p,t-n} * c_k^p$$ coverage constraint for ifr and reservoirs $k$ from $j$ sources

$\mathrm{c}_k^p = C$ equity constraint for demand site $k$ with priority $p$

$\mathrm{c}_k^p \geq C$ equity constraint for ifr and reservoirs with priority $p$

$0 \leq \mathrm{c}_k^p \leq 1$ bound for demand site coverage variables (not ifr or reservoirs)

$x_{i,l}^{>p} = 0$ for demand sites $l$ with priority $> p$

$x_{i,k}^{p} \geq 0$ for demand sites $k$ with priority $= p$

$x_{i,k}^{f} \geq 0$ for demand sites $k$ with preference $= f$

$x_{i,k}^{>f} = 0$ for demand sites $k$ with preference $> f$

*Solve* LP, then

1. Evaluate shadow prices ($h_k^p$) of each equity constraint, is $h_k^p > 0$?
2. If so, set $x_{j,k}^p$ and $c_k$ to optimal values from solution
3. Remove equity constraints with $h_k^p > 0$

Next iteration for current priority, $p$

4. Set $x_{i,k}^f$ to optimal values

Next $f$

Next $p$

where *p* are the demand priorities, *f* are the supply preferences for each demand *k,* of *N* total demand sites. The constants $\mathbf{D}_k^{p,t-n}$ are determined for each demand site *k* with priority *p* and can be, 1) built a prior using the built-in WEAP21 demand model builder; 2) can be based on results computed from previous time steps, n; or 3) can be computed for the current time step in the case of irrigation demands. The $x_{j,i}^p$ terms define the flows from nodes *j* to *i* with priority *p*, $S_i^t$ are the reservoir storages at site *i* for time t, $C_p$ is the total coverage for priority *p*, and $c_k^p$ is the percent coverage for individual demand sites. For the given priority, supplies to each demand site, *k* are established incrementally based on their preference rank, with $x_{j,k}^{>f}$ set equal to zero and values of $x_{j,k}^{f}$ fixed to their optimal solution upon improvement of total coverage, Cp at each iteration for the current priority, p.

Upon solution of the LP, the shadow prices on the equity constraints are examined and if non-zero for demand site k, then the water supplied for this demand site is optimal for the current constraint set. The supply $x_{j,k}^{p}$ is set from the optimal solution of the current LP, its equity constraint removed, and the LP is solved again for the current Equity Group and the equity constraints re-examined. This is repeated until the equity constraint for each demand site returns a positive shadow price, and their supplies $x_{j,k}^{p}$ set. The LP then iterates across the supply preferences, and this too is repeated until all the demand sites have an assigned water supply for the given Equity Group. The algorithm then proceeds to the next Equity Group. Once all Equity Groups are solved at the current time step, the algorithm proceeds to the next time step where time dependent demands and constraints are updated, and the procedure repeats.

A series of stylized examples are presented to illustrate the robustness of the solution algorithm in solving allocation problems. We begin with a simple example described by Figure 4.9a, where there is tributary inflow between the withdrawal points for demand site A and demand site B, both members of the same Equity Group since each has a Priority 1 ranking. Although the allocation LP is written to satisfy all demands with the same priorities at an equal percentage, there are certainly examples where a demand site with the same priority has access to more water than other sites, or in the case of reservoirs and instream flow requirements, can have a coverage fraction greater than 1.0. Here, the tributary can fully supply water to B, so A should get the maximum allotment from the upstream source of 60 units.

This problem has a simple solution, which could be achieved by simply eliminating the equity constraints and maximize the sum of the coverage, $c^{1} + c^{1}$. However, a general algorithm is needed that could handle more complex allocation problems. Thus, at the end of the first iteration (note there is no iteration on supply preference, since both A and B draw water from only one source), $x_{1,}^{1} = 60$, $x_{1,}^{1} = 40$, $c^{1} = c^{1} = 67\%$. However, demand B should be able to withdraw its full requirement, even though A cannot. The shadow price on the equity constraint for Demand A is, $h^{1} = 1$ and the LP allocation iterates after fixing the supply $x_{1,}^{1}$ to 60 units and removing demand A's equity constraint. The final solution is $x_{1,}^{1} = 60$ units, or 67% of its total requirement from R1, while demand $x_{1,}^{1} = 60$ units and is 100% satisfied, receiving all its water from T1. No water exits R1 through node 3.
Supply preferences are illustrated by extending the previous example, where demand A can draw water from the surface supply or from a new groundwater source (Figure 4.9b). In this case, the demand site's preferences are to first draw from the groundwater supply constrained at 40 units, and then draw from the surface supply if needed (Preference 2). Since the groundwater water is given a preference of 1, the demand site should draw all 40 units from it, and make up the 50 unit shortfall from the surface supply. The final solution is $x_{1,}^{1}$ can supply 40 units from source GW, 50 units from R1, while 10 units flow to the node 2 tributary from R1. Demand B gets 60 units from R1 and is 100% satisfied. Ten units exit the system through node 3.

The example is again extended by placing an instream flow requirement (ifr) below the demand B diversion at node 3, where a 20 unit ifr is imposed (Figure 4.9c). The ifr joins Equity Group 1, and demand B is demoted to Priority 2 and becomes the exclusive member of Equity Group 2. In this case, the LP will iterate among Equity Groups, with demand A being 100% satisfied from 40 units of the GW source and 50 units of the R1 source. The total volume available at node 3 is 70 units, 60 from T1 and 10 from R1. To meet the ifr at 100%, 20 units must pass through node 3 and so demand B can draw only 50 units from R1 and, so, only 83% of its demand is met.

The final example illustrates the solution of a demand site supplied by a reservoir, with an assumed operating policy to meet downstream demands (Priority 1) and conserve water by reducing delivers from the reservoir. Demand site A has a demand of 100 units, with the physical reservoir volume capacities given in Figure 4.9d. The reservoir has an inactive pool of 100 units, a buffer pool of 100 units, a conservation pool of 200 units, and a flood control zone of 100 units. Thus, the total storage volume of the reservoir is 500 units. For the current time step, inflow to the reservoir is 10 units with an assumed initial storage volume of 250 units (Si-1) which is just above the buffer storage zone. The buffer coefficient, bc is set at 0.05, which means that if the reservoir's storage level drops into the buffer zone (< 200 units), then reservoir water available for release to meet downstream demands will be limited to 5% of the current buffer storage.

After solution of the current time step, demand site A is supplied 65 units of water or 72% of its demand and the reservoir storage is 195 units. Thus, the 10 units of inflow to the reservoir are passed through it, the full 50 units are drawn off the conservation pool released downstream to meet demand at A, and water available for release from the buffer zone is limited to 5 units, or 5% of the 100 units of the full buffer storage. The final storage in the reservoir for the current time step is 195 units. For the next time step, if it is assumed that the demand is again 90 units, with an inflow of 10 units, then 10 units are allowed to pass through the reservoir and only 5% of the 95 units of buffer storage are released for a total downstream delivery of 14.75 units or 14.75% of total demand at A.

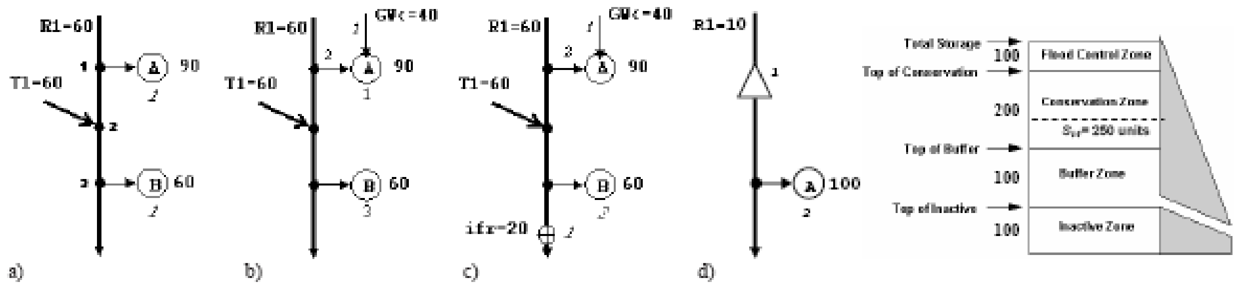



**Figure 4.9. a. Two demand sites, A and B are members of the same Equity Group indicated by the "1" below each symbol. The numbers near each object represent 1) the water supply available from the river, R1 and the tributary T1; and 2) the demands for A and B. b. same as a, but demand site A now has a secondary source, labeled GW which is its preferred source indicated by the *1* along its transmission link, with its secondary source from R1. c. Same as b, but with the addition of an instream flow requirement (ifr) with priority 1; d) A reservoir example, with a priority 2 water storage target, and a demand site (A) with a priority 1 demand. The stylized reservoir on the right hand side illustrates reservoir storage volumes (top of conservation storage = 400 units; top of buffer storage = 200 units).**

## 5. A WEAP21 Model of the Sacramento Basin

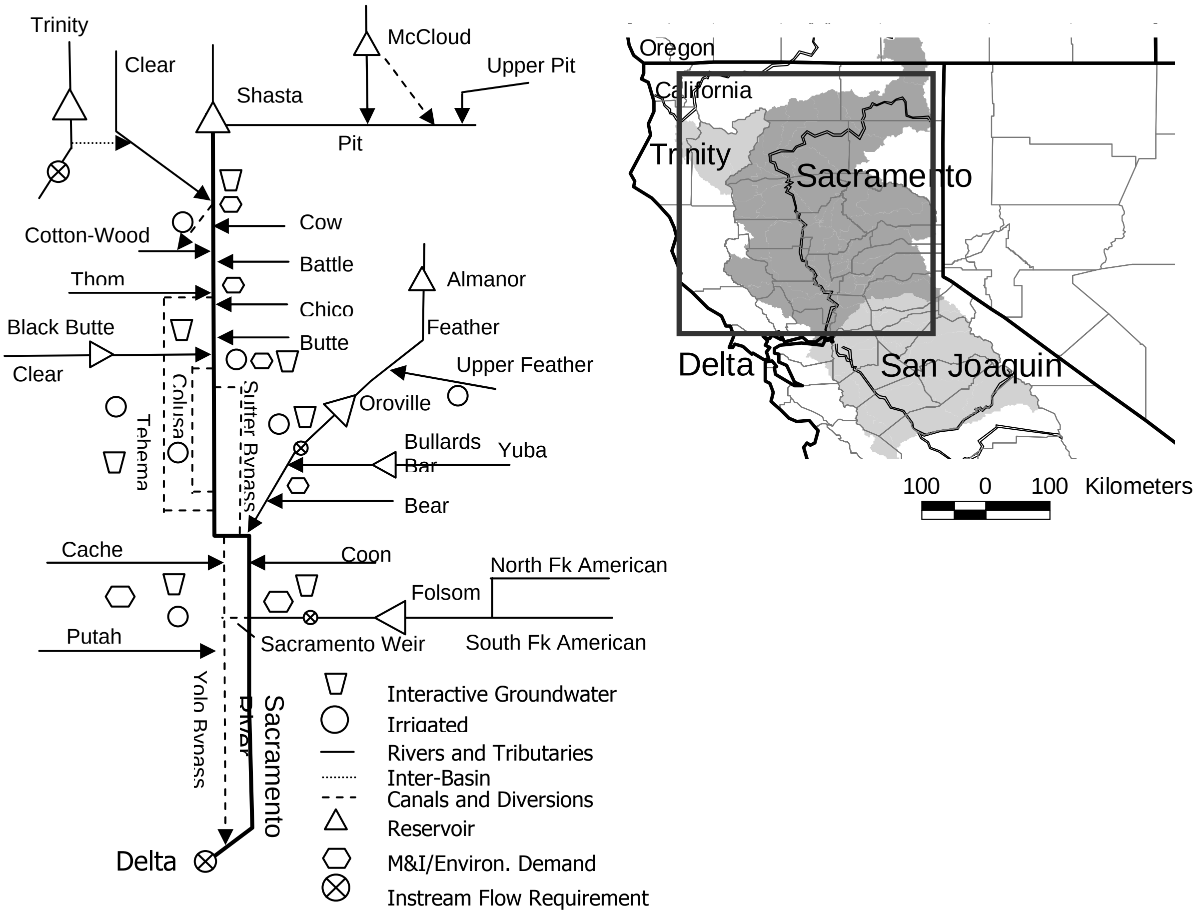
Of the approximately 27,600 million $m^3$ of average annual runoff in the Sacramento Basin, the vast majority of which flowed into the San Francisco Bay under pre-development conditions, about 6,900 million $m^3$ is exported to satisfy out-of-basin demands. Roughly 11,000 million $m^3$ is used to meet urban and agricultural demand within the basin. To meet this demand, Sacramento Basin runoff is supplemented with a diversion of roughly 1,000 million $m^3$ from the neighboring Trinity River Basin, leaving roughly 11,000 million $m^3$, or 40 percent of the total basin runoff unallocated and available to flow from the Delta to the Bay. The values in Table 1 are based on average surface water availability, but the variability in surface water supplies in the Sacramento Basin is quite dramatic.

While much of the upland portion of the Sacramento Basin is not underlain by productive aquifers, several areas do benefit from the presence of substantial groundwater resources, and during dry years these resources provide a critical water supply buffer that can protect against shortage. From a water supply point of view, the most important aquifer is the Sacramento Valley aquifer that lies below the entire Central Valley portion of the Sacramento Basin, with estimates of total aquifer storage in the first 100 meters of alluvium of about 60,000 million $m^3$ or about 2 times the annual discharge of the Sacramento watershed (Purkey et al. 1998).

The section describes how the Sacramento Basin was characterized within the WEAP21 model framework by detailing the division of the Basin into sub-catchments and representative areas, how these sub-catchments serve as a key organizing agent for this water planning model; the representation of the water infrastructure, its control and water demands; and the calibration of the system in terms of both the physical hydrology and the managed water system.  Finally, we illustrate how the model could be used for planning purposes by reformulating the allocation priorities to reflect the Central Valley Project Improvement Act which introduced environmental priorities.

In all, this WEAP21 implementation for the Sacramento River includes the major tributaries; the major alluvial aquifers of the Central Valley; the major trans-basin diversion from the Trinity River; the main reservoirs (McCloud, Trinity, Shasta, Black Butte, Oroville, Almanor, Buzzard, and Folsom); the major irrigation canals and their demand centers (e.g. Cottonwood Irrigation canal, Tehma Canal, the Colusa Canal, and others) and aggregated minor irrigation districts; and the major and minor municipal and industrial demand centers (Figure 5.1).  Three flood conveyance systems include the Yolo, the Sacramento Weir, and the Sutter bypasses. Importantly, the WEAP21 allocation scheme is *demand* oriented. The landscape's evaporative demands and non-consumptive demands are internally estimated within WEAP21 at each time step, which are the key drivers for water delivery. Except to meet flood control targets or instream flow requirements, releases from reservoirs are triggered by downstream demands, not by prescribed release volumes based on contracts.

**Figure 5.1. The Sacramento, San Joaquin, and Trinity Rivers of California.**



The development of the WEAP21 model of the Sacramento Basin began with a broad Geographical Information System (GIS) analysis based on the United States Geological Survey's (USGS) Hydrologic Unit Classification (HUC) eight-digit cataloging or watershed units (here, referred to as HUC8); available stream gage data for the basin; and a daily 1/8-degree gridded meteorological dataset of precipitation, temperature, and wind speed (Maurer et al. 2002). The HUC8 sub-divides the Sacramento Basin into 34 broad sub-catchments, and these four datasets were used to further disaggregate the Sacramento Basin into 54 sub-catchments according to 1) local knowledge of unique hydrologic response; 2) the need to reflect important climatological gradients; and 3) the location of stream gages to best represent the contributing area of the watershed up to a particular gage to aid in model calibration.

Once the boundaries of each sub-catchment were defined, the USGS 30-meter National Land Cover Data set (NLCD92) was used to define the land use and land cover (LULC) fraction within each SC. These LULCs include both natural and human modified types and include natural covers (deciduous and evegreen trees, shrubs, grassland, wetlands, barren land and open water); irrigated covers (cereals, oilcrops, orchards, pasture, rice, rowcrop); and both urban pervious and impervious areas. In many instances an SC is represented by only a few LULC's, most notably the perimeter SC's which are dominated by evergreen and deciduous trees, while some of the valley floor SC's contain nearly all the LULC types.

## 5.1. Upper Store Water Holding Capacity and LAI

For each of the 54 sub-catchments, an average monthly climate time series was derived from the individual 1/8 deg gridded daily time series as an average of all grid cell values contained within the sub-catchment (Maurer 2002). Monthly precipitation was given as the sum of the daily values. By using a monthly accumulation as apposed an "average day of the month", precipitation can be quite large for any given month, thus a strict use of soil water holding capacity would not work since the capacity would often be too small. Instead, a rooting depth estimate of each land class was used as a surrogate for the available water holding capacity (Schenk and Jackson 200a; and Canadell et al. 1996). Initial estimates for the upper store soil water capacity ($S_w$) were: evergreens 2000 mm, deciduous trees 1500 mm, shrubs and orchards 1000 mm and herbaceous plants including grasslands, pasture, and crop types of 900 mm. During calibration, these values were adjusted to improve the hydrologic and water resource simulation.

Leaf and Stem Area Index (*LAI*) was used in the hydrologic parameterization of the surface runoff process, with the notion that a greater amount of plant canopy foliage and stem mass tend to buffer the surface runoff response (e.g. Kergoat, L. 1998, 1999; Asner et al. 2002). Mean values of *LAI* were prescribed for each natural land cover class, with deciduous and orchards assigned values of 4.0; shrubs 3; and natural grass 2.5. Irrigated crops, particularly rice made use of the *LAI* parameter but did according to a strict definition of the value for the commodity type. For the agricultural land cover types, the *LAI* parameters reflected land use practices such as precision field leveling and field scale levees which aid in reducing surface runoff. Rice was assigned an extreme *LAI* value of 40 to reduce surface runoff and row and oil crops adopted a value of 10. Urban impervious areas were assigned an LAI value of 0.5 to reflect a near immediate surface runoff response.

## 5.2. Estimating Upper and Lower Store Conductivities

The sub-catchment interflow volume, $I_f$ from the upper store and sub-catchment base flow volume, $B_f$ from lower store are given as relatively simple expressions of their relative storage,

$$I_f(t) = \sum_{j=1}^{N} A_j \left( f_j k_j z_{1,j}^2 \right) \quad \text{Eq. 1}$$

$$B_f(t) = \sum_{j=1}^{N} A_j \left( k_2 \; z_{2,j}^2 \right) \quad \text{Eq. 2}$$

where $A_j$ is the area of the land cover fraction, $j$ and $k_j$ and $k_2$ are the upper and lower store maximum monthly conductivities in mm/month (e.g the flux rates when $z_{1,j}$ = 1.0 and $z_2$=1.0). Initial conductivity estimates were made by selecting several sub-catchments with historical flow records, computing and then separating the resulting monthly runoff hydrograph into baseflow and interflow components, and then estimating the monthly conductivity parameter from these averages, the watershed area, and an estimate of the average relative storage of both the upper and lower stores.

As an example, the average monthly streamflow volume for the American River at Folsom is given in Figure 5.2d, where the average baseflow was estimated as the 90% exceedance value, estimated as 95 million m$^3$. To make a first estimate of the lower store conductivity, $k_2$, we divided this baseflow volume by the total watershed area, $A_t$ of approximately 5000 km$^2$, which resulted in an average baseflow flux of 20 mm/month per km$^2$. From Equ. 2 and assuming the average relative storage is 30% of the maximum available storage for all fractions $j$, then $k_2 \approx \frac{(B_f / A_t)}{z_2^2}$, or $k_{2,j}$ = 220 mm/month, for all $j$. The upper store conductivity is estimated in much the same way. The average interflow contribution was estimated as the difference between the 90% and 30% exceedance, where the 30% exceedance was estimated to be 250 million m$^3$, resulting in an average monthly interflow volume of 155 million m$^3$. From Equ. 1 and assuming a constant $k_j$ for each land use class, an average relative storage of 60%, and a flow fraction of 0.5 then $k_j \approx \frac{(I_f / A_t)}{z_2^2 f}$, or $k_j$ = 180 mm/month. The higher relative storage for $z_{1,j}$ reflects the fact that the upper store has smaller capacity and exhibits greater seasonal variability when compared to the lower store. In the Sacramento Valley, conductivity rates for rice were set as 125 mm/month to reflect the lower conductivity rates of silts and clays.

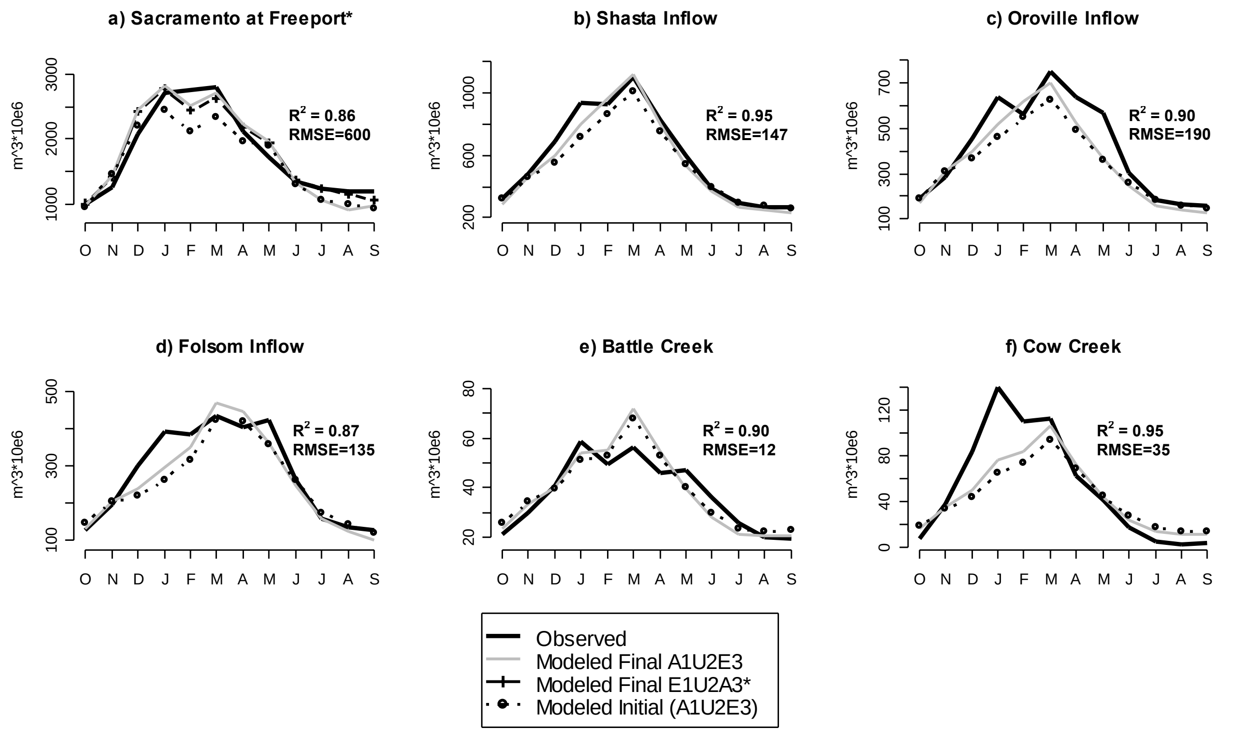



**Figure 5.2. Observed and modeled average monthly streamflow for a) The Sacramento at Freeport, (plot includes average flows based on both the A1U2E3 and the E1U2A3* scenarios); the inflows to the three major reservoirs, b) the Pit and Upper Sacramento Rivers; c) the Feather River; and d) the American River; and two minor tributaries including e) Battle Creek and f) Cow Creek. Inset includes correlation coefficient ($R^2$) and the root mean square error (RMSE, *10E6 m3).**

## *5.3. Groundwater*

When an alluvial aquifer is introduced in the model, the 2-layer soil water model becomes a 1-layer model and the vertical flux from linked sub-catchments represents the aquifer recharge. The WEAP21 SB model included five valley floor alluvial aquifers: Redding, Lower Butte, Lower Stone Corral, Lower Thomes, Lower Feather, Lower American, and Lower Sacramento, with a total storage at the beginning of the simulation of 4,200 million m3 or about 2/3 the total estimate to represent the active portion of the aquifers from which water is drawn and which streams interact. Each aquifer's associated sub-catchments provide the recharge flux to its linked groundwater system, but the SC's are also points of demand if they contain an irrigated land cover which can draw water from their associated aquifers. Each aquifer is also tied to a set of river segments in a stylized representation of stream-aquifer interaction, which tracts the position of the water table relative to the stream level. In this way, the aquifer itself becomes a point of demand when the relative position of the stylized groundwater table falls below the prescribed height of the river. In this case, the river becomes a "losing stream" and water is lost to the aquifer. In contrast, when the aquifer height is above the river, the aquifer supplies water to the river and the river becomes a "gaining stream". The aquifer height is represented stylistically for the whole aquifer, so there are no local features such as cones of depression.

Broad parameter estimates were made for each aquifer. Initial estimates of the representative horizontal distance ($h_d$, Figure 4.5) or the farthest edge of the aquifer to the river, were as short 20 kilometers for the Redding aquifer and as long as 80 kilometers for the Stone Corral aquifer. The river reach length, $l_w$ represents the hydraulic connection between the aquifer and the river and ranged from 25 km for the Lower Butte groundwater basin and as long as 75 km for the Lower Sacramento groundwater basin. The aquifer hydrologic properties include specific yield, $S_y$; an estimate of the saturated conductivity, *Ks* (m/month); and an estimate of the wetted depth $d_w$ (m) of the stream through which the stream and aquifer exchange water. Parameter values for specific yield (0.20), saturated conductivity (6 meters/month), and wetted depth (from 10 to 40 meters) were prescribed for each stream-aquifer pair. These values were derived through a trial-and-error process that attempted to broadly track the observed variations found in groundwater well elevation data available from the California Department of Water Resource (DWR 1993), with $h_d$ and $S_y$ adjusted to improve calibration (see 4.2.2).

## 5.4. Water Demands

Water demands, satisfied by a particular surface or groundwater supply, include both consumptive demands such as irrigated agriculture and turf and garden watering in urban environments and non-consumptive demands such as instream flow requirements and municipal and industrial demands which can return delivered water back to the supply system. Other consumptive demands include evaporative losses from reservoir surfaces and transmission losses from canals and municipal and industrial water supply systems (these are simply given as percentages of flow and are assumed lost from the system). We briefly describe these demands and how there were represented in the WEAP21 model of the Sacramento.

### 5.4.1. Irrigation Demands

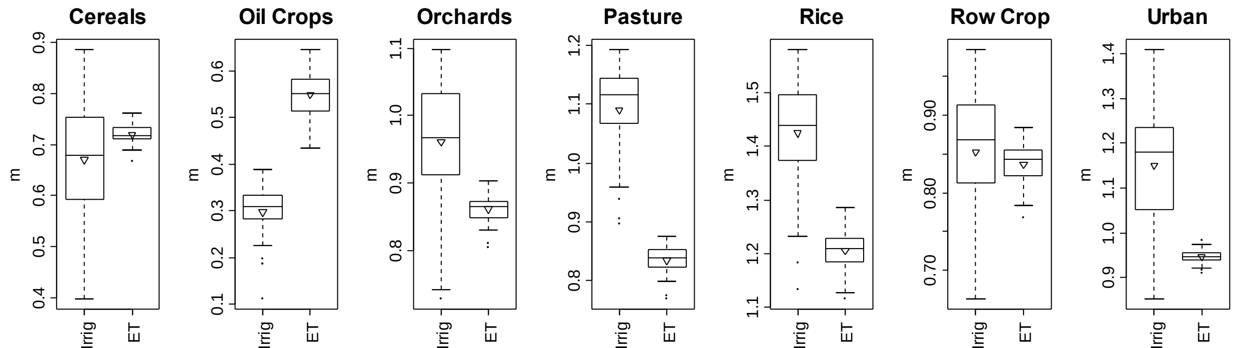
Estimates were made for non-irrigation demands such as instream flows, off-stream wildlife refuges, and municipal/ industrial water demands. Municipal water demands are given on a per-capita basis with a total Sacramento Basins population estimate of one million in 1962, growing to 2.33 million by 1998, with a majority of that growth occurring near the City of Sacramento. With information on crop-water-use requirements and estimates of municipal and industrial water demands, total water demand was estimated on a per-monthly basis. Because agricultural land use changes are difficult to describe in detail over the entire Sacramento Basin for the 1962 to 1998 period, we have assumed a constant partitioning of agricultural land in each agricultural area. Only urbanization converts agricultural land to the urban land use class over time.

Irrigated crops can be one of the many land use/land cover fractions within a sub-catchment and thus share the same surface hydrologic model as the "natural" land cover types. Irrigated land covers differ, however, in that the user can assign unique upper and lower relative storage irrigation thresholds (e.g *L* and *U* in Figure 4.4) and irrigation schedules, which together dictate the quantity and timing of irrigation water applied. Sub-catchments with irrigation require water sources to meet that demand and in WEAP21 the user associates surface and/or groundwater supplies to the appropriate sub-catchments that contain irrigated land covers.

Irrigation schedules were defined for the seven irrigated types including cereals, oil crops, orchards, pasture, row crops, grains, and urban turf and garden. The irrigation schedule for cereals was defined from February through July; oil crops April through June; orchards from March through October, rice from April through August; row crops from March through September. Pasture could be irrigated year-round and it was assumed that the irrigation strategy of municipal irrigated land covers such as lawns and gardens was similar to pasture and thus made use of the same parameter set.

The upper (*U*) and lower irrigation (*L*) relative storage thresholds are used to estimate seasonal and annual irrigation depths based on established irrigation practices (DWR 2005). For example, a healthy pasture in the Sacramento Basin needs about a meter of irrigation water annually. Rice can require nearly two meters of water annually, as it adopts a flooded-field irrigation strategy, but its total evaporative demand is actually close to that of many other irrigated commodities of between 1000 to 1500 mm per year. With the WEAP21 hydrology module, pasture was prescribed with an upper soil water storage capacity of 800 mm, an upper threshold *U* of 0.60 and a lower threshold, *L* of 0.40. This combination led to an annual average irrigation application of a little over one meter and a total evaporative demand of about 0.85 meters (Figure 5.3). To mimic the flood irrigation process for rice, the upper and lower irrigation thresholds were set at 0.95 and 0.80, respectively. This forces WEAP21 to continually supply water to the irrigated area in order to keep the relative storage near complete saturation during the growing season, thus mimicking the flooding strategy. The annual average rice irrigation demand and evapotranspiration depths were estimated to be 1.6 m 1.0 m, respectively. The modeled irrigation demand and evapotranspiration depths are summarized for all commodities in Figure 5.3.

**Figure 5.3. Box-and-whiskers plot of irrigation demands and actual evapotranspiration (ET) by commodity (A1U2E3 Scenario), showing the maximum, high ¼, median (horizontal line), low ¼ and minimum values from all 37 yeas. The mark within the box is the period average.**




### 5.4.2. Municipal and Industrial Demands

Municipal and industrial (M&I) demands were estimated for the major municipal centers throughout the Sacramento Basin including Sacramento, Redding, etc. and were defined as a simple per-capita demand multiplied by total regional population. From this, an estimate of monthly withdrawal requirements for non-consumptive M&I demands were made, with return flows losses prescribed as 10 percent of the diversion and assumed lost from the system. Average annual M&I withdrawals from both surface and groundwater supplies were about 1.5 million $m^3$, which does not include estimates of turn and garden watering that are automatically estimated using the embedded hydrology module. Ecosystem demands include both instream flow requirements and diversions for nature reserves that have explicit surface diversion rights.

Because water is transported out of the basin for use in other parts of the Central Valley and in Los Angeles Basin, we needed to represent these external demands in order to trigger the release of water for these downstream diversions. While total delta exports derived from both the Sacramento and San Joaquin are estimated at about 7,7000 million $m^3$ annually, we assumed that the majority of this diversion is from the Sacramento and imposed an average annual demand of 6,9000 million $m^3$ and were assumed time invariant but with a larger share given in the summer months.

### 5.4.3. Instream Flow Requirements

Key instream flow requirements included fisheries flow thresholds on 1) the Upper Sacramento River below Keswick, with an October to August flow requirement of 100 cms and a September flow of 170 cms. If the beginning-of-month storage at Shasta was less than 2,500 million m3, then the September requirement was relaxed to 125 cms; 2) the Feather River, above the Yuba confluence, with a minimum flow requirement of 35 cms October through February and 28 cms from March through September; 3); the American River, below Folsom Dam, with a maximum, minimum flow requirement of 6 cms from April through August and 8.4 cms from September through March. The Lower Sacramento IFR was set at 300 cms for all months at Freeport. The Trinity minimum instream flow requirement was given as a constant value of 10 cms to reflect the large diversions from this river into the Sacramento Basin.

## 5.5. Reservoirs

Generally, the operating strategies of the major reservoirs on the Sacramento River are to 1) draw them down from late spring into early fall to meet the peak demand period and 2) ensure adequate storage to capture the winter and early spring flood flows, while hydropower being a secondary benefit in most cases.  To reflect these operational objectives, reservoir operating rules are expressed as monthly average reservoir volumes thresholds (Figure 5.4). These include a conservation volume above which water is immediately passed downstream and within which water can be fully released to meet downstream demands.  The next storage zone is called the buffer zone and defines a portion of the reservoir where system demands are restricted and downstream demands can only be met as a percentage (the buffer coefficient) of the available storage within the buffer zone. Below the buffer zone is the inactive storage that cannot be used to meet demands.

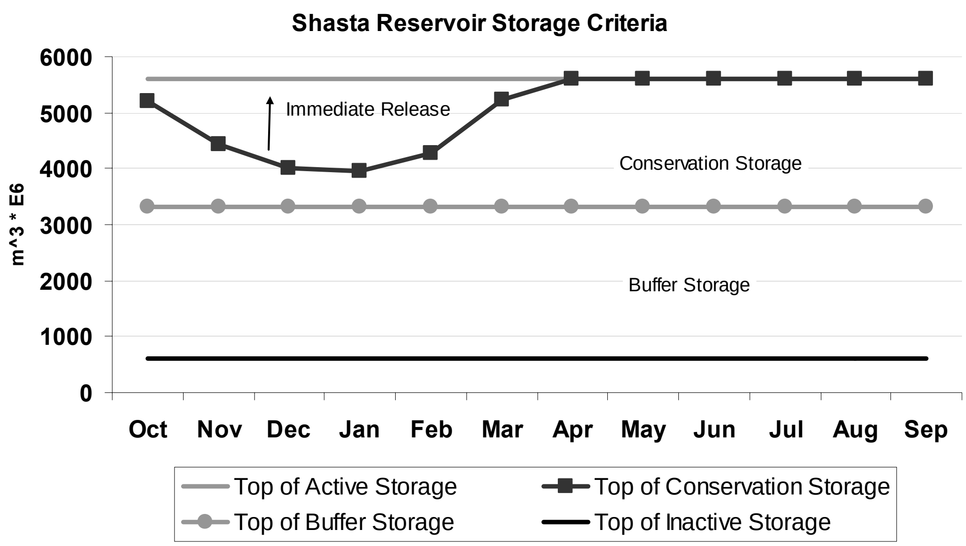



**Figure 5.4.  Monthly average storage volume "rules" for the Shasta reservoir.**

## 5.6. Simulating the Water Resources of the Sacramento Basin with WEAP21

For the entire study domain, the irrigation requirements for the major crops have been estimated using WEAP's built-in crop requirements module and the municipal and industrial water demands. Estimates of historic net water demand for the Sacramento Basin attribute roughly 67% to irrigated agriculture, about 27% to environmental demands (instream flow requirements, wildlife refuges, parks, etc.) and only six percent to urban uses.  The estimated average net water use in the Sacramento Basin is about 15,000 million $m^3$ of which about 10,000 million $m^3$ are attributed to irrigated agriculture with 6,800 million $m^3$ used consumptively, while net water use for environmental needs are 4,800 million $m^3$, with only 245 million $m^3$ consumptively depleted. Municipal and industrial uses are about 1,000 million $m^3$, which deplete only 300 million $m^3$. Irrigated agriculture and delta exports are clearly the key system drivers. Model evaluation compared Sacramento mainstream and tributary stream flows, reservoir storage, diversions of water from the Trinity River, agricultural and municipal water use, and groundwater storage against historically observed conditions.

### 5.6.1. Priorities and Preferences

Recall that the 1935 authorization of the CVP established water priorities as "first, for river regulation, improvement of navigation, and flood control; and second for irrigation and domestic use; and third for hydropower."  We encompassed these priorities within the WEAP21 framework by assigning different priority values to water demands and instream flow requirements for two different scenarios. Reservoir operating rules were left unchanged to reflect the highest priority given for flood control. Individual reservoirs were assigned different filling priorities based on individual operating assumptions. For example, Shasta and Oroville were assigned the lowest reservoir fill priority (Priority 5) under the assumption that these reservoirs are primarily meant for irrigation demand in the watershed and to meet the State Water Project requirements. Folsom Reservoir was assigned a high fill priority (Priority 3) from 1962 until 1988 which tended to keep more water in storage, to better serve recreational uses. After 1988, the operating policies on Folsom changed to reduce storage in the reservoir so it could be more stringently used in flood protection and a larger share of its waters used for domestic, industrial, and agricultural uses. To reflect this change, the Folsom reservoir fill priority was assigned a value of five from 1988 onwards and the conservation pool

The first scenario assumed that meeting agricultural water demand requirements (Priority 1) superseded meeting instream flow requirements and environmental demands (Priority 3), while urban and delta export demands were assigned Priority 2. This scenario is referred to as the A1U2E3 Scenario and was used as the calibration and was considered the Business as Usual scenario. The second scenario was a simple swap of the agricultural demand priority with the environmental requirements, thus agricultural demands became Priority 3 and environmental requirements became Priority 1. This second scenario is referred to as the E1U2A3 Scenario.

Demand site preferences are typically choices between surface or groundwater supplies. For example, an irrigation district can draw water from either a surface or groundwater source. We have assumed that in the Central Valley, irrigators prefer surface water, but during times of scarcity will revert to groundwater to make up for surface water shortage. Thus, an irrigation demand with access to both surface and groundwater will first draw surface water (Preference 1) and then groundwater (Preference 2) when the supply is tight. Although there are certainly capacity constraints on groundwater extraction, for purpose of illustration we have only imposed an upper limit on groundwater supplies such that groundwater cannot meet more than 40% of the expected demand in the large irrigation areas of the Central Valley. The DWR estimates that on average; a little over 30% of demands are met through groundwater.

### 5.6.2. Hydrologic Calibration for the 1962 to 1998 period

The period of October 1962 to September of 1998 was used to calibrate and assesses the Sacramento Valley water model as simulated by WEAP21. Recall that WEAP21 is demand driven, with allocations made based on the priorities assigned to demands and supply preferences which are used to specify how demands are to be met from various sources. The model does not use prescribed *rules* that determine when to make releases; rather releases from reservoirs or pumping from groundwater storage are based solely on endogenously estimated demands and the priorities and preferences of the system. Reservoir releases are also made or withheld to satisfy reservoir storage requirements and/or to accommodate flood management objectives.

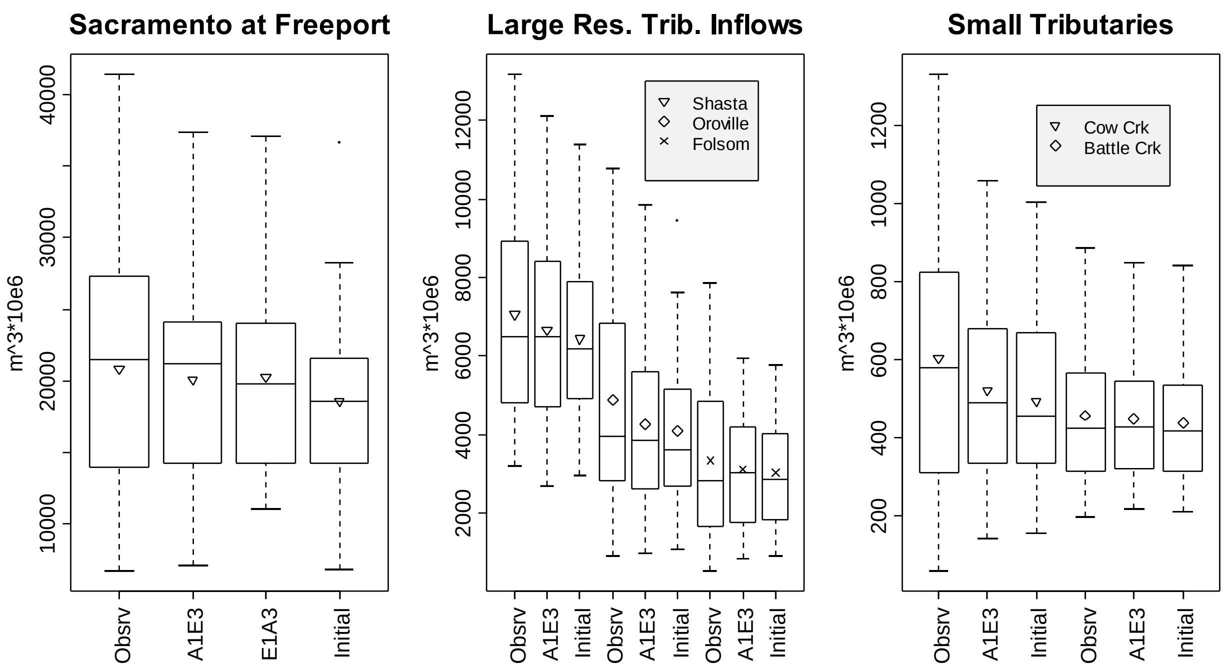
**Streamflow**

In all, this WEAP21 model included the representation of thirty individual rivers and tributaries of the Sacramento River, including smaller tributaries such Cache, Battle, Cow, and Cottonwood Creeks etc.; and larger tributary rivers of the Sacramento including the Feather, American, Yuba, and Pit Rivers. In the case of small tributaries, their contributing areas often included two to three sub-catchments whose runoff incrementally contributed to streamflow generation. The larger rivers, most notably the Pit, Feather, and American included many sub-catchments and their own individual tributary streams.

The hydrologic calibration involved both a quantitative and qualitative evaluation of the hydrologic response of individual tributaries and the overall system, and then an adjustment of parameters to best reflect the deficiencies in the initial parameter estimates. Of course, calibration of the multi-parameter model deployed in WEAP21 is problematic as it is done manually, making it difficult to determine a best set of parameters that yield an "optimal" hydrologic and water resource simulation. Calibration included a trial-and-error process that adjusted the upper store soil water capacity, $S_w$ and the upper store conductivity value, $k_j$ , whose initial values were estimated according to the procedure described in Section 3.2 above.

Figures 5.2 and 5.5 summarize the observed and model estimated streamflow for the select points throughout the watershed. Figure 5.2 is a plot of the monthly mean observed streamflow for the 37 year period ("Observed"), the simulated streamflow based on the initial model parameter set using the A1U2E3 scenario ("Modeled Initial A1U2E3"), and the simulated streamflow with the final parameter set using the A1U2E3 scenario ("Modeled Final A1U2E3"), and includes a statistical summary (correlation coefficient and root mean square error), of the monthly observed and modeled flow volumes. Figure 5. 2a represents the managed flows of the entire Sacramento River and thus includes the mean monthly series labeled "Modeled Final E1U2A3" based on the reprioritization of agricultural (from Priority 1 to Priority 3) and environmental (from Priority 3 to Priority 1) priorities. For the E1U2A3 scenario, surface deliveries of agricultural were curtailed, particularly in dry years, to meet the downstream flow requirement, leading to generally higher summer baseflows (Figure 5.2a).

**Figure 5.5. Box-and-whiskers plots of observed and simulated total annual runoff for the same Sacramento Rivers as in Figure 4. The far left plot is for the Sacramento flow at Freeport (Obsrv is the observed flow; A1E3 and E1A3 are the simulated flows using the final parameters for the two scenarios, Initial is the simulated flows using the initial parameters and the A1U2A3 parameter set. The middle and right plots are for the other river systems without major infrastructure controls, with simulated flows shown only for the A1U2E3 scenario.**




Figures 4.2b-e are the flows into the major storage works of the Sacramento River (Shasta, Oroville, and Folsom), and the flows from two smaller tributaries, Cow and Battle Creek. The most notable deficiency of the hydrologic simulation using the initial parameter set was the tendency to under-predict winter peak flows. This is most evident in the overall system response (Figure 5.2a), which shows an approximate 20% smaller mid-winter runoff volume. The peak winter flows of the Pit and Feather tributaries are smaller than those observed, while the American peak flows are quite close to the observed flows. With the initial model parameters, simulated peak flows were generally under-predicted while the low-flows were slightly over-predicted. Figure 5.5 is a box-and-whiskers plot of the annual flows for the same points on the river, showing the maximum, high ¼, median (horizontal line), low ¼ and minimum

values, with the mark within the box the period average. This annual depiction of flows generally suggests an under-prediction of total and peak flows.

These results suggested that initial estimates of the upper store water capacity, $S_w$ were too large resulting in seasonal fluctuations of relative storage, $z_1$ that were too small. Since the surface runoff component is positively correlated with $z_1$, a reduction in the upper store's capacity should lead to increases in mid-winter relative storage and a corresponding increase in surface runoff, and correspondingly smaller relative storages in the summer with less runoff and less actual evapotranspiration. Thus, smaller values of $S_w$ will tend to increase the seasonal fluctuations of relative storage- yielding higher values of $z_1$ in the winter leading to more surface, interflow and percolation discharge and subsequent rapid drying of the upper store as the warm, dry summer season ensues, giving rise to less runoff and actual evapotranspiration during the warm, summer months. The initial values of $S_w$ were reduced by 25% and the upper store conductivity was reduced from 180 mm/month to 150 mm/month to effectively reduce the upper store's drainage at high values of relative storage. The effects of this re-parameterization are shown in Figures 4 and 5, where peak flows tend to increase and base flows decrease.

The hydrologic attributes of the small Battle and Cow Creek tributaries are interesting. The Battle Creek catchment was influenced by volcanic deposition, leading to a prolific underground spring system that yields high summer baseflows with reduced seasonal and interannual variability. Cow Creek, Battle Creek's northern neighbor was not as geologically influenced by these historic volcanic episodes, and its hydrologic response is similar to many of the smaller tributaries of the Sacramento, which includes high mid-winter and spring peak flows and low summer baseflows. To reflect this difference, the parameters of the Upper and Lower Battle Creek sub-catchments were altered by: 1) reducing the partitioning parameter, $f$, to a value of 0.15 to reflect larger vertical fluxes to the second store; 2) raising the upper store's conductivity by 30% and the total water capacity by 50% for each land cover type; and 3) increasing the second store's water capacity by 50%, from 2000 mm to 3000 mm mm/month. This allowed for an improved reproduction of the Battle Creek baseflows, although peak flows still tended to be over-estimated. Cow Creek low flows tended to be over-estimated, while the high January peak flows were missed all together, largely a function of the climate forcing data which causes WEAP21's snowmelt algorithm to accumulate a snowpack in the winter months in Upper Cow, while in fact, Cow Creek tends to be more rainfall than snowmelt driven.

**Sacramento Valley Alluvial Aquifers**

The Sacramento Valley aquifer system was represented as a set of stylized alluvial groundwater basins, hydraulically connected to the river system and thus capable of capturing important groundwater-surface water interactions. Initial estimates of the representative horizontal distance and specific yield parameters led to generally good long-term agreement between observed and modeled groundwater fluctuations, but tended to under-estimate important seasonal fluctuations, with an apparent late spring build-up of ground water storage in the Sacramento Valley (Figure 5.6). The inability to capture important seasonal fluctuations suggested that the initial parameter estimates of representative horizontal distance, $h_d$ and the specific yield, $S_y$ were too large.

The initial representative horizontal distances were halved and ranged from 10 to 40 kilometers, while the specific yield was reduced from 0.2 to 0.065. Figures 5.5 and 5.6 show the effect of this re-parameterization, with marked increases in seasonal fluctuations of the representative groundwater level, $y_d$. Interestingly, the Colusa County well data exhibits a marked increase in groundwater levels around 1980, which were apparently sustained during the drought period between 1987 through 1992. Conversely, our model results show a decline in groundwater levels during this period, as groundwater is substituted for surface water to meet irrigation demands. Figure 5.7 depicts the groundwater-surface water interaction given as the outflow of groundwater to surface water, where positive (negative) values indicate water flux to (from) the river. During the intense drought of 1976 and 1977 and the prolonged drought of the early 1990's, the simulated net exchange between the surface-groundwater interface becomes negative indicating a net-loss of river water to the alluvial aquifer, while at all other times, the model results suggested a net flux of groundwater to the river system. A net flux of about 500 million $m^3$ was estimated during above normal water years, with this number exceeding 1,500 millions $m^3$ during very wet periods such as the early 1980's. Model results suggest that groundwater's contribution to streamflow as sub-surface outflow during wet periods ranges from about 2 to as much as seven percent, while during dry periods the net loss of river water to aquifer in the Sacramento basin can is about indicating that the average contribution to streamflow from the Sacramento Basin is about

**Figure 5.6. Observed and modeled groundwater tables, where the light, thin lines are the observed relative heights of several randomly selected groundwater monitoring wells found in Tehema (left) and Colusa (right) counties, respectively. The light, thick line is the modeled relative height using initial estimates of Specific Yield, $S_y$ and the representative horizontal distance, $h_d$. The dark, thick line is the relative height above the river using the final parameter estimates of $S_y$ and $h_d$.**

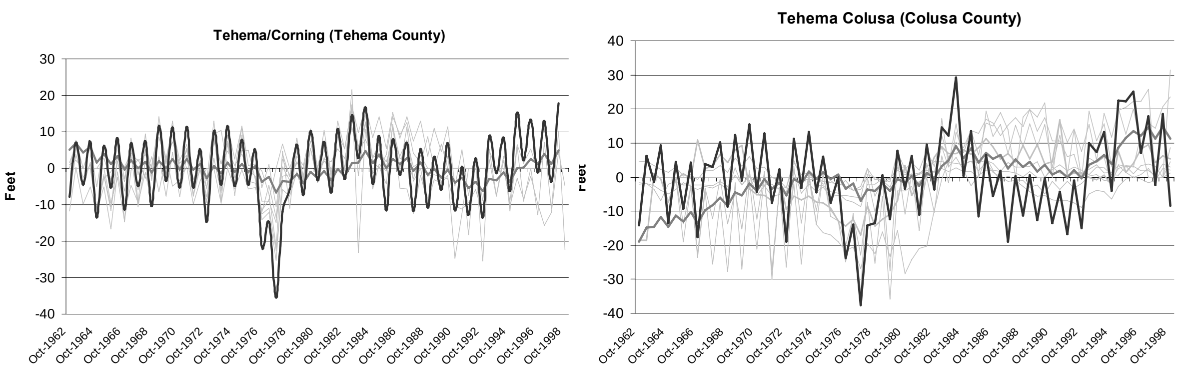
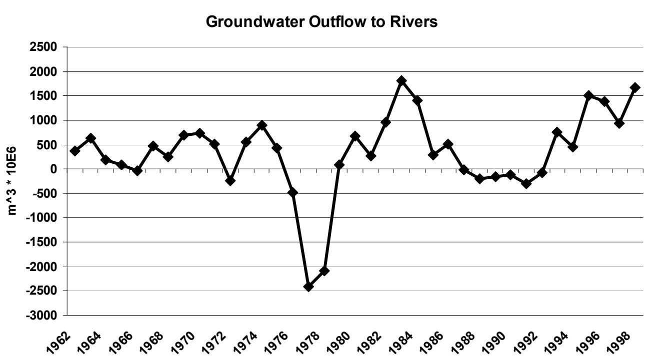



**Figure 5.7. Net annual groundwater flux to (positive) and from (negative) the surface water system of the Sacramento Valley Rivers.**



**Water Supply and Demand**

The 37 year period from 1962 to 1998 included 20 above normal years, with 16 of those classified as "wet" (DWR 1998). There were 17 below normal years, with three classified as "below normal", six as "dry", and seven as "critical". Recall that evaporative demands of both irrigated agriculture and urban landscapes are climatologically dependent, so during wet years, some soil moisture demand can be met through natural precipitation, while dry years do not have such an advantage. Excluding exports, the total average annual model estimated demands (agriculture, urban, and environment) were 10,850 million $m^3$ during wet years and 12,700 million $m^3$ during dry years. These are the estimated demands assuming an unlimited water supply. Model results thus suggest about a seventeen percent increase in total demand for dry compared to wet years based purely on estimates of soil moisture deficits.

Table 1 provides an estimated mass balance for 1995, a slightly wet year in the Sacramento Basin (DWR 1998). Table 1 also includes model results from the A1U2E2 scenario as average values based on wet and dry designations. The estimated Sacramento Basin runoff for 1995 was about 27,600 million $m^3$, with Sacramento Basin Urban and Agricultural supplies of 900 and 10,000 million $m^3$ respectively, leaving nearly 40% unallocated. The simulation results suggest that the total average annual delivery during wet years and dry years was about 10,500 million $m^3$ and 11,502 million $m^3$, respectively. Thus, dry-year shortfalls were 10 percent of the total demand, while wet-year short-falls were only 2.7 percent of the total demand. The unallocated portion of Sacramento river water is more than 50 percent of the total flow during wet years, but drops to around 10 percent during dry years, suggesting a considerable vulnerability of the Sacramento system to dry periods.

Trinity River diversions are included in Table 1. Trinity diversions began in the early 1960's with increasingly larger diversions made over time, with as much as 90 percent of its water diverted to the Sacramento-San Joaquin basins. In an average year the Trinity River diversion was as much as 1100 million m3, with Table 1 showing model estimated diversion of a little over 600 million m3. Modeled diversions tend to be smaller than actual diversions, largely because the model makes use of groundwater to meet the majority of Sacramento Bain demand shortfalls.

**Table 5.1: Approximate Sacramento Basin Water Budget. *Note: Modeled estimates include the contribution from groundwater inputs, which are not explicitly accounted for in the observational data. When the model is run without irrigation, and thus no explicit groundwater extraction, the Sacramento Basin Runoff for the 37-year average drops to 28,600 million $m^3$. **The observational data did not explicitly include Environmental demands**

| | | Annual Volume (million $m^3$) | | | |
|---|---|---|---|---|---|
| | | *Observed* | 37 yr Avg | Wet Yr. Avg | Dry Yr. Avg |
| Sacramento Basin Runoff | A | *27600* | 30100 | 40200 | 19900 |
| Import from Trinity River | B | *1100* | 623 | 610 | 630 |
| Total Sacramento Supply* | C:A+B | *28700* | 30723 | 40810 | 20530 |
| Exports | D | *6900* | 6900 | 6900 | 6900 |
| Unexported | E:C-D | *21800* | 23823 | 33910 | 13630 |
| Urban Water Supplied | F | *900* | 802 | 760 | 843 |
| Agriculture Water Supplied | G | *10000* | 9621 | 9151 | 10091 |
| Environmental Supply** | H | ** | 572 | 575 | 569 |
| Total Supply | I | *10900* | 10995 | 10486 | 11503 |
| Unallocated | J:C-I | *10900* | *12828* | *23424* | *2127* |
| As Percentage of Sacramento Runoff | K:J/A | *39%* | 43% | 58% | 11% |

**Reservoir Storage and Operation**

During dry periods, particularly the two year critical drought of 1976 and 1977 and the critically dry period from 1987 through 1992, the surface storages of the major reservoirs were drastically drawn down to meet water requirements. This is illustrated in Figure 9, which shows both the observed and modeled storage estimates for the three major reservoirs; Folsom, Oroville, and Shasta using the A1U2E3 scenario. The model's estimate of Shasta's reservoir storage was generally good, with simulated drawdown greater than observed in some years (for example, the 1962 and 1977 water years), but very good agreement during the severe drought of 1976 and 1977 and generally agreeable reproduction of storage volumes during the 1990's drought. Correlations and errors between observed and model storage were acceptable (Fig. 10).

The simulation of Oroville's storage was acceptable, noting that the model tended to release too much water following the 1976-77 drought, leading to lower storage than was observed particularly in the 1980's, with generally good agreement between modeled and observed storage during the 1990's. The simulation of Folsom reservoir storages was also fairly well represented by the model, recalling that both the filling priority and the conservation pool storage were lowered in 1988 to reflect a higher priority for flood protection. The reservoir was generally kept more full during normal years (for example, 1962-1968 and 1982-1991), deeply drawn down during the 1976-1977 and 1990's droughts, and drawn down more extensively during more normal water years beyond 1988 in response to the changing reservoir rules, although our estimates of Folsom drawdown in the mid 1990's remained under-represented.

**Figure 5.9. Observed (thick, light line) and simulated storage for Folsom, Shasta and Oroville Reservoirs. Inset within each plot are the monthly correlation coefficient ($R^2$) and the root mean square error (RMSE, *10E6 m3) of the monthly flow.**

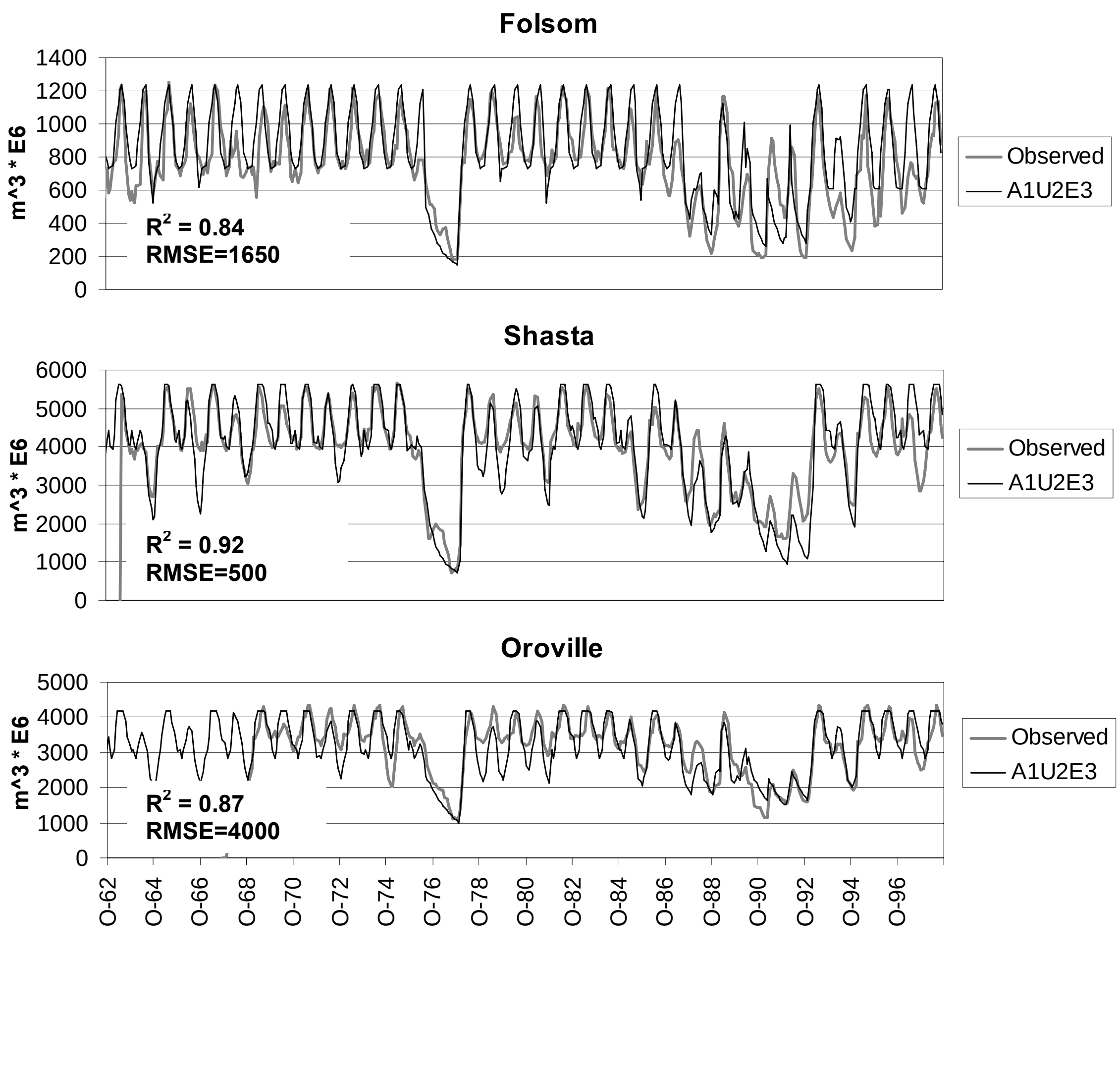
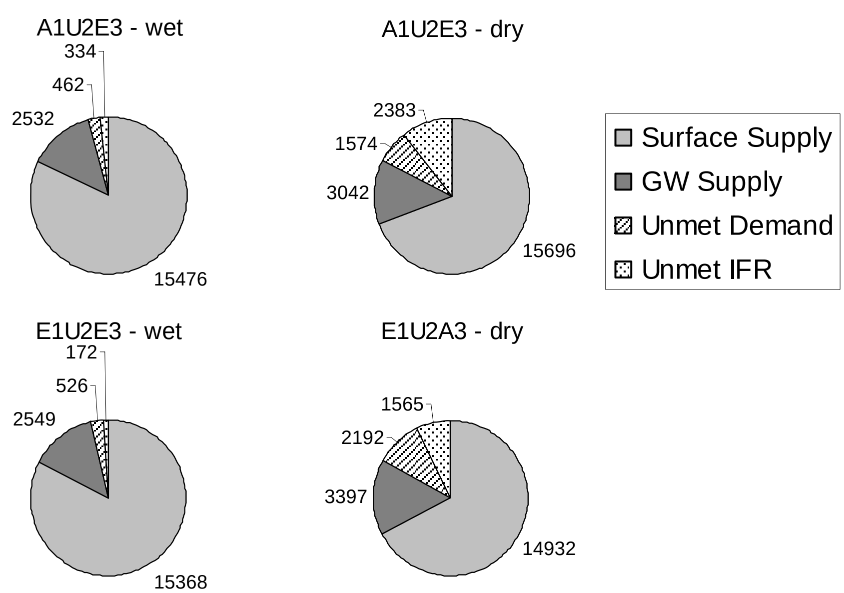


Figure 10 summarizes total average annual water supplied to both within basin and export demands from both surface and groundwater sources, stratified by wet and dry seasons and for the A1U2E3 and E1U2A3 scenarios. Recall the E1U2A3 scenario represents a re-prioritization, whereby environmental instream flow requirements must be met before agriculture and urban demands. Total water supply actually increases in dry years due to enhanced demands, as local precipitation is not available to satisfy soil moisture deficits that are made-up through irrigation. During wet years and irregardless of priorities, model results suggest that nearly all the instream flow requirements can be satisfied and that roughly 23% of total in-basin demands are met through groundwater sources.

In dry years, assigning instream flow requirements a higher priority than agriculture and urban demands (the E1U2A3 scenario) resulted in a simulated reduction of instream flow requirements of more than 50% when compared with the A1U2E3. The satisfaction of instream flow requirements are met at a cost to agriculture and urban demands, with total unmet demands increasing by about 40%. Groundwater's share in meeting agricultural and urban demands increases to 26% in dry years in the A1U2E3 scenarios and to nearly 30% for the E1U2A3 scenario. Certainly while a substantial share of agriculture, urban, and instream flow demands can be met during dry periods, the overall mass balance highlights the sensitivity of the Sacramento Basin to drought, with drastic reductions in reservoir storage (Figure 9), nearly all the water in the system allocated (Table 1), and fairly dramatic draw down of the Central Valley alluvial aquifers (Figures 6&7).

The WEAP21 IWRPM framework was shown to adequately capture the overall mass balance of the Sacramento Basin, at a fairly high level description of important regional and temporal characteristics. A key feature of the model is its ability to characterize the complete hydrologic cycle, which allows the planner to track mass balance changes in terms of both the magnitude and nature of the water balance, and mass conservation in heavily managed watershed such as the Sacramento Basin can be achieved and is fully transparent.

**Figure 5.10. Average annual surface (light gray) and groundwater supply volumes (dark gray) for the A1U2E3 wet (upper left) and dry (upper right) scenarios and the E1U2A3 wet (lower left) and dry (lower right) scenarios (*1E6m$^3$). The hatched slices are the unmet irrigation demands, while the dotted slices are the unmet instream flow requirements (IFR).**



# 6. Climate Change Impacts On Water For Agriculture In The Sacramento Valley

In the previous sections, we have outline the integrated water resources modeling framework that will be used to assess the potential impacts of climate change on the freshwater systems of the Sacramento watershed. The description of the tool (Section 4) and its validation (Section 5) are necessary to lend credibility to its use as a climate change impact assessment tool. In this section, we describe a series of experiments where future scenarios that include land use and climate change are used to drive the WEAP21 model for assessing climate change impact and adaptations in the Sacramento Valley.

There are two very strong trends that will directly affect the demand for and the availability of water in the Sacramento River Basin. The first driver is the steady growth in population, particularly around existing urban areas and transportation corridors. It is projected, for instance, that in Sacramento County the population will increase from a present (2000) 1.2 million people to 3.3 million by 2100. The second driver is changing land use, which relates to population growth, as that growth has led to the extension of urban area into other land use types.

Projections of future land use patterns based on assessments of current patterns of land development and modification in California have been developed by Professor John Landis of U.C. Berkeley (Landis and Reilly, 2003). This project implements these scenarios within the WEAP modeling framework (discussed in Section 4). Projections are based on a spatial-statistical model of development patterns based on a number of factors including physical site, economic, and neighborhood characteristics. Projected spatial land use changes for 2020, 2050, and 2100 are shown in Figure 6.1 and demonstrate that by 2100 over 100,000 ha, almost double, will convert to urban use. For the purposes of this project, we assume in total that most of the converted land was originally agricultural land. The uncertainties associated with these projections depend on the extent to which population and employment growth trends and urban settlements can be extended far into the future.

Other examples of land use/land cover projections come from the California Water Plan published by the California State Department of Water Resources Bulletin 160-93, which projects that irrigated area in the Sacramento River, San Joaquin River, and San Francisco Bay regions will decrease from the current 1.66 million hectares to 1.63 by the year 2020, a reduction of 30,000 hectares, most likely in favor of urban growth. In an average flow year, this corresponds to a reduction of 860 MCM of applied agricultural water (940 MCM in a drought year). This reduction in cultivated area is driven by salinity problems and land retirement, increased irrigation efficiency and recycling, more competitive world markets, and agricultural land being urbanized. Therefore the increase in population leads to a pressure both in terms of municipal water demands and in terms of food and environmental security as there is less water available for environmental needs with increasing encroachment on non-urbanized lands.

We will combine these potential land use/land cover and population changes into the integrated analytical framework of WEAP, and evaluate how the status and distribution of California’s land use/land cover and population may, in concert with climate change, affect the provision of aquatic ecosystem goods and services of the Sacramento (which is inclusive of irrigated agriculture).

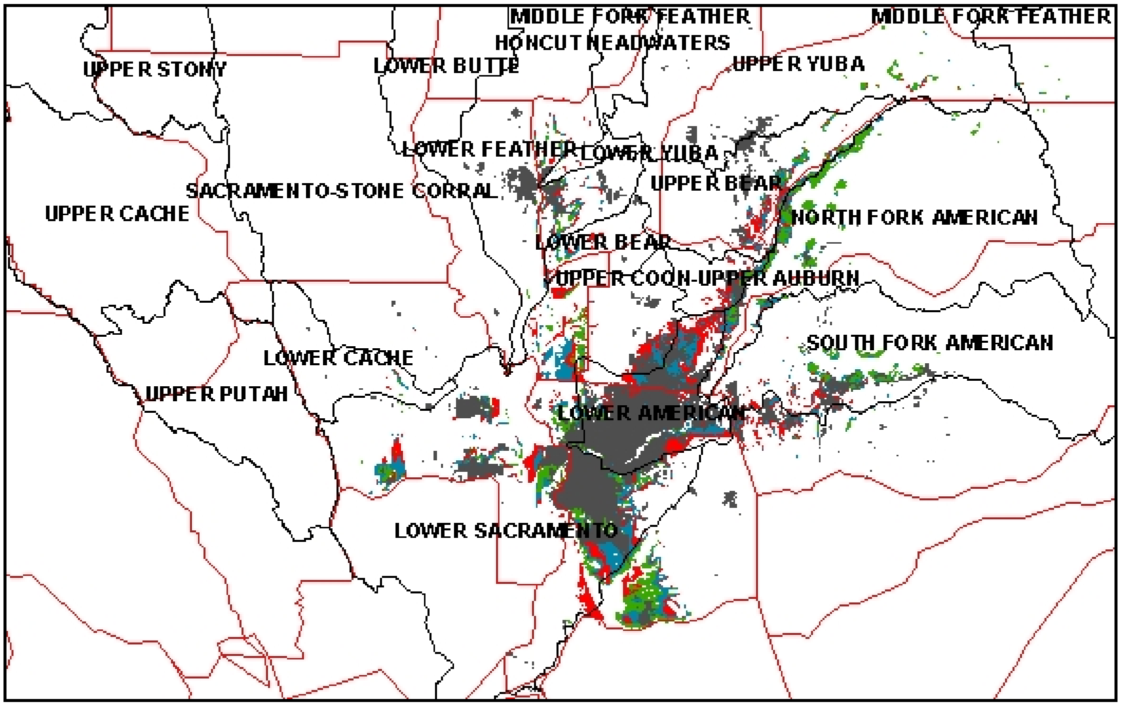


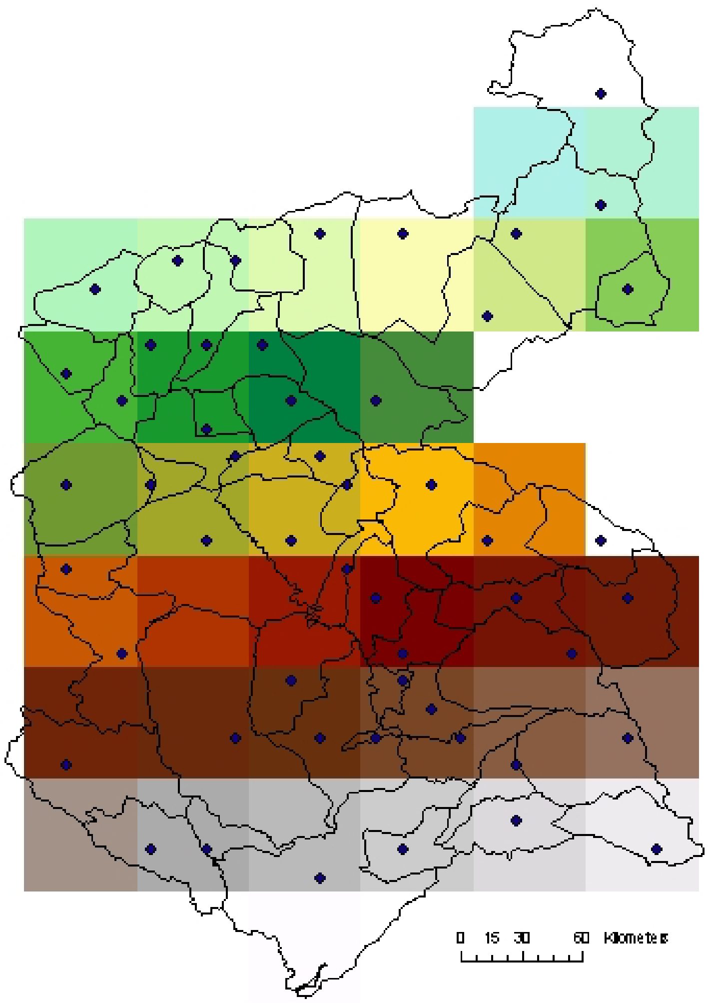

**Figure 6.1. Land Use Projections for 1998 (gray), 2020 (green), 2050 (blue), and 2100 (red). Red solid lines are county demarcations. Black solid lines are HUC demarcations. (Landis and Reilly, 2003)**

General circulation models (GCMs) simulate the global climate and are currently a key tool for generating future climate change scenarios. While these models are built on first-order principles, their spatial scale of simulation (100s of kilometers) is often not fine enough to capture regional climate characteristics. Furthermore, GCM runs for historical time slices tend to show local and regional discrepancies with respect to measured variables such as precipitation and temperature. To generate climate scenarios for impact assessment at appropriate scales, both regional climate models (RCMs) and statistical downscaling methods have become increasingly popular.

A key determinant of a GCM's ability to accurately characterize the current climate is its ability to simulate key climate mechanisms such as mean average climate, climate variability, and the inter-relationship of climate variables. The better the model's simulation of current climate, the more confidence can be ascribed to its projections of future climate. Precipitation is a very difficult variable for GCMs to consistently and reliably project. In estimating the global spatial pattern of precipitation, the most accurate models correctly estimate only half of the observed spatial pattern of precipitation. There are some indications that this capability is improved in more recent versions of the models. Among the 30 or more GCM simulations available, the Hadley Centre (United Kingdom) model appears to perform best in simulations of precipitation patterns in recent years (reference?).

One major shortcoming of essentially all GCMs is their spatial resolution. Although model resolution has increased 2- to 4-fold in recent generations, the most sophisticated models have grid dimensions of a few hundred kilometers. In a typical GCM, each grid box contains one value each for average elevation and average climate; that is, there is no spatial variation within the grid box (Figure 6.2). At their current resolution, GCMs drastically smooth out most of California's complex topography. For example, current GCMs do not contain important terrain features such as the Coastal Range, the Central Valley, and the Sierra Nevada. However, model resolution is increasing and this may be an important factor in the more accurate GCM estimates of current climate. Comparisons of climate change patterns for California that emerged from an analysis of 21 GCMs showed that all models estimated warmer temperatures for the state under assumptions of greater radiative forcing from increased greenhouse gas emissions (ref?). The degree to which the state warms depends, in large part, on the sensitivity of each model to higher greenhouse gas concentrations. More sensitive GCMs naturally exhibit a greater estimate of climate warming. Interestingly, the 21 GCM models in this analysis project yielded significantly different changes in precipitation for California. The model estimates range from a 56 percent increase in winter precipitation in the Canadian model (CCCTR) to a 10 percent decrease in winter precipitation in a Japanese GCM (CCSR/NIES). Approximately two-thirds of the models estimate some increase in the state's precipitation.

**Figure 6.2: GCM grid overlay over the Sacramento Watershed**




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

The two GCMs used to generate the future climate conditions for the current investigation were the Parallel Climate Model (PCM) developed at the National Center for Atmospheric Research and the CM2 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). Outputs from these models were downscaled by applying the methodology developed by Maurer et al. (2002) to create a 1/8 degree gridded data set for daily climate variables. This downscaled daily data set was used to derive average monthly time-series of precipitation, temperature, and wind speed for each of the 54 sub-catchments in the WEAP model. Cayan et al. (2005) also calculated the relative humidity time series required to run the WEAP hydrology module based on the downscaled climate variables and other grid-scale parameters.

This section of the paper summarizes the predicted changes in precipitation and temperature over the next century. This analysis is followed by a discussion of the impacts of changing precipitation and temperature on the hydrologic response in the upper watersheds above the major reservoirs in the system and a discussion of the impacts of changing temperatures on crop water demands in the irrigated portion of the Sacramento Valley below these facilities. Later sections discuss how the combined effects of altered water supply and demand regimes influence the ability of the water resources system to be operated to meet defined targets. Section 4.0 concludes by evaluating the relative impact of implementing water management adaptation strategies at the irrigation district level in response to future conditions.

### *6.1. Climatic Analysis*

In the following analysis, precipitation and temperature data are presented for the four alternative climate change model/scenario combinations: GFDL A2, GFDL B1, PCM A2, and PCM B1. These climate variables are presented as the averages of the 54 climate locations used as inputs to WEAP, although the trends are very similar throughout the Sacramento Valley. Graphs are presented for four distinct periods: 1960–1999, 2005–2034, 2035–2064, and 2070–2099. Each of the four periods was compared to the historic data set that was used to calibrate the WEAP model over the period 1960–1999 (Maurer 2002). An important caveat to consider when looking at the historical baseline, however, is that neither GCM used estimated historical forcing and, thus, the GCMs do not replicate the exact historical climate. Instead they were calibrated to generate statistically similar climate patterns of the historical period. The historical baseline should be viewed as a reference against which to view the time evolution of climate change impacts associated with each model/scenario combination.

#### 6.1.1. Precipitation

Figure 6.3 shows changes in annual precipitation. The results are presented as exceedance probability plots, which sort the sequence of years into dry (exceeded in roughly 75%–100% of years), normal (exceeded in roughly 25%–75%of years), and wet years (exceeded in roughly 0%–25% of years) for each of the four periods of our analysis. The graphs show that the two GFDL scenarios predicted a decreasing trend in precipitation over the next century, with wet years showing the largest shift in annual rainfall. The two PCM scenarios showed less pronounced changes in annual precipitation. PCM B1 predicted slightly wetter conditions at the end of the century, while the PCM A2 showed a decrease in precipitation in normal-dry years and an increase in precipitation in normal-wet years.

**What Is the Historical Baseline?**

The actual historical climate was a spatially distributed field of climate variables that was observed at a limited number of climate stations. The WEAP model requires that climate inputs be introduced for each sub-catchment, whether or not a climate station is located within its boundaries. Maurer (2002) produced a grid of interpolated climate variables based on the limited set of observations. The assumptions used to carry out the interpolation are implicit in the output, which may not capture the exact spatial distribution of historic climate fields.

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

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

### 6.1.2. Temperature

Figures 6.4 and 6.5 show changes in average temperature for winter (October through March) and summer (April through September) periods. Hash marks above and below shaded boxes indicate maximum and minimum values. Each of the four scenarios predicted increases in average winter and summer temperatures over the next century. GFDL A2 showed the highest increases in temperature: 3.0°C (5.4°F) for winter and 5.0°C (9°F) in summer. PCM B1 showed the smallest change in temperature: 1.5°C (2.7°F) for winter and 1.4°C (2.5°F) in summer. The GFDL B1 and PCM A2 scenarios predicted intermediate changes in temperature. GFDL B1 predicted changes of 1.9°C (3.4°F) in winter temperature and 2.8°C (5°F) in summer temperature. PCM B1 predicted changes of 2.2°C (4°F) in winter temperature and 2.5°C (4.5°F) in summer temperature.

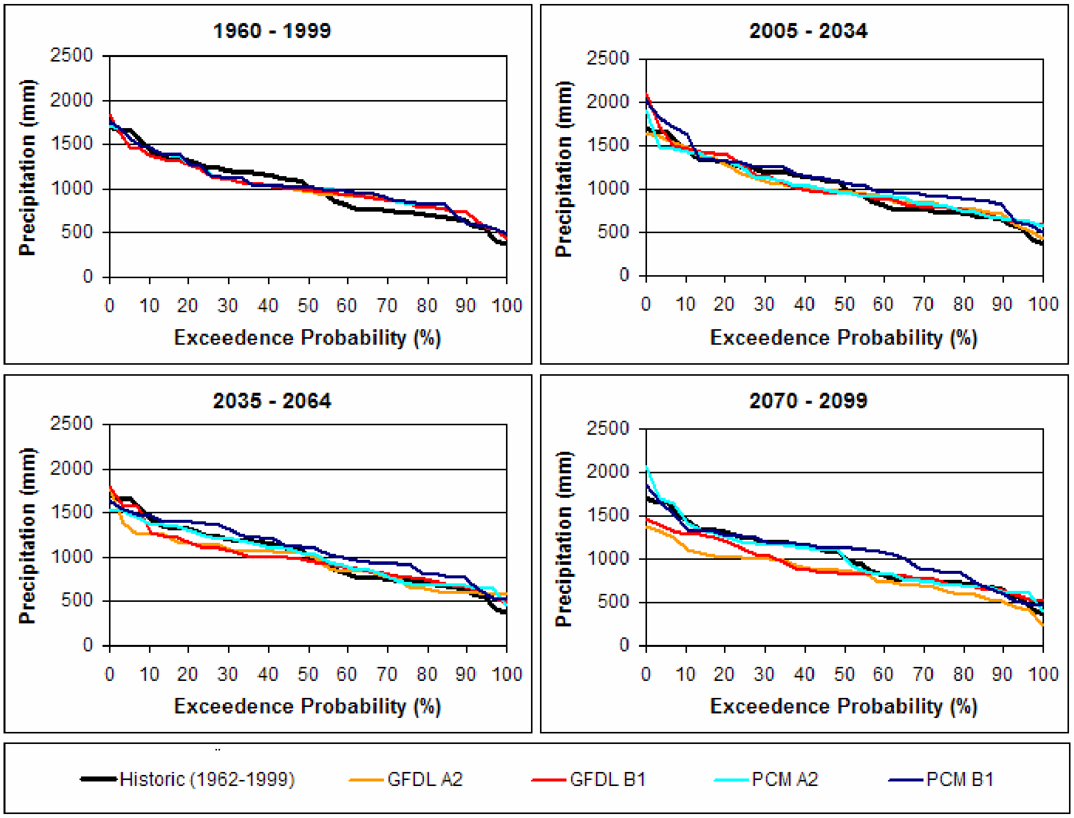



**Figure 6.3. Total annual precipitation**

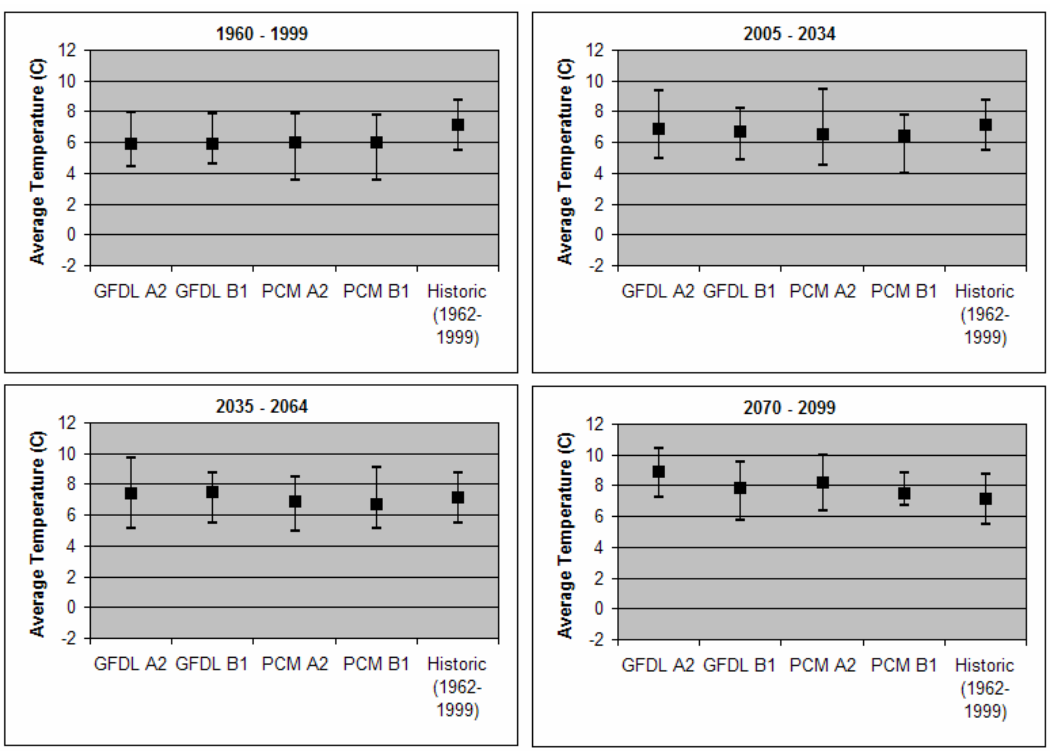



**Figure 6.4 Average, maximum, and minimum temperatures October–March**

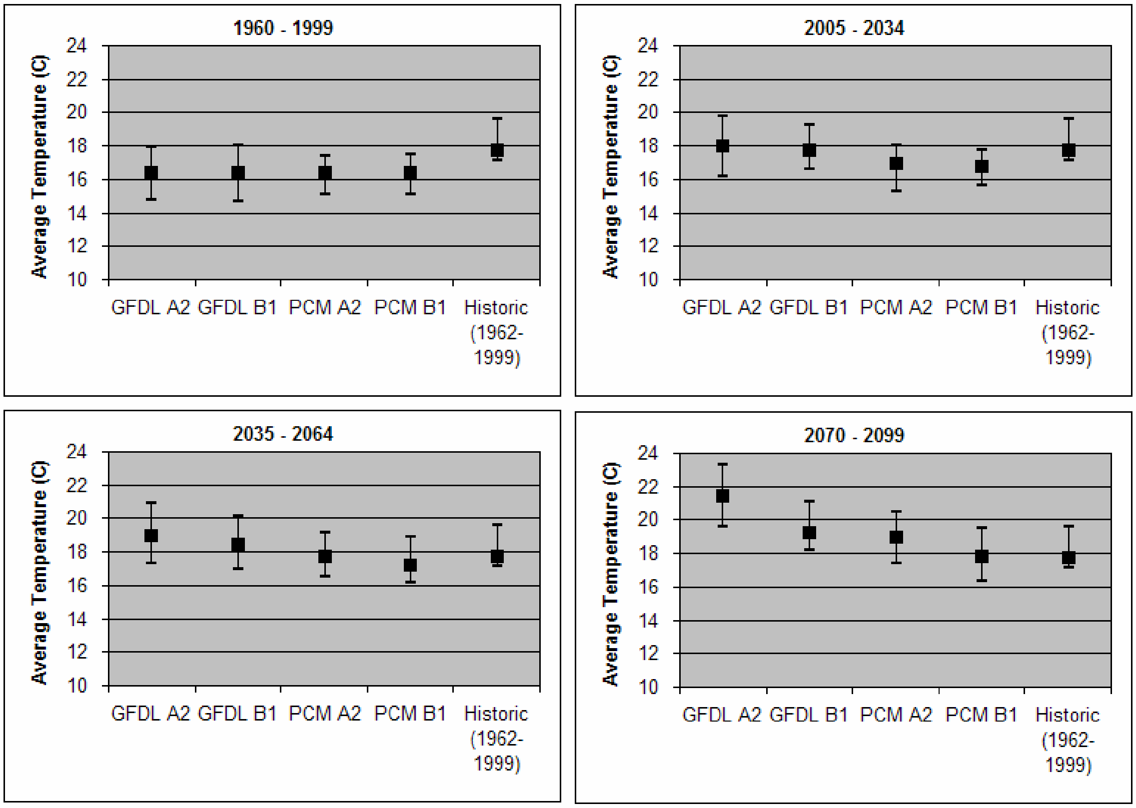



**Figure 6.5. Average, maximum, and minimum temperatures April–September**

The graphs depicting the winter and summer temperatures for the 1960–1999 period demonstrate clearly how the simulated climate variables from the historical period do not match this historical baseline. A direct comparison with the historical baseline is complicated, however, by the fact that the historic data are influenced by the implicit assumptions of the interpolation routine used by Maurer (2002), which may not faithfully capture the actual continuous historic climate fields. Assuming that the interpolated historical data do represent the historic climate fields, then the climate scenarios selected by the Climate Action Team, which start from relatively cool conditions, suggest that the analysis that flows from these climate scenarios represents a relatively conservative analysis of future climate change impacts.

## *6.2. Analysis*

### 6.2.1. Impacts with No Climate Change

Even without climate change, an increase in population and consequent increase in domestic demand and changes in land use (increased urbanization) will increase pressures on water resources in the Sacramento watershed. Population changes and land use changes are used throughout the analyses. We assume that the increase in urban land use is at the expense of all other land types equally.

There is already concern about meeting water requirements in 2020 without climate change. Bulletin 160-98 of the California Water Plan Update estimates that, at 1995 levels of development, water shortages already exist and are on the order of 2,000 million cubic meters (MCM) in average water years for the entire state. In drought years the shortage nearly triples to 7,000 MCM. By 2020, due to population-driven demand growth, it is estimated that the shortages will be 3000 MCM in an average water year and 8,000 MCM in drought years for the state of California, and 105 MCM and 1220 MCM for the Sacramento watershed, average and drought years respectively (Department of Water Resources, 1998). The Sacramento is in part vulnerable to water shortages as substantial supplies are exported to meet demands in other parts of the state. An aspect of the future that has not been so explicitly explored in the state is the impact of land use changes on the hydrology of the system, and in particular a shift of land use from agriculture to urban areas.

Model results are much higher than these Sacramento projections of deficit for an average year without climate change – at 505 MCM. One possible explanation is that the Department of Water Resources water budget did not consider exports from the Sacramento region to other parts of the state. The export from the Sacramento delta to the San Joaquin Valley and Los Angeles are currently modeled as major demands (combined urban and agricultural demand of approximately 7,400 MCM). Another possible explanation for this is that the California state projections do not account for the impact of land use change as predicted by Landis and Reilly (2003) (described in section 3.1) on the basin hydrology, which is likely negatively impacted.

Of this 505 MCM shortfall, agricultural demand accounts for 482 MCM while the remainder is for urban demands. Furthermore, in-stream flow requirements for the anadromous fish recovery program (AFRP), particularly for the American River tributary, are consistently not met. On average, flow requirements in the month of July are not met 69% of the time. This is consistent with current conditions in this river.

## 6.3. *Impacts with Climate Change*

### 6.3.1. Hydrologic Analysis

This section presents the impacts of the climate change scenarios on the Sacramento Basin hydrology, with a focus on inflows to the three major reservoirs in the basin: Lake Shasta, Lake Oroville, and Folsom Lake. The objectives of this section are as follows:

- Show how well WEAP represents historic hydrologic conditions, by comparing historic data (as characterized by CalSim-II input files) with outputs of WEAP run for historic climatic conditions (Table 6.1).
- Compare streamflow data generated by VIC and WEAP models (Table 6.2 and Figure 6.6)
- Analyze hydrologic conditions for the climate change scenarios. The focus here will be on changes in annual inflows (Figure 6.8), in streamflow timing (Figure 6.9) and in drought persistence (Figure 6.10).

### 6.3.2. WEAP simulation of historic reservoir inflows

The following show a comparison between historic hydrologic conditions and outputs of WEAP run using historic climatic data (Maurer et al., 2002) for the three major watersheds in the Sacramento Basin. The model's goodness of fit for each of the watersheds was judged using the following equation (Table 6.1 shows the results for the three watersheds):

$$R^2 = 1 - \frac{\sum (WEAP_i - CalSim_i)^2}{\sum CalSim_i^2}$$

Where $WEAP_i$ = annual inflow as generated by WEAP and $CalSim_i$ = historic annual inflow.

The results show that WEAP has a very good representation of both Feather and Sacramento-Pit streamflows but not as good for the American River.

**Table 6.1. Goodness of fit for WEAP results**

| Watershed (reservoir inflow) | $R^2$ |
|---|---|
| Sacramento-Pit (Shasta) | 0.99 |
| Feather (Oroville) | 0.97 |
| American (Folsom) | 0.68 |

### 6.3.3. Comparison of WEAP and VIC Predictions of Reservoir Inflows

This section compares VIC and WEAP hydrologic conditions under climate change scenarios for the three major watersheds in the Sacramento Basin. The comparison between the two models is consistent for each of the climate change scenarios; Figure 6.6 shows GFDL B1 results as an example. In order to reduce the number of figures presented, a comparison for just one GCM output is shown: GFDL B1. Again $R^2$ is used as defined above as a measure of the goodness of fit between the two models. The results as presented in Table 6.2 show that VIC and WEAP have a very good agreement for the Sacramento-Pit and Feather Rivers with less correspondence for the American watershed.

**Table 6.2. R2 between WEAP and VIC results**

| Watershed (reservoir inflow) | $R^2$ |
|---|---|
| Sacramento-Pit (Shasta) | 0.99 |
| Feather (Oroville) | 0.95 |
| American (Folsom) | 0.85 |

The deviation between the simulated WEAP input to Folsom Lake and the simulated VIC inflows raises questions about what is going on in the American River system. We can not point to a bias in either model, since comparing outputs from different models is complicated by uncertainty about which model is correct. The underlying performance of the hydrologic formulation in the WEAP model was supported, however, when output from a more refined model of the American River was compared with unperturbed natural flows observed in the North Fork of the American River, with good results (Figure 6.7).

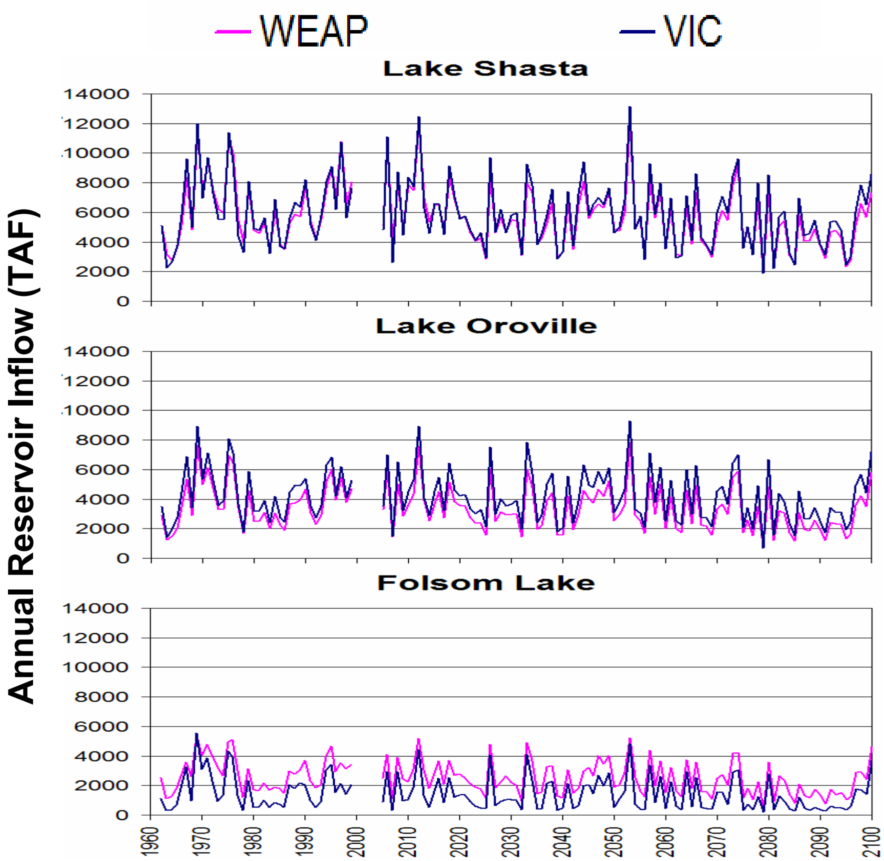



**Figure 6.6. Comparison of WEAP and VIC inflows to Shasta, Oroville, and Folsom reservoirs for climate change conditions under GFDL B1 scenario. (Inflow given in thousand acre-feet.)**

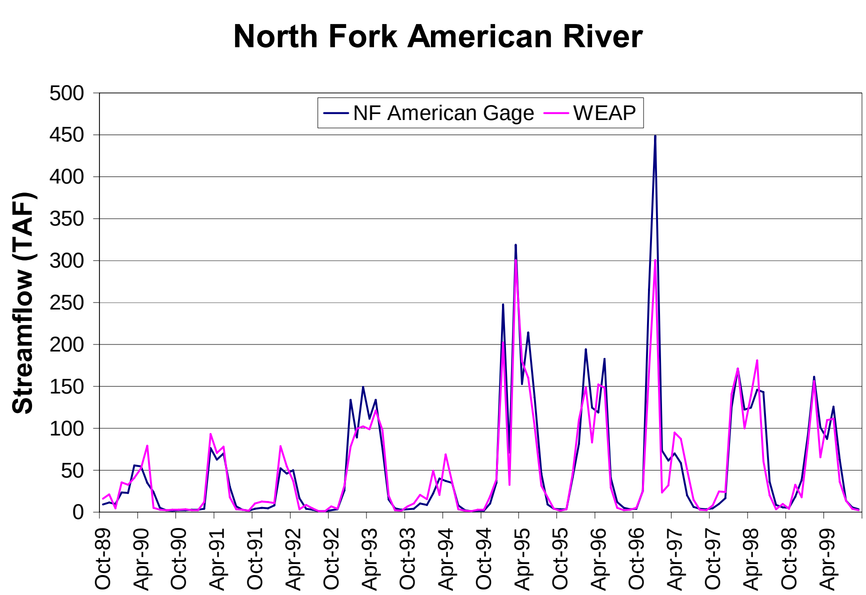



**Figure 6.7. Comparison of WEAP results and observed unaltered natural flows in the North Fork of the American River**

### 6.3.4. Climate change impacts on reservoir inflows

This section focuses on the analysis of three very relevant aspects of the hydrologic conditions that could be expected under the climate change scenarios included in this assessment: annual inflows to reservoirs, changes to streamflow timing, and drought persistence. These are the factors that are likely to change under climate change and which raise the issue of whether the water management arrangements that exist in the system can respond to these changes.

**Changes to annual inflows**

Figures 6.8 show changes in the exceedance probability of annual inflows to major reservoirs in the Sacramento Basin for two time periods: 2035–2064 and 2070–2099. The results presented are consistent with the results shown above in terms of changes in annual precipitation, i.e., PCM B1 is a wet scenario and therefore has higher annual inflows to the major reservoirs, and GFDL A2 is a dry scenario and therefore has lower annual inflows. The other two models fall in between. This finding is consistent with the supposition that a drier climate would reduce the overall water supply.

**Changes to streamflow timing**

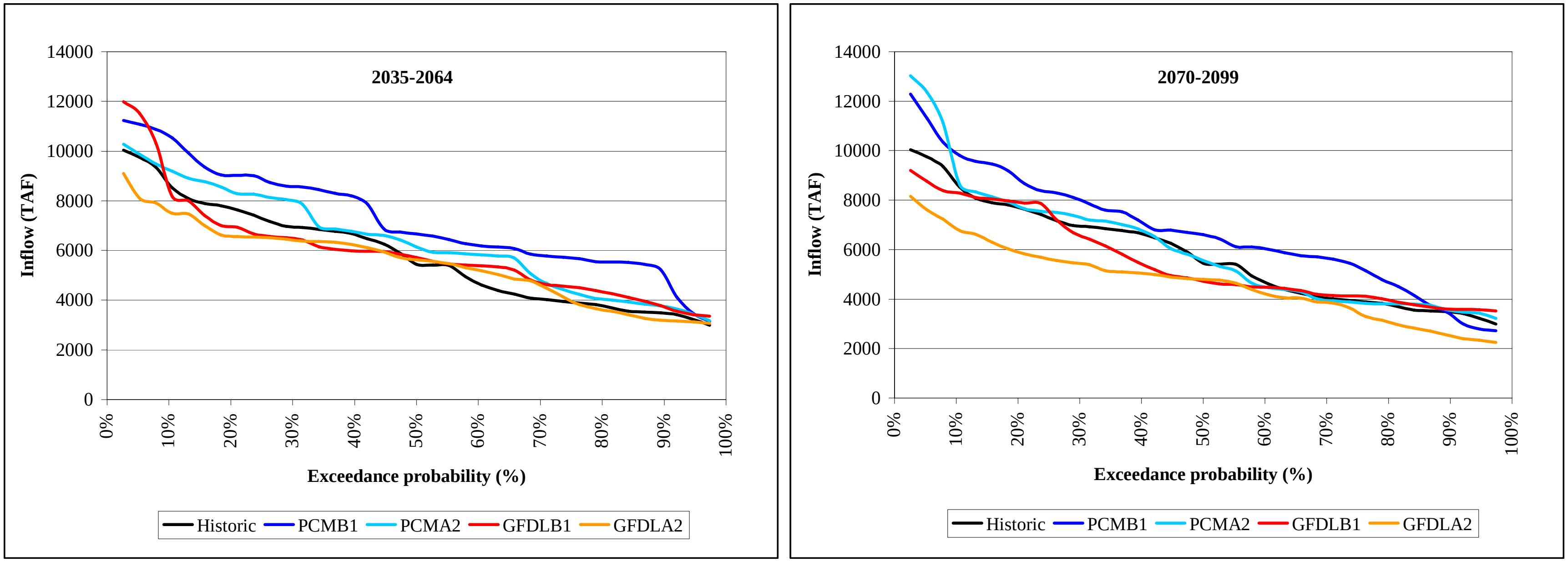
Figure 6.9 shows changes in monthly average inflows (surrogate for changes in streamflow timing) to major reservoirs in the Sacramento Basin for the 2070–2099 time period. All the scenarios show an earlier timing of streamflows as compared to historic conditions. The impacts are higher for the Feather and American watersheds, which is expected considering that both basins have more dependence on snow melt runoff as much of the Sacramento watershed above Lake Shasta lies below the snow line. The impacts are also higher for those scenarios with higher increases in temperature (e.g., GFDL A2), consistent with the results shown above in terms of changes in temperature. Once again the results are consistent with the supposition that warmer temperatures lead to earlier loss of the snow pack.

### 6.3.5. Changes to drought conditions

A major advantage of the WEAP model is that it can be used to examine scenarios that don't preserve the historic sequence of wet and dry years. Thus, WEAP can simulate conditions under different levels of drought persistence that might occur with climate change. This paper includes an estimate of possible changes in future hydrologic conditions in terms of drought persistence. Drought conditions in the Sacramento Basin were described using a construction of the 40-30-30 Sacramento (Four River) Index. This index is composed of inflows to Shasta, Oroville, and Folsom Reservoirs plus streamflow at Yuba River. Based on the value of this index, a water year is classified as wet, above normal, below normal, dry, or critical. Assuming that a drought will be indicated by a year below the dry threshold, an accumulated deficit representing the positive difference between the "dry" threshold and the 40-30-30 Index was calculated. Deficits are accumulated in consecutive dry years and whenever the index is above the "dry" threshold, the deficit is reset to zero.

Figure 6.10 shows the accumulated deficits for the historic period (the 1976–77 and early 1990s droughts are apparent), the four climate change conditions included in this analysis, plus one last climate change scenario corresponding to the PCM model run under the A1fi emission scenario. The results show that drought persistence will be smaller for the two PCM scenarios considered in this analysis, but not if the A1fi emission scenario is included. Under A1fi, the prediction is that droughts comparable in magnitude to the early '90s drought will occur with regularity. On the other hand, the GFDL B1 scenario predicts milder conditions as compared to the historic scenario in terms of drought persistence. However, this is clearly not the case under GFDL A2 scenario, which includes a very severe drought ("mega-drought") during the last 15 years of the century.

The future pattern of drought persistence associated with each GCM/emission scenario combination is directly related to the sequence of climate data associated with each combination. Wet scenarios such as PCM A2, PCM B1 and GFDL B1 produce future climate sequences that contain less dramatic drought conditions than recent history. More precipitation means fewer droughts. Dry scenarios such as PCM A1fi and GFDL/A2 are associated with drought conditions that are more numerous or more severe than in recent history. Less precipitation means more droughts. When considering this information on drought persistence, it is important to keep in mind that the climate time series associated with each GCM/emission scenario combination represents a single realization of the future climate. It would be possible to develop ensembles of future climate time series, which would allow for a more robust depiction of potential future drought conditions. In the interest of time, the Climate Action Team chose not to develop and use ensembles.




**Inflows to Shasta**

| Historic conditions (1962-1998) | |
|---|---|
| 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 5,444 | 3,479 |

| | GFDL A2 | | GFDL B1 | | PCM A2 | | PCM B1 | |
|---|---|---|---|---|---|---|---|---|
| | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 2035-2064 | 5,621 | 3,184 | 5,708 | 3,734 | 6,143 | 3,738 | 6,666 | 5,001 |
| 2070-2099 | 4,804 | 2,518 | 4,728 | 3,599 | 5,561 | 3,552 | 6,606 | 3,381 |

**Figure 6.8. Exceedance probability of annual inflows to Shasta. Comparison between climate change scenarios and historic conditions.**

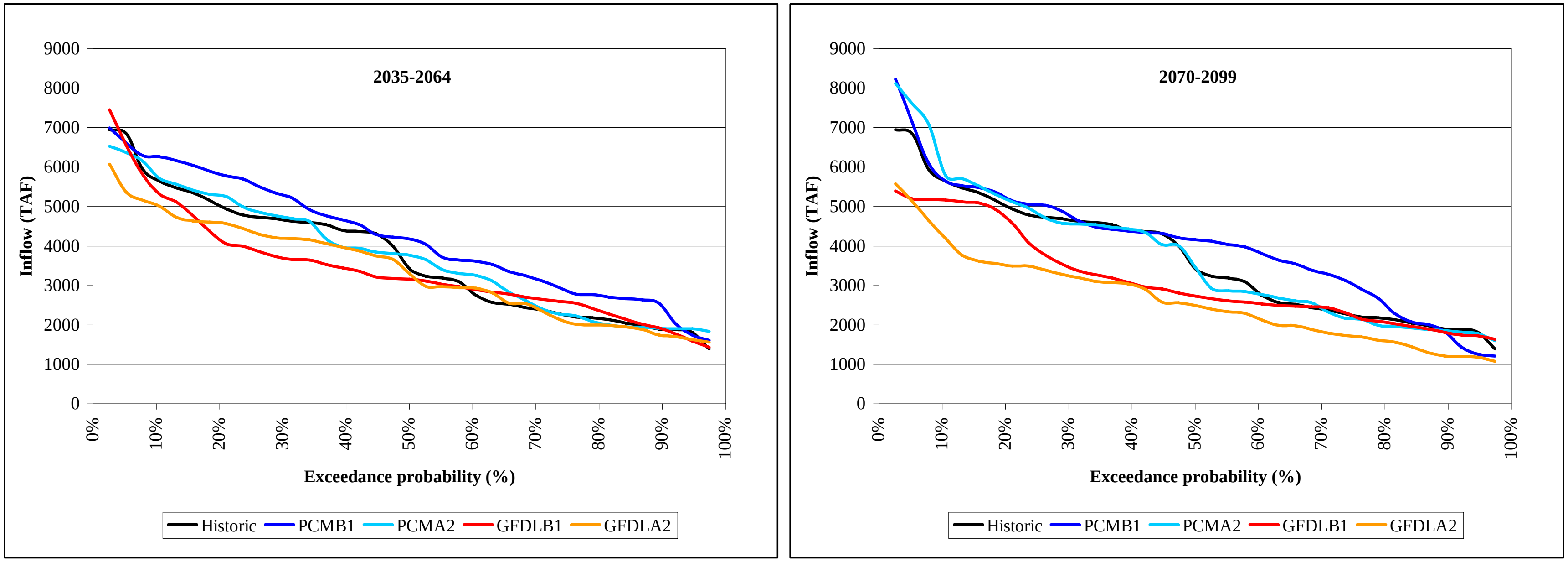
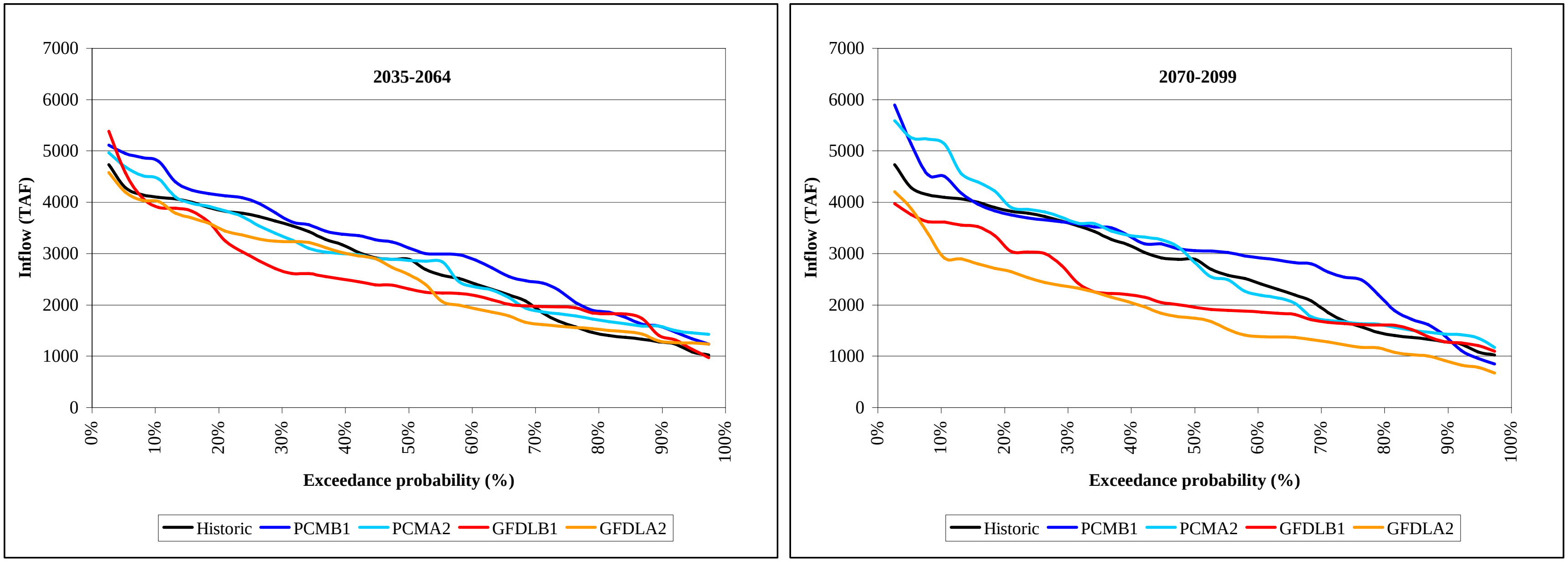



**Figure 6.8 cont. Exceedance probability of annual inflows to Oroville. Comparison between climate change scenarios and historic conditions.**

**Inflows to Oroville**

| Historic conditions (1962-1998) | |
|---|---|
| 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 3,426 | 1,895 |

| | GFDL A2 | | GFDL B1 | | PCM A2 | | PCM B1 | |
|---|---|---|---|---|---|---|---|---|
| | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 2035-2064 | 3,305 | 1,735 | 3,160 | 1,893 | 3,766 | 1,910 | 4,181 | 2,448 |
| 2070-2099 | 2,494 | 1,203 | 2,731 | 1,792 | 3,465 | 1,852 | 4,157 | 1,750 |




**Inflows to Folsom**

| Historic conditions (1962-1998) | |
|---|---|
| 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 2,886 | 1,270 |

| | GFDL A2 | | GFDL B1 | | PCM A2 | | PCM B1 | |
|---|---|---|---|---|---|---|---|---|
| | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 2035-2064 | 2,593 | 1,287 | 2,314 | 1,389 | 2,866 | 1,572 | 3,107 | 1,565 |
| 2070-2099 | 1,739 | 898 | 1,950 | 1,274 | 2,822 | 1,433 | 3,060 | 1,341 |

**Figure 6.8 cont. Exceedance probability of annual inflows to Folsom. Comparison between climate change scenarios and historic conditions.**

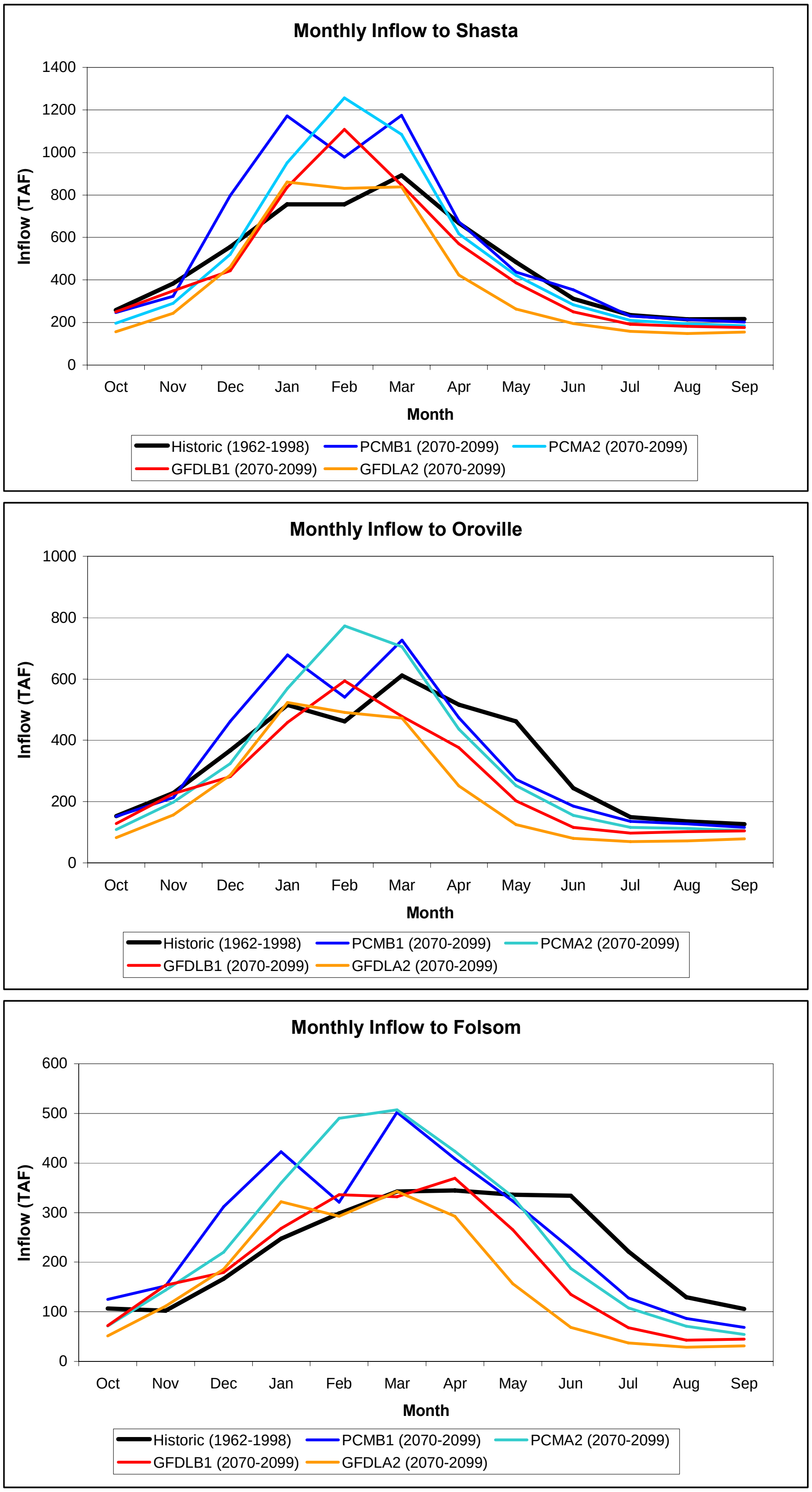



**Figure 6.9. Changes in monthly inflows to Shasta, Oroville, and Folsom Reservoirs**

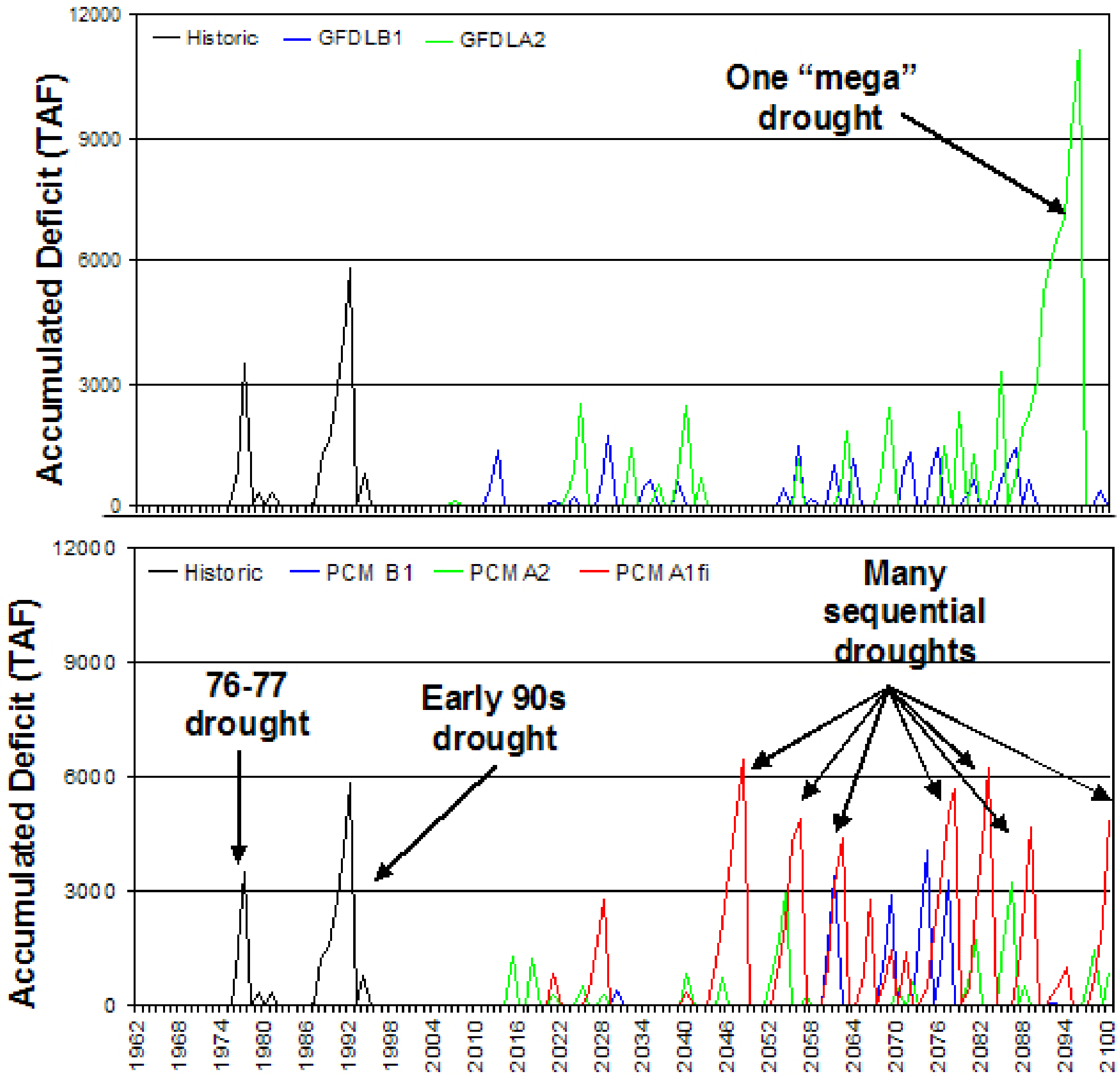



**Figure 6.10. Changes in drought conditions**

## *6.4. Demand Analysis*

Annual supply requirements for Sacramento Valley agricultural areas are summarized in Figure 6.11 and Table 6.3. These are the sums of the crop water requirements calculated from the future climate time series using WEAP's internal Penman-Montieth routine, adjusted based on assumed losses in delivering water to meet these requirements, for all irrigated crops in a particular sub-catchment. All four scenarios showed an increasing trend in water requirements with time, with the GFDL A2 scenario exhibiting the most pronounced increase. These increasing supply requirements are due primarily to increasing summer temperatures for each of the four scenarios.

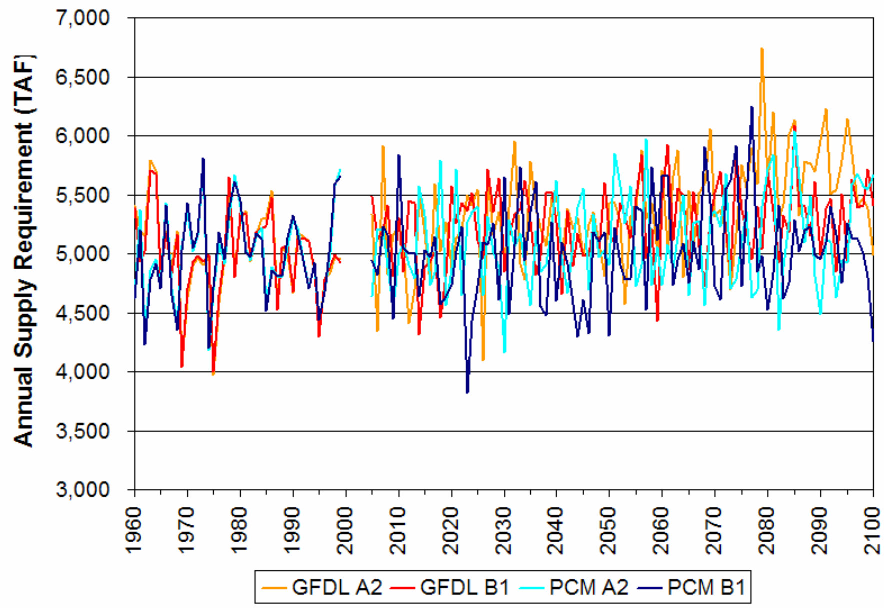



**Figure 6.11. Annual supply requirements: Sacramento Valley agriculture**

**Table 6.3. Changes in annual supply requirements: Sacramento Valley agriculture**

| | GFDL A2 | | | GFDL B1 | | | PCM A2 | | | PCM B1 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Average Annual Requirement (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Requirement (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Requirement (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Requirement (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) |
| 1960-1999 | 5,008 | 0 | 0% | 5,002 | 0 | 0% | 4,990 | 0 | 0% | 4,993 | 0 | 0% |
| 2005-2034 | 5,139 | 131 | 3% | 5,191 | 189 | 4% | 5,025 | 34 | 1% | 4,944 | -48 | -1% |
| 2035-2064 | 5,297 | 289 | 6% | 5,231 | 229 | 5% | 5,131 | 141 | 3% | 4,979 | -13 | 0% |
| 2070-2099 | 5,658 | 650 | 13% | 5,348 | 345 | 7% | 5,188 | 198 | 4% | 5,107 | 115 | 2% |

## *6.5. Operations Analysis Without Adaptation*

This section considers the impacts of each of the climate change scenarios on water supply and delivery. For the purposes of this analysis, the impacts to water supply were evaluated using reservoir carryover storage and groundwater levels as indicators. Delivery reliability under each scenario was evaluated using total annual measures of surface water deliveries and groundwater pumping.

Delivery reliability was evaluated for Sacramento Valley agriculture users. Separate assessments were made for the agricultural areas serviced by the Sacramento and Feather Rivers, because of the different contractual arrangements for these two rivers. It should be noted, however, that project areas (i.e., CVP along the Sacramento River and SWP along the Feather River) are aggregated with non-project agricultural areas for each of these regions. Section 6.5 ends with an analysis of delivery reliability for the Stone Corral HUC, where sub-catchments were distinguished according to their contract types.

### 6.5.1. Sacramento Valley agriculture

Water districts that have contract agreements for surface water deliveries from the two main water projects—the Central Valley Project (CVP) and State Water Project (SWP)—dominate agriculture in the Sacramento Valley. Both projects operate large reservoirs on separate rivers that they use to store and release water to their respective contractors. The CVP operates Lake Shasta on the Sacramento River along with storage and diversion infrastructure on the Trinity River. The SWP operates Lake Oroville on the Feather River. Water that is released from these reservoirs is diverted at various control points along the rivers. WEAP simulates the operation of these reservoirs by assuming that water demands in the agricultural areas, as defined by crop water requirements, are the drivers for reservoir releases.

WEAP attempts to satisfy crop water requirements by delivering water through canals and by pumping groundwater. The extent to which it is able to meet the full crop requirements depends upon surface water supplies and capacity constraints on canals and groundwater pumping. Presently, with the exception of CVP contractors in Stone Corral HUC, surface water deliveries to agriculture are not constrained by the amounts specified in water user contracts. For this reason, the interpretation of climate impacts on water supply and delivery is similar for both the CVP and SWP. Therefore, model results for both the Sacramento and Feather River areas are presented together.

Each of the four climate change scenarios was run continuously over a historical period (1960–1999) and a future period (2005–2100) using downscaled GCM climate data. The results of these scenarios are summarized in the following graphs of carryover storage levels for Lake Oroville and Lake Shasta, annual surface water deliveries to agriculture from the Feather and Sacramento Rivers, and, for each basin, annual groundwater pumping by agriculture and groundwater levels. With the exception of groundwater levels, which are presented as time-series graphs, each metric is presented in exceedance probability form for four distinct periods: 1960–1999, 2005–2034, 2035–2064, and 2070–2099. Each of the four periods is compared to a historic baseline that was generated by running the WEAP model over the period 1962–1998 using historical gridded climate data (Maurer 2002).

### 6.5.2. Carryover storage

Carryover storage in Lake Shasta and Lake Oroville was defined as the amount of water remaining in each of these reservoirs at the end of September (i.e., the end of the water year). Simulations showed that carryover storages in both Oroville (Table 6.4 and Figure 6.12) and Shasta (Table 6.5 and Figure 6.13) decrease with time, with the GFDL A2 scenario experiencing the largest change and the PCM B1 scenario showing only a slight change. This trend is consistent with the inflow hydrographs that were previously discussed, which showed significant reductions in reservoir inflows with time using the GFDL model and little change in inflows when using the PCM model. Decreases in reservoir carryover storage volumes resulted primarily from decreasing inflows, but were enhanced by increases in surface water deliveries to agriculture (see Section 6.5.3).

**Table 6.4. End-of-September storage in Oroville**

| | GFDL A2 | | GFDL B1 | | PCM A2 | | PCM B1 | |
|---|---|---|---|---|---|---|---|---|
| | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 1960-1999 | 2,725 | 1,661 | 2,716 | 1,639 | 2,876 | 1,733 | 2,858 | 1,733 |
| 2005-2034 | 2,646 | 1,723 | 2,535 | 1,629 | 2,775 | 1,779 | 2,901 | 2,483 |
| 2035-2064 | 2,300 | 1,562 | 2,378 | 1,604 | 2,758 | 1,541 | 2,920 | 1,841 |
| 2070-2099 | 1,684 | 1,107 | 2,059 | 1,563 | 2,299 | 1,494 | 2,677 | 1,550 |

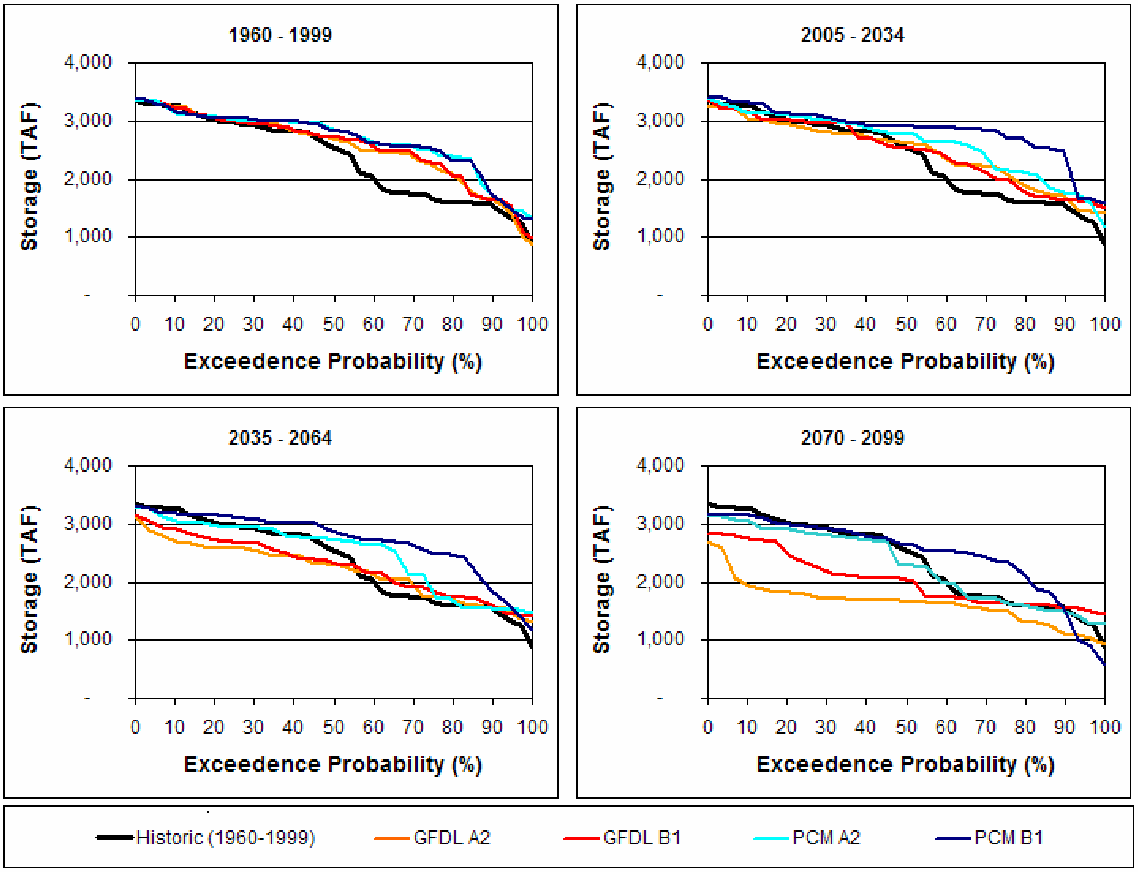



**Figure 6.12. End-of-September Oroville storage**

**Table 6.5. End-of-September storage in Shasta**

| | GFDL A2 | | GFDL B1 | | PCM A2 | | PCM B1 | |
|---|---|---|---|---|---|---|---|---|
| | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) | 50 Percent Exceedence (TAF) | 90 Percent Exceedence (TAF) |
| 1960-1999 | 3,235 | 1,793 | 3,244 | 1,793 | 3,532 | 1,931 | 3,507 | 1,894 |
| 2005-2034 | 3,113 | 1,816 | 2,982 | 1,793 | 3,270 | 2,177 | 3,459 | 2,921 |
| 2035-2064 | 2,705 | 1,671 | 2,798 | 1,674 | 3,245 | 1,553 | 3,457 | 2,253 |
| 2070-2099 | 1,793 | 822 | 2,422 | 1,698 | 2,705 | 1,465 | 3,150 | 1,789 |

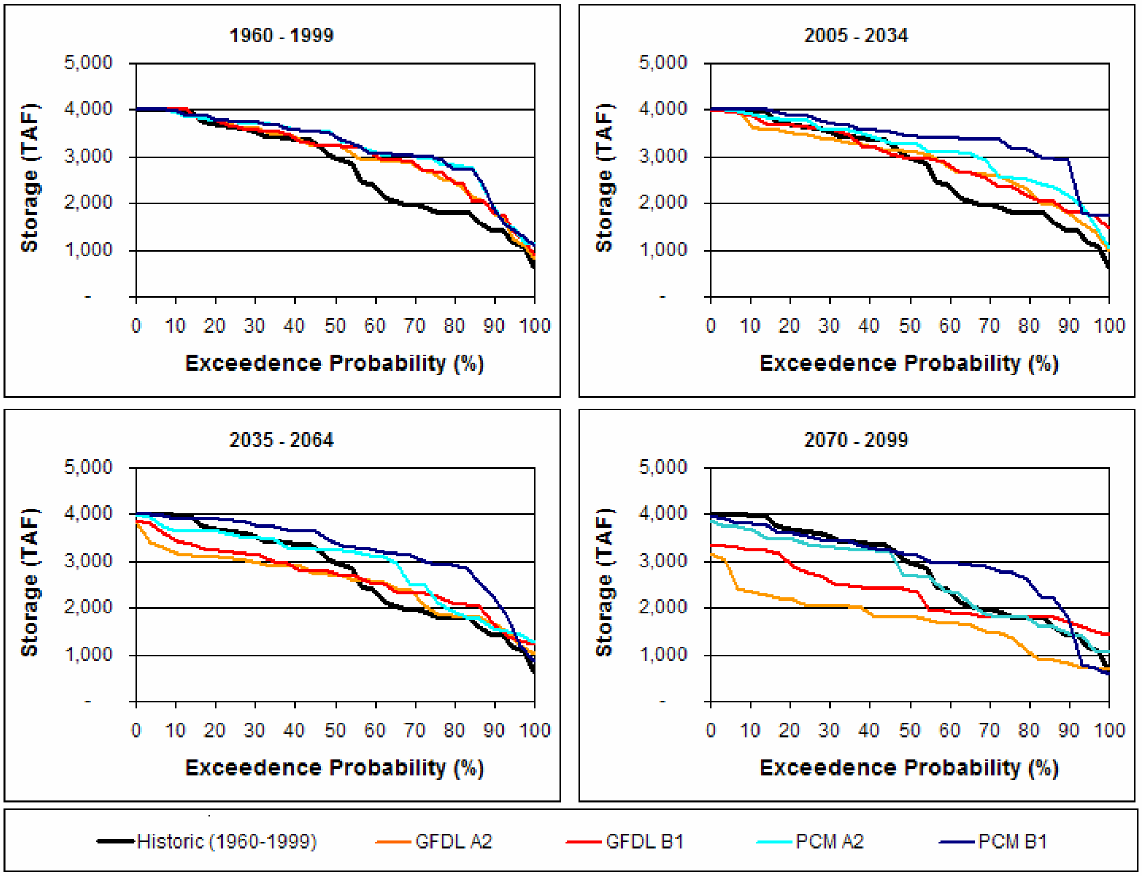



**Figure 6.13. End-of-September Shasta storage**

### 6.5.3. Surface water deliveries

Surface water deliveries to agriculture from the Feather and Sacramento Rivers are summarized in Figures 6.14 and 6.15 and Table 5.6. The model logic made in allocating surface water to agriculture is that all M&I and environmental water needs in a given time step are satisfied before surface water is allocated to agriculture. These results show a trend of increasing surface water diversions with time for all scenarios. The increases in deliveries were likely driven by increasing crop water demands, as summer temperatures increased for all scenarios with time. Similar to the changes in summer temperatures, increases in diversions were more pronounced for the two GFDL model runs. Interestingly, for the warmest and driest scenario, GFDL A2, there were years at the end of century when surface water deliveries were much lower than the other scenarios (exceedance probabilities above 75%), despite higher crop water demand. In these years, the GFDL A2 scenario could not deliver as much water to agriculture because there was insufficient storage in Shasta and Oroville.

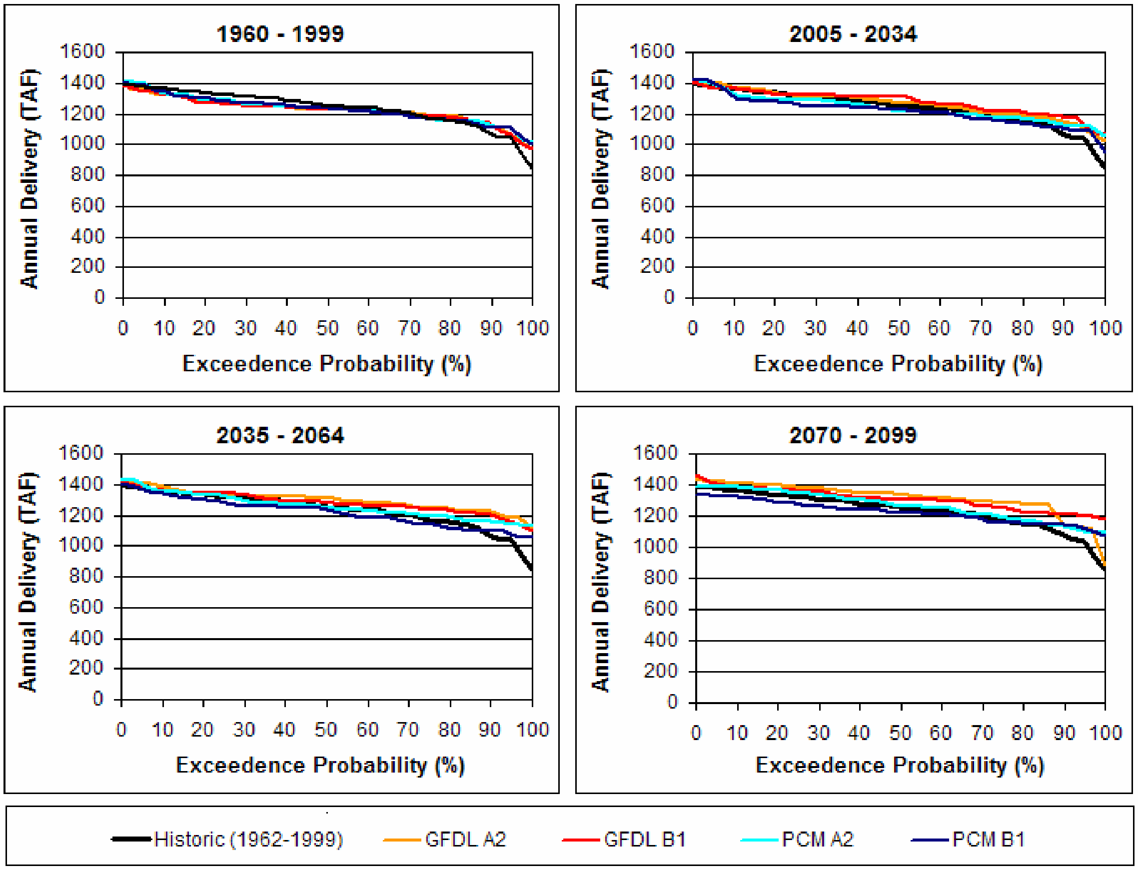



**Figure 6.14. Agricultural surface water deliveries from the Feather River**

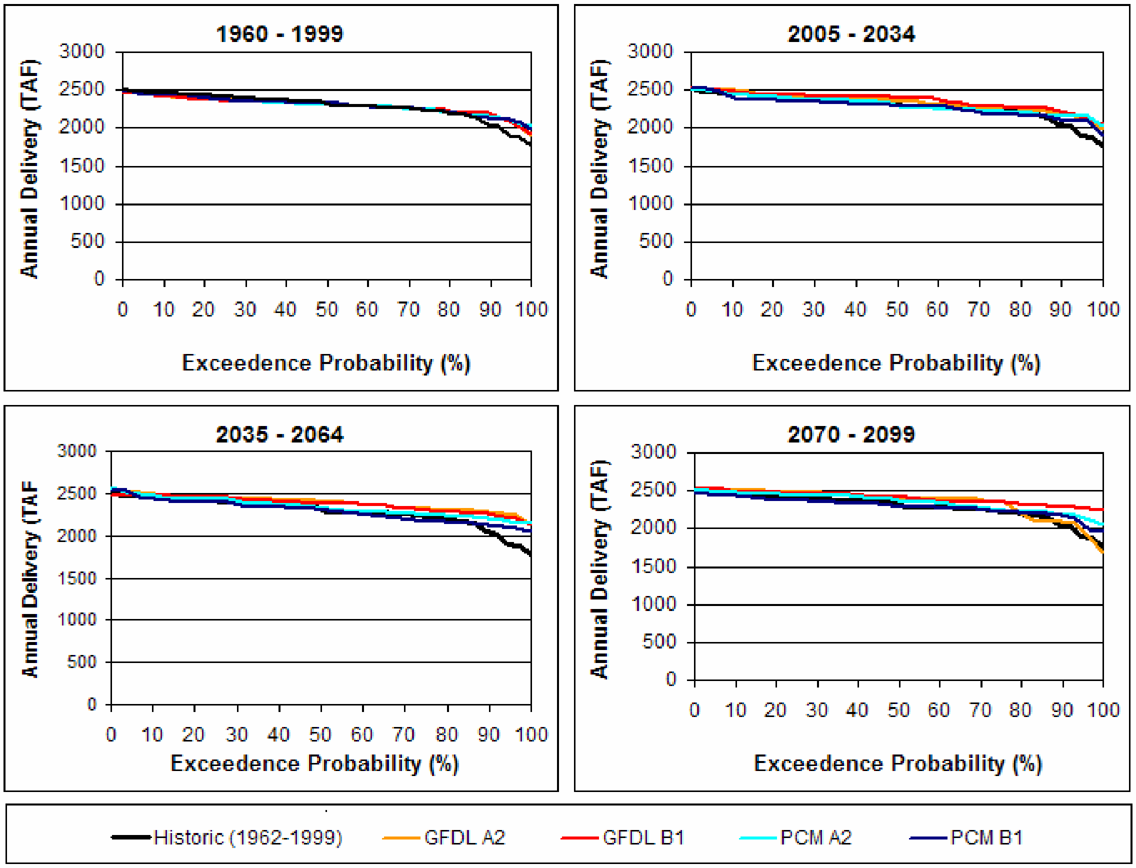



**Figure 6.16. Agricultural surface water deliveries from the Sacramento River**

**Table 6.6. Average annual surface water deliveries: Sacramento Valley agriculture**

| | GFDL A2 | | | GFDL B1 | | | PCM A2 | | | PCM B1 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) |
| 1960-1999 | 3,537 | 0 | 0% | 3,535 | 0 | 0% | 3,523 | 0 | 0% | 3,521 | 0 | 0% |
| 2005-2034 | 3,613 | 77 | 2% | 3,636 | 101 | 3% | 3,568 | 44 | 1% | 3,515 | -6 | 0% |
| 2035-2064 | 3,696 | 160 | 5% | 3,672 | 137 | 4% | 3,595 | 72 | 2% | 3,517 | -4 | 0% |
| 2070-2099 | 3,672 | 136 | 4% | 3,719 | 184 | 5% | 3,624 | 100 | 3% | 3,533 | 12 | 0% |

### 6.5.4. Groundwater pumping

Annual groundwater pumping for the agricultural areas serviced by the Feather and Sacramento Rivers are summarized in Figures 6.16 and 6.17 and Table 6.7. References to annual deliveries in these graphics refer to the annual level of groundwater pumping. The model logic stipulates that areas with access to both surface water and groundwater will rely on available surface water supplies and shift to groundwater in times of scarcity. For both regions, groundwater pumping was relatively stable for all scenarios for the periods covering 1960 to 2064. In the last period, 2070–2099, pumping increased significantly in dry years (exceedance probabilities less than 30%) for the GFDL A2 scenario, when surface water deliveries were less reliable. Oddly, the wettest scenario, PCM B1, also showed a pronounced increase in groundwater pumping in dry years. This increase, however, was due to a sequence of dry years from 2073 through 2077, which resulted in substantial depletion of reservoir storage in Oroville and Shasta.

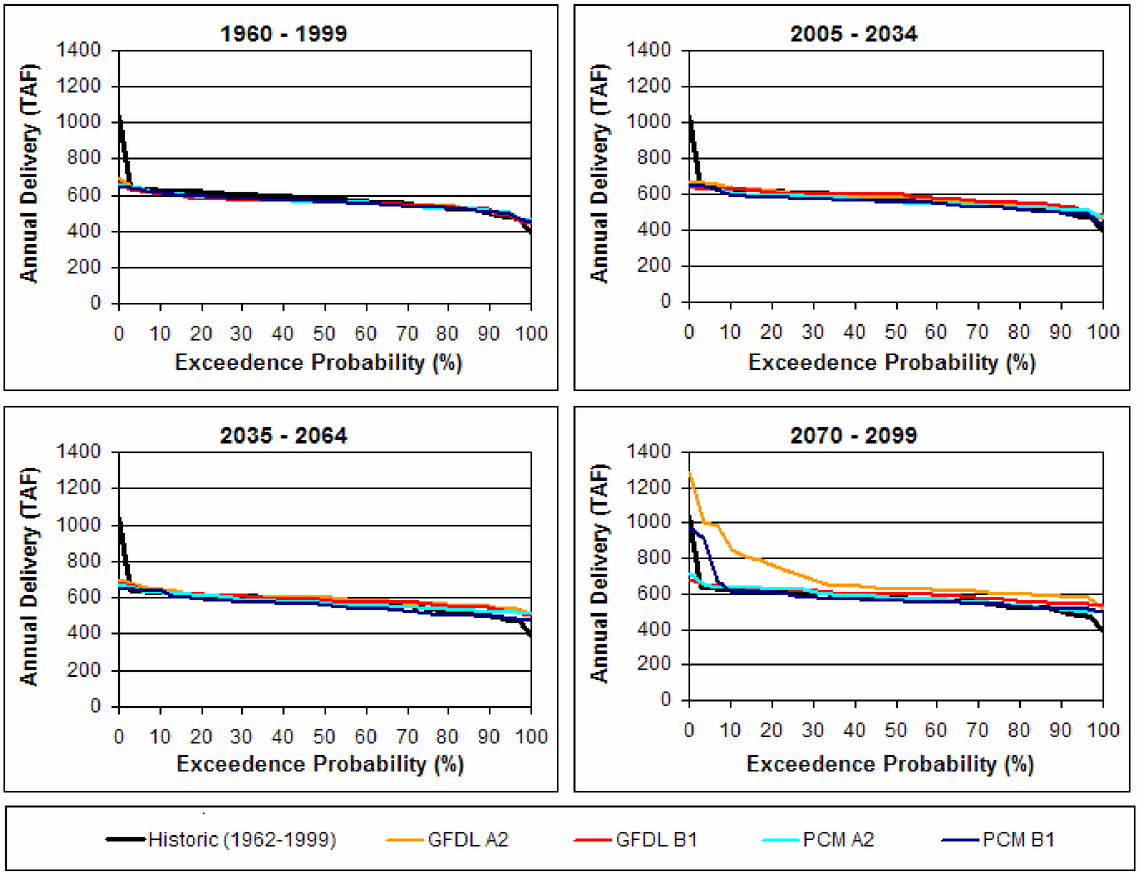



**Figure 6.16. Groundwater pumping for Feather River agriculture**

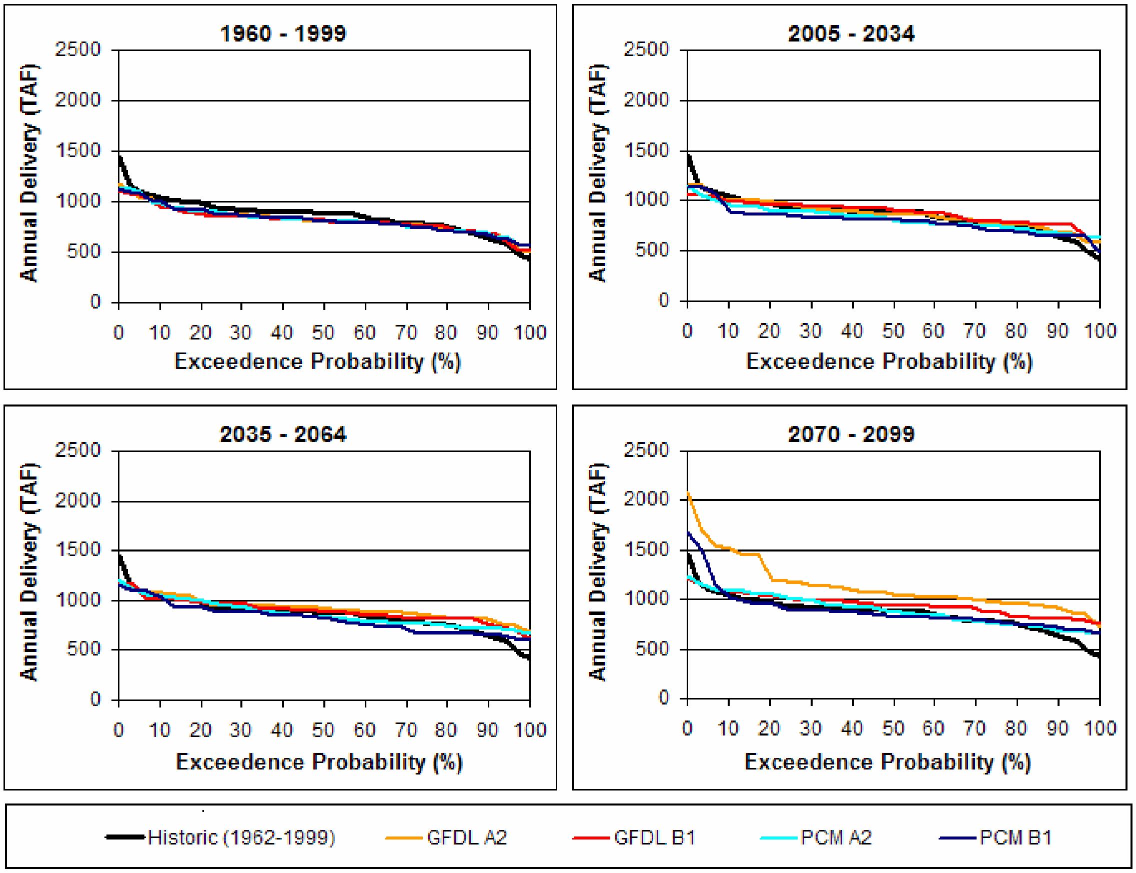



**Figure 6.17. Groundwater pumping for Sacramento River agriculture**

**Table 6.7. Average annual groundwater pumping: Sacramento Valley agriculture**

| | GFDL A2 | | | GFDL B1 | | | PCM A2 | | | PCM B1 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) | Average Annual Delivery (TAF) | Difference from 1960-1999 (TAF) | Difference from 1960-1999 (%) |
| 1960-1999 | 1,379 | 0 | 0% | 1,372 | 0 | 0% | 1,382 | 0 | 0% | 1,380 | 0 | 0% |
| 2005-2034 | 1,443 | 64 | 5% | 1,464 | 91 | 7% | 1,386 | 4 | 0% | 1,355 | -26 | -2% |
| 2035-2064 | 1,517 | 138 | 10% | 1,484 | 111 | 8% | 1,440 | 58 | 4% | 1,374 | -7 | 0% |
| 2070-2099 | 1,831 | 452 | 33% | 1,545 | 173 | 13% | 1,473 | 91 | 7% | 1,477 | 96 | 7% |

### 6.5.5. Groundwater levels

Average depth to the water table is presented for the Butte Basin and the Colusa Basin in Figures 6.18 and 6.19. Both aquifers showed relatively stable fluctuations around a mean for most of the period between 1960 and 2070. Recall that during this period the surface water deliveries were increasing with growing crop water requirements, such that groundwater pumping levels were only marginally increased. During the final period of analysis (2070–2099), however, an extended ten-year drought in the GFDL A2 scenario shifted agricultural water supplies to groundwater. As a result, groundwater levels decreased sharply. The reader should recall that agricultural demands for these simulations were based on a fixed cropping distribution. It is conceivable that shifting cropping patterns as a result of surface water scarcity and groundwater drawdown would mitigate some of this effect. This will be explored in more detail in a later section.

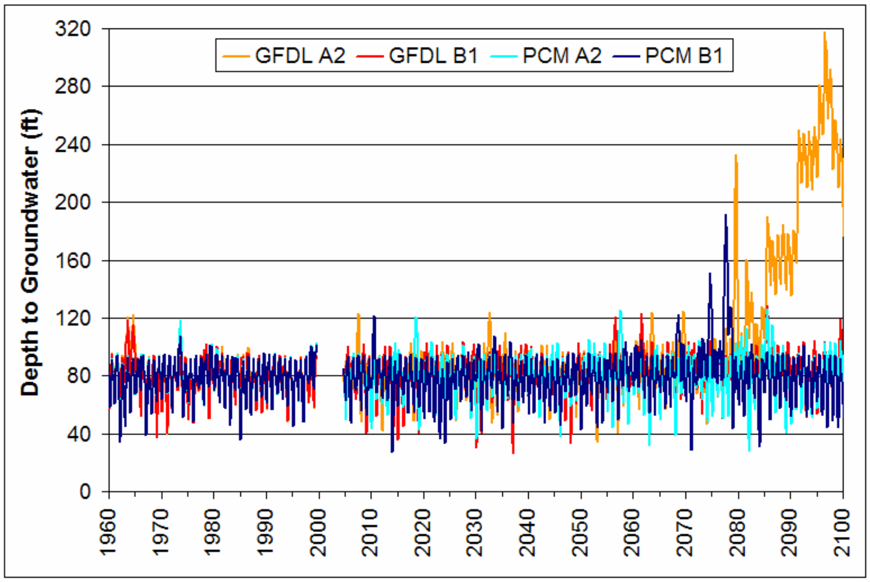



**Figure 6.18. Changes in groundwater depth for the Butte Basin**

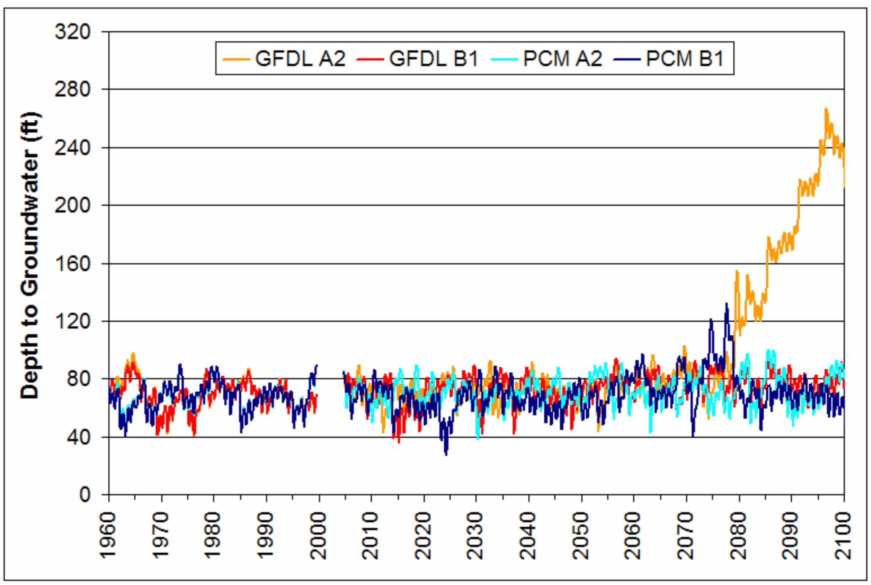



**Figure 6.19. Changes in groundwater depth for the Colusa Basin**

### Stone Corral HUC

Water user districts in the Stone Corral HUC account for over 40 percent of CVP water contracts in the Sacramento Valley. The Stone Corral HUC also contains the two largest districts in the two broad categories that define CVP agricultural contractors: settlement contractors and agricultural services contractors. These two classes of contracts are distinguished by their allocation priority, with settlement contractors having senior water rights. Spatial disaggregation in this area allowed us to consider the effects of climate change on these separate classes of contractors.

The following analysis presents results for the Glenn-Colusa Irrigation District (GCID) and the Tehama-Colusa Canal Authority (TCCA), which are the two largest contractors in their respective classes. GCID contracts a total of 825 thousand acre-feet (TAF) of water per year from the CVP and TCCA's annual water contracts from the CVP total 285 TAF. At present, these are the only water contracts constraining deliveries to agricultural areas. Results are shown only for the GFDL A2 scenario for the periods covering the middle and end of the 21st century, because this was where the impacts of climate change on water supply and delivery were the most pronounced.

### 6.5.6. Surface water deliveries

Surface water deliveries to GCID and TCCA are presented in Figures 6.20 and 6.21. The first thing to note is that neither district ever delivers its full contract amount. For GCID, this is because its contracts exceed the crop water requirements calculated by WEAP. In TCCA's case, it is likely due to the manner in which its contracts were distributed monthly over the growing season. This analysis assumed that the fraction of the annual contract that can be delivered in any month followed the same distribution that is used in the joint USBR-DWR planning model, CalSim II. If this distribution was out of phase with the pattern of crop water demands over the growing season, then total deliveries would not have reached total contract amounts, because contracts were binding only in months of peak crop water demand.

Both districts had higher deliveries during the final period, 2070–2099, during wet-to-normal years, because sufficient water was available to satisfy the increased crop water demands. Surface water diversions to both districts were impaired in dry years due to water scarcity. However, TCCA experienced a more pronounced decline in delivery reliability, because its allocation priority was secondary to deliveries to settlement contractors.

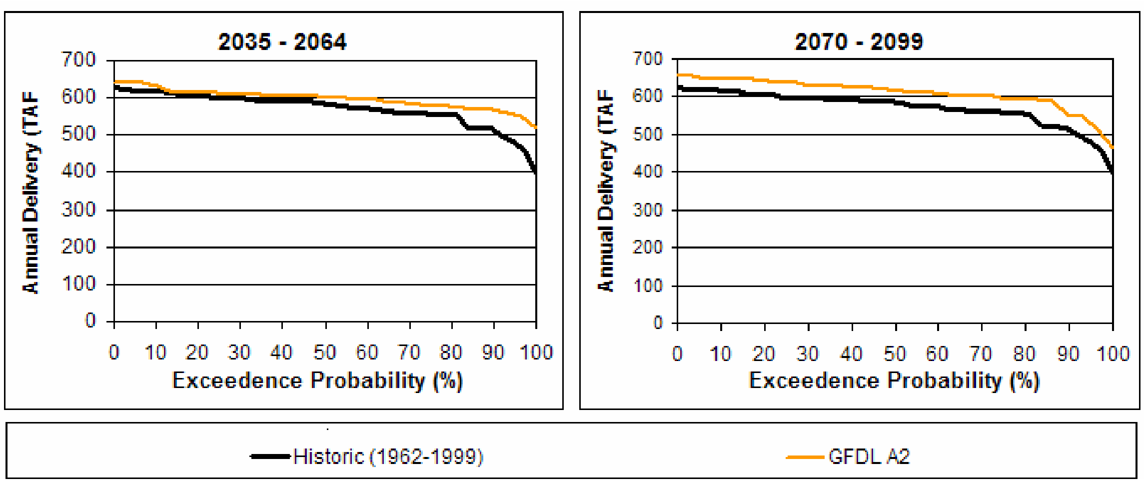



**Figure 6.20. Annual diversions—Glenn-Colusa Canal**

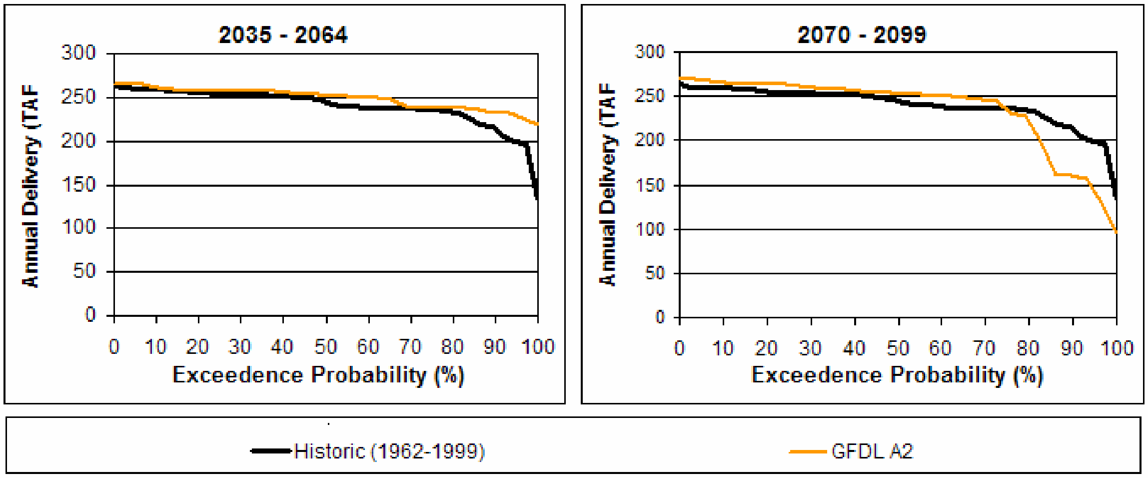



**Figure 6.21. Annual diversions—Tehama-Colusa Canal**

### 6.5.7. Groundwater pumping

Annual groundwater pumping for both GCID and TCCA are shown in Figures 6.22 and 6.23. Both districts showed the greatest groundwater pumping during the last period of analysis. Consistent with the previous set of graphs, GCID was able to satisfy its crop water demands for most years with surface water supplies and only relied on groundwater pumping in the driest years. TCCA, on the other hand, had a base level of groundwater pumping that was stable for most years, but increased sharply in dry years when river diversions were significantly reduced.

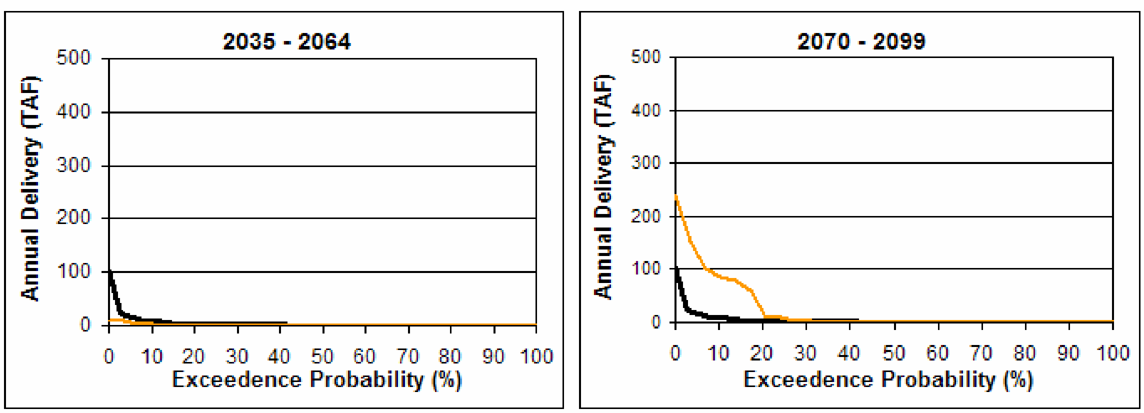



**Figure 6.22. Annual groundwater pumping—Glenn-Colusa Irrigation District**

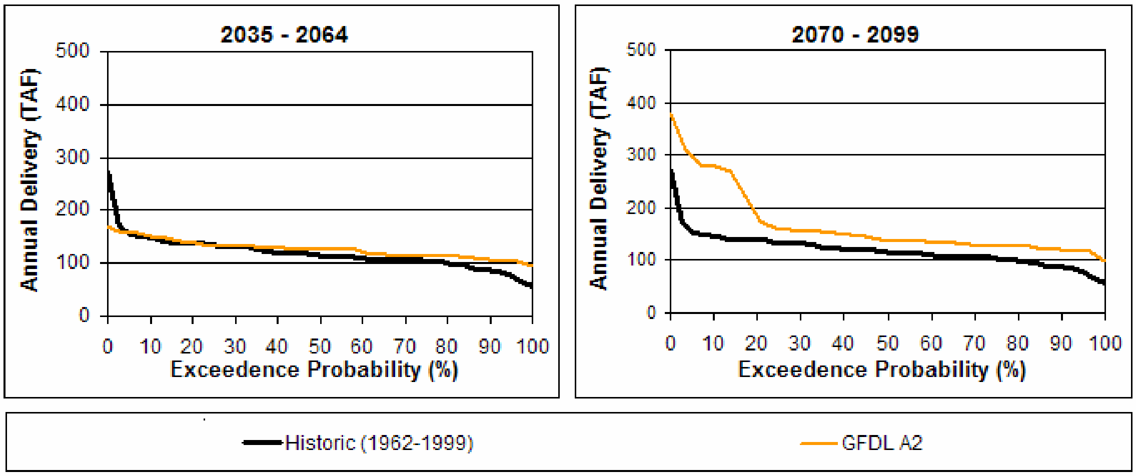



**Figure 6.23. Annual groundwater pumping—Tehama-Colusa Canal Authority**

## *6.6. Operations Analysis with Adaptation*

The previous section outlined the impacts of climate change on agriculture in the Sacramento Valley under the assumption that cropping patterns and irrigation technology remain unchanged over the duration of a 100-year simulation. Under certain scenarios there was increased water scarcity at the end of the century that resulted in sharp decreases in surface water deliveries and increases in groundwater pumping. In the case of the GFDL A2 scenario, this impact was reflected in significant simulated declines in water table elevations throughout the valley towards the end of the 21st century.

This section describes how adaptation strategies may mitigate the impacts of climate change. Improved irrigation efficiency and changes in cropping patterns in response to water supply conditions were implemented in the model as described in Appendix C. The first part of the current section shows how these changes affect water supply requirements for several regions of the previously aggregated Stone Corral HUC. This discussion is followed by an assessment of predicted climate change impacts on agriculture in the Sacramento Valley when adaptation is simulated.

To facilitate the presentation of results, attention will focus on the climate change scenario that showed the largest impact on water resources in the Sacramento Basin, GFDL A2. Simulations were focused on the years 2050 to 2100, because this was the driest and warmest period of the scenario.

### 6.6.1. Water supply requirements with adaptation

The following analysis presents results for three future alternatives: a simulation without adaptation, a simulation with increases in irrigation efficiency, and a simulation with improved irrigation efficiency and shifts in cropping patterns related to the simulated status of available water supplies. Where adaptations were in place, it was anticipated that the overall water requirements for irrigation would be reduced through improvements in irrigation efficiency and shifting of farmland to less water-intensive crops in times of reduced water supply. In investigating the impact of adaptation strategies, model results for three of the regions created out of the disaggregation of Stone Corral HUC were considered: TCCA South (A2), GCID (B), and Non-District Users North (F3).

For the purposes of this study, it was assumed that external regulatory pressures motivated irrigation districts to improve irrigation efficiency without regard to future climatic conditions. These improvements in irrigation efficiency were phased in gradually throughout the first 50 years of the 21st century and reached a maximum in 2050, after which efficiencies remained constant. Figures 6.24 through 6.26 show the effects of increased irrigation efficiency in terms of water supply requirements for the three regions mentioned above. Each graph shows the following:

- The 2050–2100 base supply requirement without changes in irrigation efficiency (Base, blue)
- An average of the same supply requirement covering the first and last 25 years in the period (BaseAveragebyperiod, green), which shows how supply requirements increase in the advent of the "mega-drought" occurring at the end of the 21st century
- The 2050–2100 supply requirement with changes in irrigation efficiency (Irrigation Efficiency, red)
- Its associated average for the first 25 and last 25 years in the time period (IrrEffAveragebyperiod, cyan)
- The average historic (1962–1998) supply requirement as a reference

The results show a decline in supply requirements as improvements in irrigation efficiency are implemented. However these changes are not consistent across the different regions. GCID, for example, experiences a relatively small decline in supply requirement when compared with Non-district Users North (F3) due primarily to differences in crop patterns. While almost 75% of the irrigated land in GCID is planted to rice, a crop with little potential for improved irrigation technology because it relies upon flooded fields, Non-district Users North has almost 50% of land in cereals and pasture, two crops with high potential for improvements in irrigation technology.

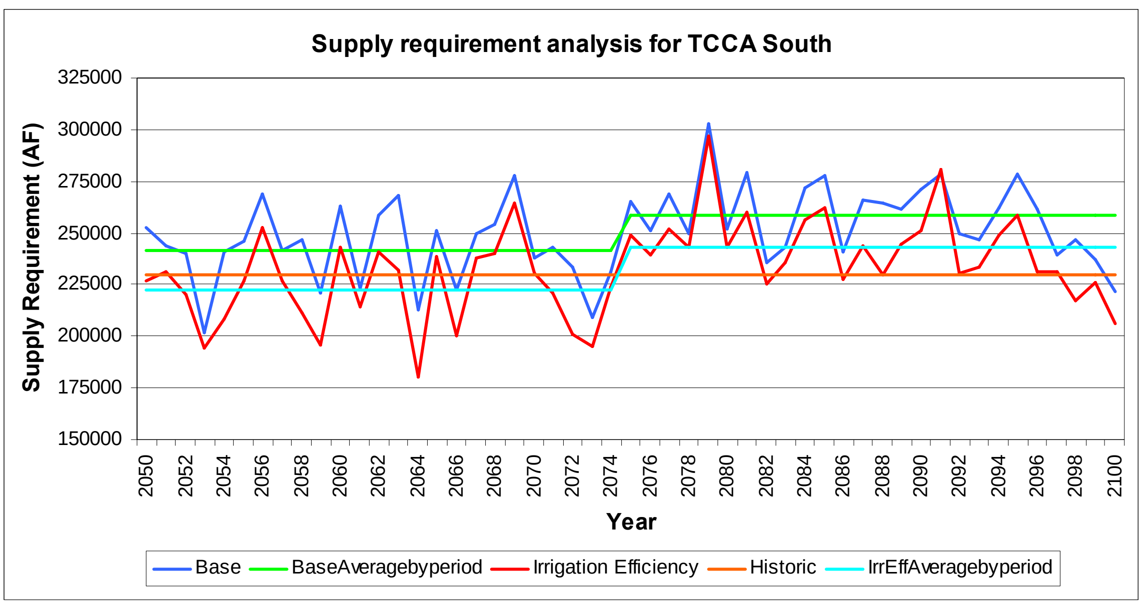



**Figure 6.24. Changes in supply requirement associated with improvements in irrigation technology—TCCA South**

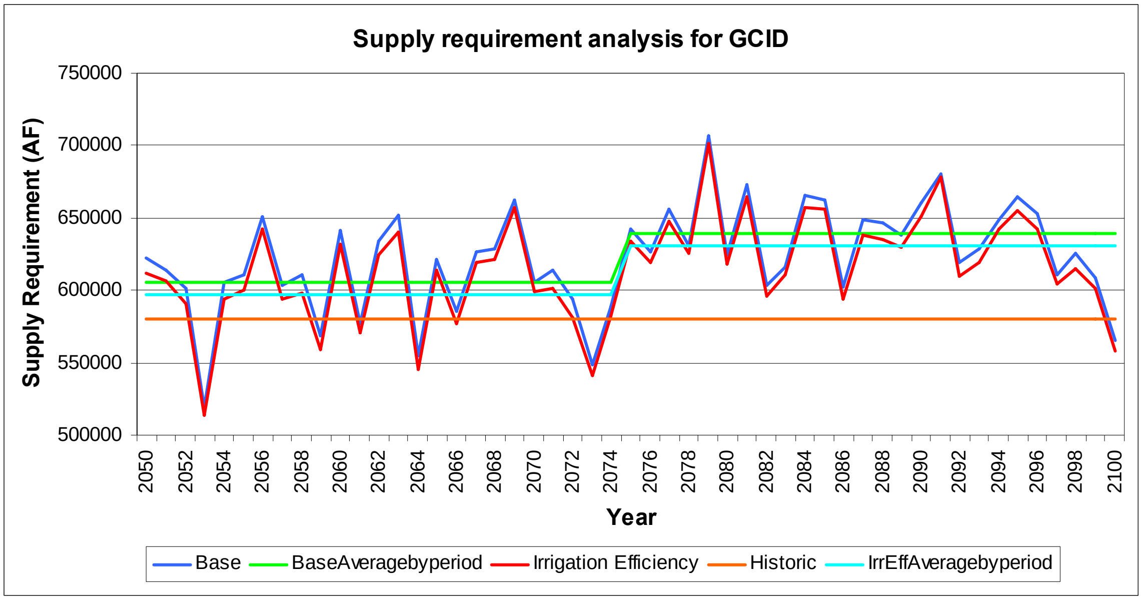



**Figure 6.25. Changes in supply requirement associated with improvements in irrigation technology—GCID**

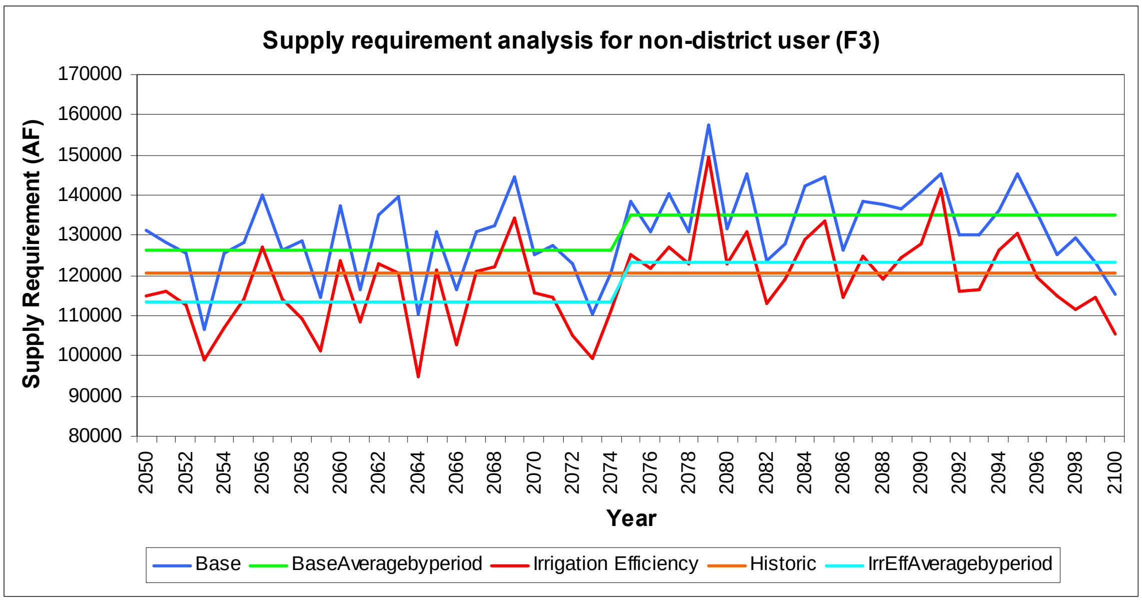



**Figure 6.26. Changes in supply requirement associated with improvements in irrigation technology—Non-district Users North**

In addition to improvements in irrigation technology, another potential adaptation to climate change would involve adjusting cropping patterns as a function of the evolving status of available water supplies. This adaptation reflects the fact that at the beginning of the growing season, farmers decide which crops to plant based on anticipated surface water supplies and groundwater levels. How farmers respond to these changing conditions is a function of a number of factors, which change depending on the reliability of various available water sources. For example, non-district areas base their cropping decisions solely on the depth to groundwater, because they lack guaranteed surface water supplies. As a CVP settlement contractor, changes cropping decisions GCID change only when inflows to Lake Shasta reach a critical level (i.e., less than 3.4 million acre-feet), at which time its allocations are reduced by 25%. The TCCA South region, composed of CVP agricultural services contractors, suffers cuts to its allocations based on both the predicted inflows into Shasta and also the current reservoir storage levels.

The implication is that indexes of available supply must be calculated for each year in order to permit the various types of water user to make appropriate cropping decisions. Based on the value of these supply indexes, a multinomial logit model of cropping shares, estimated from historical data, is employed to determine the distribution of crops and fallow land in that year for the given user. These logit equations and the details of their estimation are described in detail in Appendix C, along with the formulas used to define the evolving water supply indices. The structure and coefficients of these various expressions have been programmed into WEAP so that at the start of every cropping season over the course of the 21st century, an adaptive simulated cropping pattern can be defined.

The implications of these shifts in cropping pattern are shown in Figure 6.27. Crop shares for the three regions are analyzed at two different points in time: 2050 and 2092 for the GFDL A2 climate scenario.[1] The 2092 period coincided with the end-of-century mega-drought included in that scenario. Regions such as TCCA South, with weak entitlements and variable allocations, shifted their crop patterns under a very dry condition by increasing land fallowing and decreasing the share of irrigated crops. Users with more reliable water supplies, such as GCID, maintained more constant crop shares. Finally, users relying solely on groundwater pumping showed very little change in crop patterns. This was due to the low sensitivity to the depth to groundwater of overall crop decisions that emerged from the econometric analysis (see Appendix C).

When coupled, the effect of improved irrigation efficiency and a dynamic crop pattern based on dynamic simulated water supply and groundwater conditions is a decline in water supply requirements during the period of analysis. This can be seen by examining Figures 6.28 through 6.30 that include a dynamic crop share decision. The effect of changing cropping patterns is reflected in the difference between these two sets of graphs. These differences are summarized in Table 6.8.

**Table 6.8. Summary Comparisons between Figures 6.24-27 and 6.28–30**

| | | User | | |
|---|---|---|---|---|
| **Scenario** | **Period** | **TCCA South** | **GCID** | **Non District North** |
| Hist | 1962-1998 | 230 | 580 | 121 |
| Base (no adaptation) | 2050-2074 | 242 | 606 | 126 |
| | 2075-2099 | 259 | 639 | 135 |
| Irrigation Efficiency | 2050-2074 | 222 | 597 | 113 |
| | 2075-2099 | 243 | 631 | 123 |
| Irrigation Efficiency and Dynamic Crop | 2050-2074 | 224 | 587 | 114 |
| | 2075-2099 | 235 | 616 | 124 |

1. The implications of the changes in water supply and cropping pattern for farm costs, revenues, and profits in the Sacramento Valley are evaluated separately from WEAP in a post-processing module and will be reported in a separate memorandum.

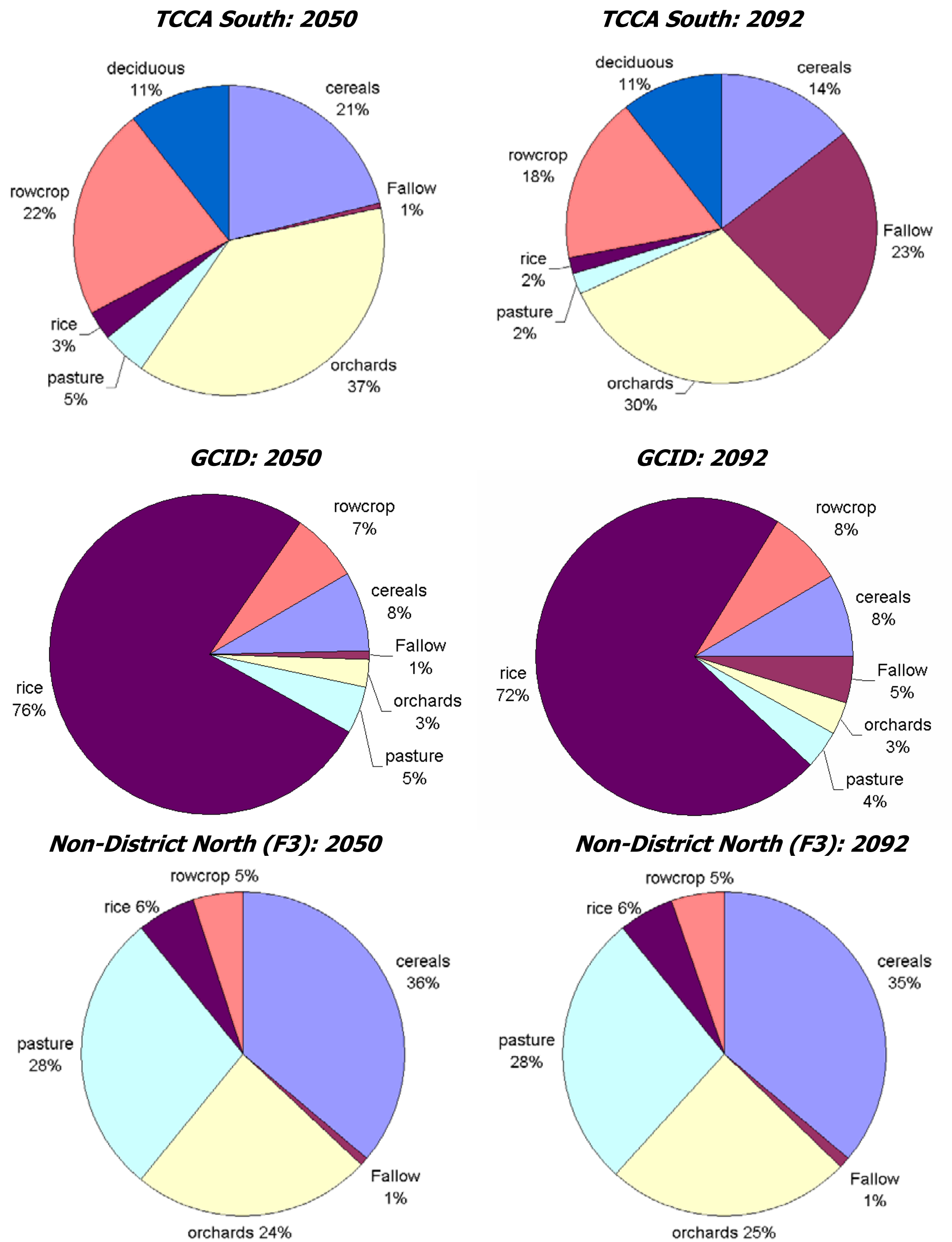



**Figure 6.27. Simulated changes in cropping patterns for three regions of the Sacramento Valley between 2050 and 2092 under the GFDL A2 climate scenario**

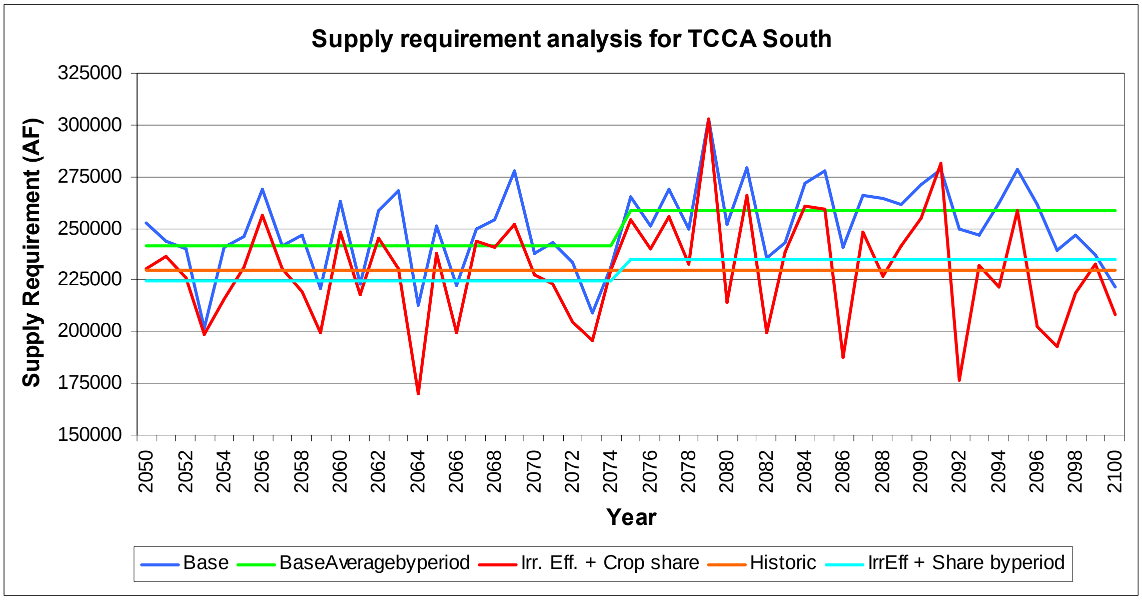



**Figure 6.28. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—TCCA South**

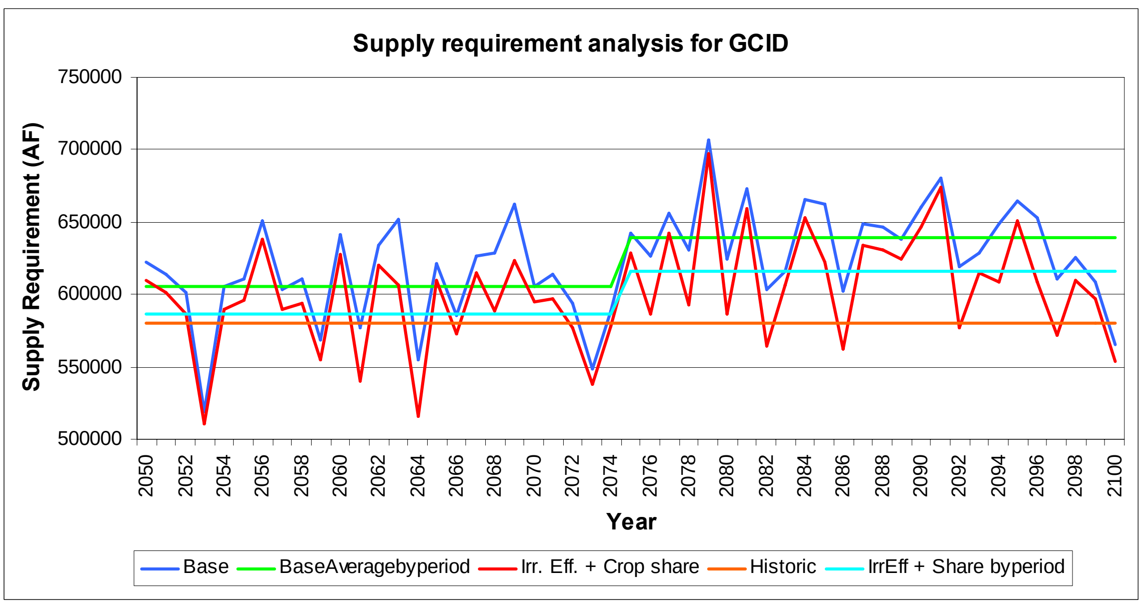



**Figure 6.29. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—GCID**

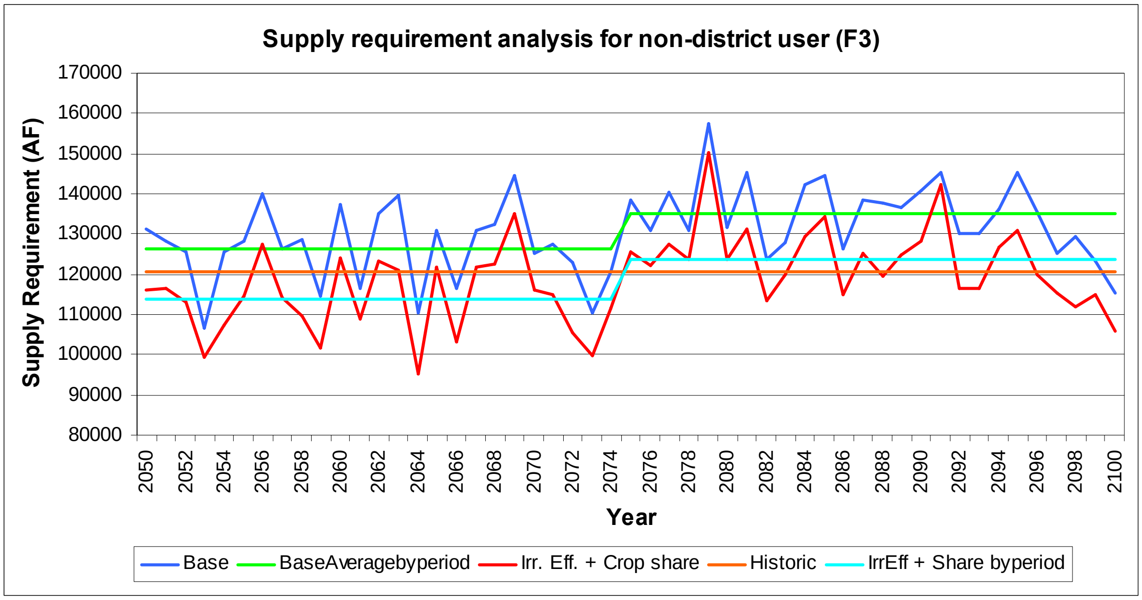



**Figure 6.30. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—Non-District Users North**

### 6.6.2. Water supply and delivery

The previous section showed that adaptation strategies have varying impacts at the irrigation district level depending upon water rights and the type of crops grown within districts. In general, improvements in irrigation efficiency were most effective in reducing crop water demands in districts that did not plant a large portion of their land in rice, which was not a targeted crop for irrigation technology advancement due to its need for ponded water over extended periods of the growing season. Fallowing agricultural land in dry years also achieved substantial water savings, but had the biggest impact in districts that were most susceptible to reduced surface water deliveries (i.e., CVP agricultural contractors). The combined effect of both adaptation strategies showed that in the driest years some districts could reduce irrigation requirements by 20 to 30 percent.

This section focuses on the cumulative effect of implementing adaptation strategies more broadly throughout the Sacramento Valley. The analysis presents WEAP simulations for each of the climate change scenarios with both adaptation strategies implemented across all agricultural areas of the Sacramento Valley. These simulations suggested that increasing temperatures and declining precipitation result in patterns of agricultural water supply and delivery. Adaptation strategies reduced the absolute effect, but the relative impacts between scenarios and with time remained the same. As such, graphics of the with adaptation simulations corresponding to Figures 6.24 through 6.30 would look very similar to those associated with the "without adaptation" simulations, with only the values on the y-axes changing significantly. For this reason, Table 6.9 compares the impacts of simulations run with and without adaptation for only the driest and warmest future period (2070 to 2099).

**Table 6.9. Water supply and delivery (2070–2099): with and without adaptation**

| | GFDL A2 | | | GFDL B1 | | | PCM A2 | | | PCM B1 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Without adaptation | With adaptation | Difference | Without adaptation | With adaptation | Difference | Without adaptation | With adaptation | Difference | Without adaptation | With adaptation | Difference |
| Average Annual Agricultural Water Requirement (TAF) | 5,658 | 4,856 | 802 (-14%) | 5,348 | 4,612 | 735 (-14%) | 5,188 | 4,502 | 687 (-13%) | 5,107 | 4,339 | 768 (-15%) |
| Average Annual Agricultural Deliveries (TAF) | 3,672 | 3,279 | 393 (-11%) | 3,719 | 3,301 | 418 (-11%) | 3,624 | 3,230 | 393 (-11%) | 3,533 | 3,124 | 409 (-12%) |
| Average Annual Groundwater Pumping to Agriculture (TAF) | 1,831 | 1,550 | 281 (-15%) | 1,545 | 1,328 | 217 (-14%) | 1,473 | 1,262 | 211 (-14%) | 1,477 | 1,230 | 247 (-17%) |
| Average Carryover Storage in Lake Shasta (TAF) | 1,728 | 1,734 | -6 (0%) | 2,324 | 2,331 | -7 (0%) | 2,621 | 2,646 | -25 (1%) | 2,925 | 2,953 | -28 (1%) |
| Average Carryover Storage in Lake Oroville (TAF) | 1,641 | 1,647 | -5 (0%) | 2,032 | 2,044 | -12 (1%) | 2,275 | 2,296 | -21 (1%) | 2,475 | 2,503 | -28 (1%) |
| Maximum Groundwater Drawdown in Stone-Corral (ft) | 267 | 225 | 42 (-16%) | 98 | 99 | -1 (1%) | 100 | 100 | 1 (-1%) | 132 | 124 | 8 (-6%) |
| Average Annual Urban Deliveries (TAF) | 381 | 499 | -118 (31%) | 393 | 507 | -115 (29%) | 391 | 506 | -115 (29%) | 389 | 505 | -115 (30%) |
| Average Annual Delta Exports (TAF) | 5,072 | 5,179 | -107 (2%) | 5,610 | 5,622 | -13 (0%) | 5,533 | 5,564 | -31 (1%) | 5,469 | 5,495 | -26 (0%) |

Improved irrigation efficiency and increased land fallowing in dry years resulted in substantial reductions in agricultural water supply requirements for all climate change scenarios. This, in turn, reduced the average annual surface water deliveries and groundwater pumping to agriculture. For the GFDL A2 scenario, which included a prolonged drought from 2085 through 2095, the reduced reliance on groundwater caused a less pronounced decline in groundwater levels. However, even with adaptation in place, total water table drawdown for this scenario was still much greater than that simulated in each of the other scenarios. For all scenarios, the reductions in crop water demands meant that irrigation districts were able to satisfy a higher proportion of their irrigation requirements.

Despite the large decrease in agricultural demands, CVP and SWP reservoirs showed little change in their operation as a result of implementing adaptation strategies. Carryover storage levels in both Lake Shasta and Lake Oroville were only 0 to 1 percent higher than they were when no adaptation was in place. This suggests that other water users in the basin captured the water savings realized as a consequence of reducing consumptive demands in agricultural areas. Table 6.8 shows that some of the additional water was shifted to Sacramento Valley urban areas and delta exporters. The remaining water was used to satisfy various environmental requirements.

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

## 7. Climate Change Impacts On Chinook Salmon In The Sacramento Valley

The Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous fish that spawns in the upper reaches of the mainstem rivers and tributaries of California's Central Valley. After spending a few months in the natal rivers or downriver nursery areas, the juveniles migrate to the Pacific Ocean where, after a stay of 2 or more years, they reach maturity (U.S. DOI, 1996). The adult fish then migrate back to their natal rivers and streams to spawn. Shortly after spawning, the adult fish die (Meehan and Bjorn, 1991). Historically, there have been four separate seasonal spawning runs of Chinook in the Central Valley (NOAA, 2001): fall and late-fall spawning runs, a winter spawning run, and a spring spawning run. The total (i.e., all seasons) peak spawning of Chinook in the Central Valley at the beginning of the 20th century was approximately 800,000–1 million adult fish (SFEP, 1992; NOAA, 2001). Spring run fish were the most abundant, followed by the fall and late-fall runs, then the winter run.

Beginning in the late 19th Century, Chinook salmon have come under increasing anthropogenic stress, resulting in major population reductions. The greatest contributor to this has been the construction of dams blocking access to spawning habitat. Suitable spawning habitat has been reduced from historic levels of about 6,000 river-miles in the Central Valley to about 300 river-miles today, concentrated in the Sacramento River's mainstem. Estimated losses of spawning and nursery habitats after the construction of the Shasta and Keswick dams alone were 50 percent (DWR 1988), and subsequent activities such as diversions and bank-protection programs have led to additional habitat losses.

The different runs have not been affected equally. Traditionally, the winter and spring runs spawned at the highest elevations; now, because dams have blocked access to much of their upper elevation spawning habitat, these two runs are most affected. Since the late 1960's, the winter run has declined from over 100,000 fish to a few thousand today (U.S. DOI, 1996). This has resulted in the winter run being listed as Endangered under both the federal and California Endangered Species Acts. The spring-run Chinook in the San Joaquin River was eliminated entirely by the construction of the Friant Dam in 1949 (SFEP, 1992). The surviving part of this run in the Sacramento River has been listed as Threatened under both the State and federal Endangered Species Acts. The least affected populations have been the fall and late-fall runs. This is because many of these fish spawn below the elevations at which most of the dams were installed. Even so, blocked access to spawning habitat has reduced these runs from a collective 500,000 fish in the 1950s to about 1-200,000 today.

Current populations of Chinook that migrate to and spawn in the Central Valley are, in part, artificially maintained by two anthropogenic activities: releases of hatchery-reared juvenile fish and, paradoxically, water management using dams. On average, 30 million fry and fingerlings per year are released from hatcheries into the rivers of the Central Valley, and approximately 30%-50% of the adults returning to spawn in the watershed are hatchery-reared (SFEP, 1992). Meanwhile, releases of cool water from dams are crucial for maintaining suitable thermal conditions for the freshwater stages of the life-cycle, most notably releases from the Shasta Dam in the Sacramento River of the northern Central Valley.

Since they are coldwater fish that avoid areas where water temperatures exceed their physiological requirements (reviewed in DWR, 1988, and McCullough, 1999), Chinook salmon may be vulnerable to climate change. It is possible that rising water temperatures in their natal rivers could adversely affect the ability of salmon to find suiTable Creeding habitats, especially since that habitat has already been reduced by dam construction. However, dams allow scheduled releases of cold water stored in reservoirs, such that the frequency and timing of these releases may have implications for salmon survival during spawning. In this paper, we assess the potential effects of future climate change and water storage on critical thermal aspects of Chinook freshwater habitat quality in the Sacramento Valley (SV) portion of California's Central Valley, and likely implications for salmon population viability.

## *7.1.* Salmon life histories and thermal requirements

While the four Chinook seasonal runs have different migration phenologies, each has evolved to minimize exposure to warmer water temperatures. Prolonged exposures of Chinook salmon to water temperatures above about 20°C can result in a number of adverse effects, depending on the life stage. Each life stage has its own optimal temperature range and its own response to temperature exposures outside that range.

*Exposure of Immigrating Adults*. In laboratory studies, increased mortality and adverse physiological effects (reduced egg and hatchling viability) occurred when adult Chinook were exposed to water temperatures that exceed about 19°C for more than a few hours (Berman, 1990; reviewed in McCullough, 1999). Hallock *et al*. (1970) report that water temperatures above 20°C can also constitute a thermal barrier to adult immigration. Immigration stopped in the San Joaquin River when water temperature exceeded 21°C, but resumed when the water temperature fell to 18.3°C (DWR, 1988).

*Exposure of Spawning Adults*. Spawning Chinook require cooler water temperatures than those that can be tolerated during the adult immigration. In hatchery studies, exposing spawning females to water temperatures that exceeded 14°C resulted in increased egg mortality (Leitritz and Lewis, 1976).

*Exposure of Eggs and hatchlings.* A number of studies have shown that the optimum upper temperature for egg and hatchling survival is 14°C or less (reviewed in McCullough, 1999). In the American River of the SV, hatchling mortality increased in water temperatures exceeding 15.5°C (Hinze *et al*., 1956).

*Exposure of Juveniles*. In laboratory studies, increased mortality of juvenile Chinook generally occurred when water temperatures exceeded 20°C (reviewed in McCullough, 1999). However, sub-lethal effects may occur at lower temperatures: reductions in growth rates were found when juvenile fish were held in water temperatures exceeding about 16°C (Bisson and Davis, 1976; Marine and Cech, 1998). Also, temperatures in excess of about 12-13°C may inhibit the development of migratory response and saltwater adaptation in juvenile fish (DWR, 1988).

Based on the above information, we assume for this study that: suitable adult immigration conditions are limited to areas and seasons where water temperatures are generally lower than 19°C; suitable spawning and rearing conditions require water temperatures of 14°C or less; and juvenile migration to the sea will be disrupted in areas or seasons where water temperatures exceed 18°C (the midpoint between the increased mortality and sub-lethal thresholds identified above). These requirements and limitations explain the timing of Chinook salmon life history events, which result in the different stages being at particular stream locations during particular times of the year.

Figure 7.1 summarizes the timing of immigration, reproduction, and emigration of the four runs of Chinook salmon in the SV. The result of these reproductive strategies is that adults and juveniles of all runs generally are not present in the lower river reaches during the warmest months of July and August. They migrate in and out of the system and through the lower rivers before or after the warmest months, and spawn and rear their young during colder months in those portions of the cooler upper reaches that are still accessible. The evolution of these migration strategies has enabled the fish to avoid waters that exceed their physiological temperature tolerances.

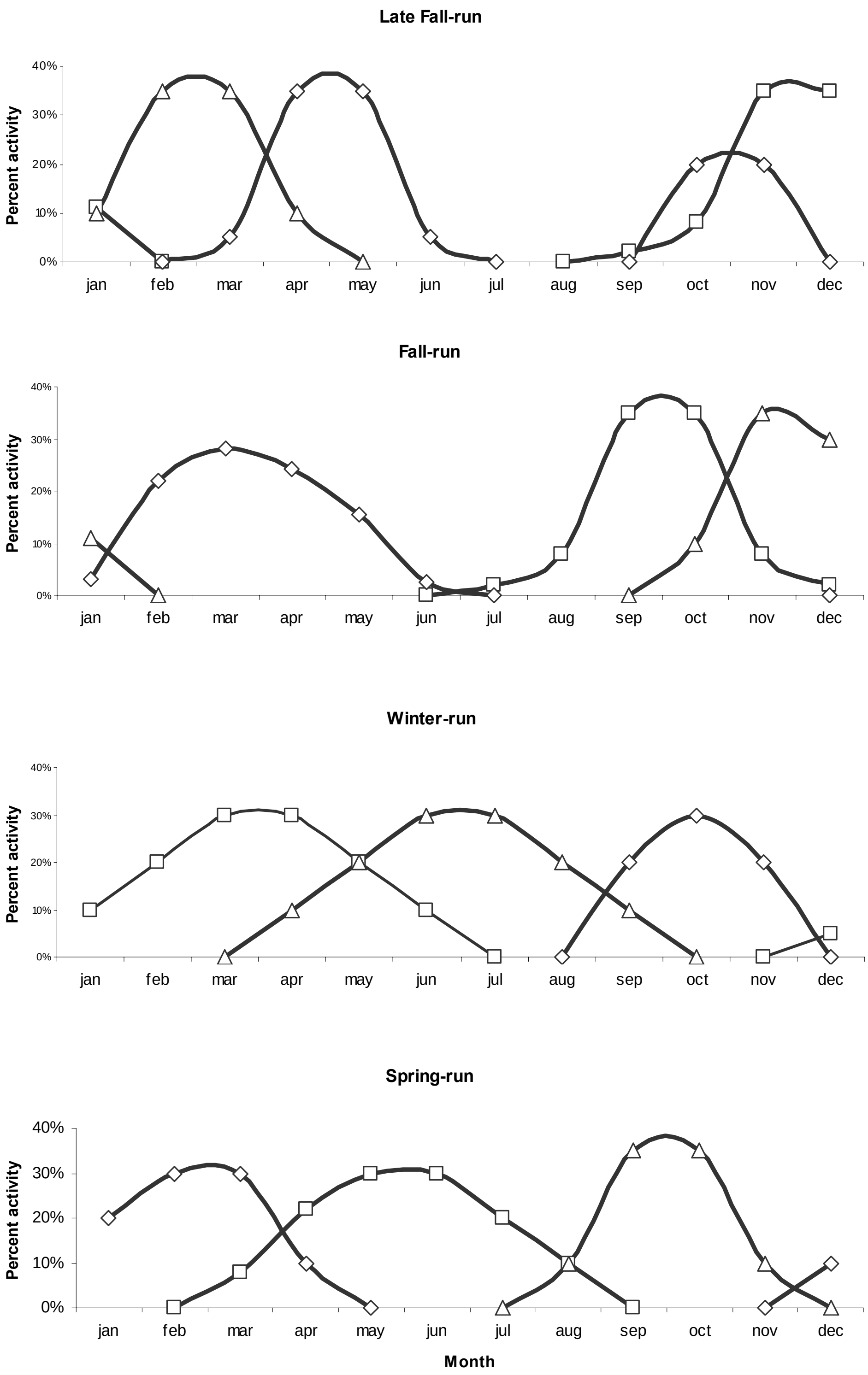



**Figure 7.1. Phenologies of reproductive events in freshwater phase of Chinook salmon life-cycle in the SV watershed.□ = adult immigration; Δ = spawning and hatching; ◇ = juvenile emigration. Compiled from data in NOAA (2001), DWR (1988), and U.S. DOI (1996).**

## 7.2. *Shasta Dam water storage and its effects on water temperature*

To assess the implications of future temperature changes for Chinook salmon, we must first examine current water storage practices at Shasta Dam, and their effects on downriver water temperatures. Immediately following the completion of Shasta Dam, the primary spawning habitat became limited to the reach between Keswick Dam (just above Redding) and Balls Ferry (about 40 km above Red Bluff), while subsequent water diversions limited spawning activity to even further downriver toward Hamilton City (Figure 7.2).

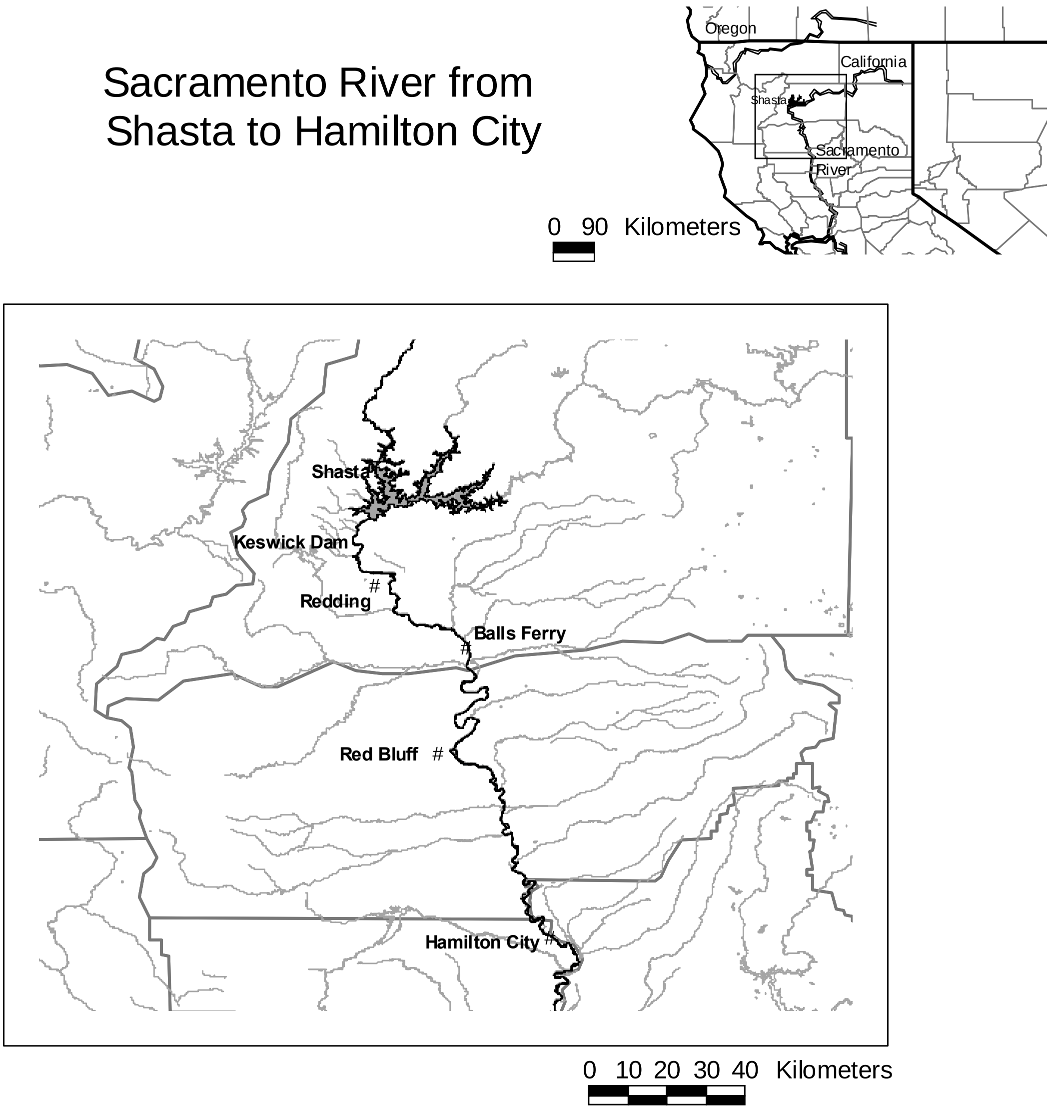



**Figure 7.2. Map of the Sacramento Watershed and important geographic locations, including counties (light gray) and state boundaries (dark line). The hatch symbols show the general locations where water temperatures are reported in the paper.**

While dams block migration pathways, they also store and release cool water that can maintain suitable water temperature and flow conditions for salmon reproduction and rearing below the dam (SFEP, 1992). The release of water from the large, cold water pools stored behind the dam provides high volumes of cold water that reduce downriver summer water temperatures. Limited river water temperature data collected below Shasta Dam following impoundment suggests that the average water temperatures are cooler by about 5°C in the spring (May and June) and cooler by 7-10°C in the summer (July and August) relative to pre-dam temperatures (DWR, 1988). Maximum water temperatures near Redding and Red Bluff before the dams were built were sometimes more than

20°C in late summer, while maximum water temperatures are now around 13°C to 14°C (DWR 1988). More moderate differences of around 2°C cooler occur in the early fall (September and October), while water temperatures in November are slightly warmer than pre-dam temperatures; this is due to warming that has occurred over the summer in the Shasta reservoir..

The availability of cold water from Shasta is not guaranteed, for as summer progresses, releases from Shasta tend to be warmer due to a deepening of the thermocline and drawdown of the reservoir. Likewise, a greater proportion of annual precipitation falling in the form of rain rather than snow tends to elevate the reservoir's water temperatures. In an attempt to counter these effects, the reservoir has been fitted with a Temperature Control Device (TCD) that triggers the release of water from select water column strata at specific temperatures. To conserve the cold water in Shasta Lake, withdrawals are made from the highest elevation possible while meeting the downstream water temperature targets established by a Sacramento River Temperature Task Group. During the spring, when the temperature of the surface water is coolest, operators release water from the highest level of the temperature control device. During the summer and fall, when surface water has warmed, water is withdrawn through the device from mid- and low-level intakes. The targeted release temperature is about 11.5ºC from May to October, with the goal of keeping temperatures above Red Bluff around 13.3ºC during this period.

Having examined some of the factors affecting water temperatures in the SV and Chinook salmon survival, we can now design an approach for reaching the objectives of this paper: to identify which salmon runs are most at risk under changing climatic conditions, and at what life stages, and to determine whether reservoir management may mitigate or exacerbate Chinook salmon vulnerability.

## *7.3. CLIMATE CHANGE IMPACTS ON SV HYDROLOGY*

Our focus in this study is on the Sacramento River, from the Shasta Reservoir to a point approximately 130 km above the City of Sacramento at Hamilton City (Figure 7.2). This includes both the main spawning and rearing habitats and the lower river areas through which adults and juveniles must migrate to reach their spawning areas and the sea. Downriver of Sacramento, the river bifurcates into the Delta, is tidally influenced, and is increasingly brackish. Our current hydrological model cannot adequately capture the complex flow paths below Sacramento that significantly alter the river's temperature regime in this region, so we focus on the spawning, rearing, and migration habitats that comprise the freshwater portion of the watershed.

### 7.3.1. Modeling Sacramento River flow and water temperature under climate change

We investigated the potential impacts of climate change and water storage on Chinook salmon in the Sacramento portion of the SV using a quantitative model of seasonal river flow and temperature regime for the river, from the Shasta Reservoir down to Hamilton City (Figure 7.2). The Keswick reservoir and its influence on streamflow and water temperature were not explicitly modeled. The model was the Water Evaluation and Planning Decision Support System Version 21 (WEAP21, Yates *et al*., 2005a; Yates *et al*., 2005b; Yates *et al*., 2005c), which included coupled water management, physical hydrology, and river temperature models that could simultaneously address both natural and water management processes (Hsu and Cheng, 2002; Westphal, *et al*., 2003).

In the process of undertaking different aspects of this research over a four year period, we developed different approaches to incorporate climate information into the WEAP21 model. In Section 6 we describe the use of climate scenarios based on the work of Mauer et al. (2002) who used the outputs from two general circulation models (GCM) to estimate future climate conditions. The models included the Parallel Climate Model (PCM) developed at the National Center for Atmospheric Research and the CM2 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). Outputs from these models were downscaled by applying the methodology developed by Maurer et al. (2002) to create a 1/8th degree gridded data set of daily climate variables.

In the effort to investigate the potential impacts of climate change on Chinook Salmon, we developed scenarios based on the work of Tebaldi et al., (2004), who regionalized and derived density distributions of future seasonal temperature and precipitation change based on the output from several Atmosphere-Ocean General Circulation Models (AOGCM)s. Their analysis resulted in projections that generally showed regionally wetter winters, with total precipitation increases approximating 15%. Mean changes in summer precipitation were close to 0 degrees C. Winter temperatures showed increases in the range of 4-6 degrees C, while summer temperatures show only slight warming. These data facilitated the development of two high-resolution climate scenarios of daily climate data at 55 locations throughout the watershed based on a K-nearest neighbor (K-nn) resampling scheme (Yates et al., 2003; See Appendix D). Table 7.1 summarizes these scenarios, where Precipitation is the seasonal average percent change and Temperature is the average incremental change, relative to the historic period 1961-2000. Figure 3 summarizes the monthly average values of these scenarios for the entire Sacramento watershed based on the data from all 55 stations. These are stylized scenarios guided by the results of the Bayesian model and include a warmer and drier scenario (abbreviated WmDry) that is characterized by drier winters, drier late springs, warmer summers, and generally warmer conditions overall. The warmer wetter scenario assumes warm, wet winters (WtWnt), followed by drier spring conditions and much warmer summers. These two scenarios bracket the distributions presented by Tebaldi et al., (2004).

**Table 7.1. Statistical characteristics of the two downscaled scenarios.**

| ***Scenario*** | **Quantitative Summary (relative to historic)** | |
|---|---|---|
| | ***Precipitation*** | ***Temperature (C)*** |
| **(1)** Warmer and Drier (WmDry) | WES = -6%; LSES = -45%<br>SLF = -34%; ANN = -11% | WES = +3.2; LSES = +4.7<br>SLF = +4.5; ANN = +3.9 |
| **(2)** Wetter Winters, Drier Springs, and Warmer Summers (WtWnt) | WES = 21 %; LSES = -46 %<br>SLF = -2 %; ANN = +15% | WES = +4.2; LSES = +6.7<br>SLF = +6.0; ANN = +5.2 |

Winter and Early Spring (WES) Dec, Jan, Feb, Mar, Apr; Late Spring and Early Summer (LSES) June, July; Summer and Late Fall (SLF) Sep, Oct, Nov; Annual (ANN)

Temperature is the average incremental change, relative to the historic period 1961-2000. Figure 7.3 summarizes the monthly average values of these scenarios for the entire Sacramento watershed based on the data from all 55 stations. These are stylized scenarios guided by the results of the Bayesian model and include a warmer and drier scenario (abbreviated *WmDry*) that is characterized by drier winters, drier late springs, warmer summers, and generally warmer conditions overall. The warmer wetter scenario assumes warm, wet winters (*WtWnt*), followed by drier spring conditions and much warmer summers. These two scenarios bracket the distributions presented by Tebaldi *et al.*, (2004).

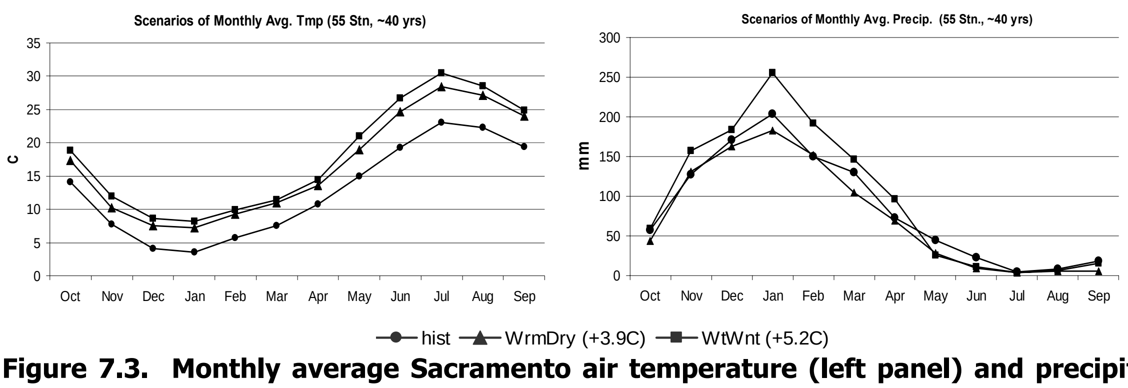



**Figure 7.3. Monthly average Sacramento air temperature (left panel) and precipitation (right panel) from historic data (hist) and the two scenarios. The values in parentheses are the annual average temperature changes for each scenario.**

The WEAP21 model was used to investigate the potential impacts of climate change and water storage on Chinook salmon in the SV by simulating the river's monthly flow and temperature from the Shasta Reservoir down to Hamilton City (Figure 7.2). The WEAP21 model of the SV includes coupled water management, physical hydrology, and river temperature models that simultaneously simulates both natural and water management processes. River water temperature is based on air temperature and flow characteristics, which are translated into water temperature changes within WEAP's surface water quality module (see Yates, *et al*., 2005)

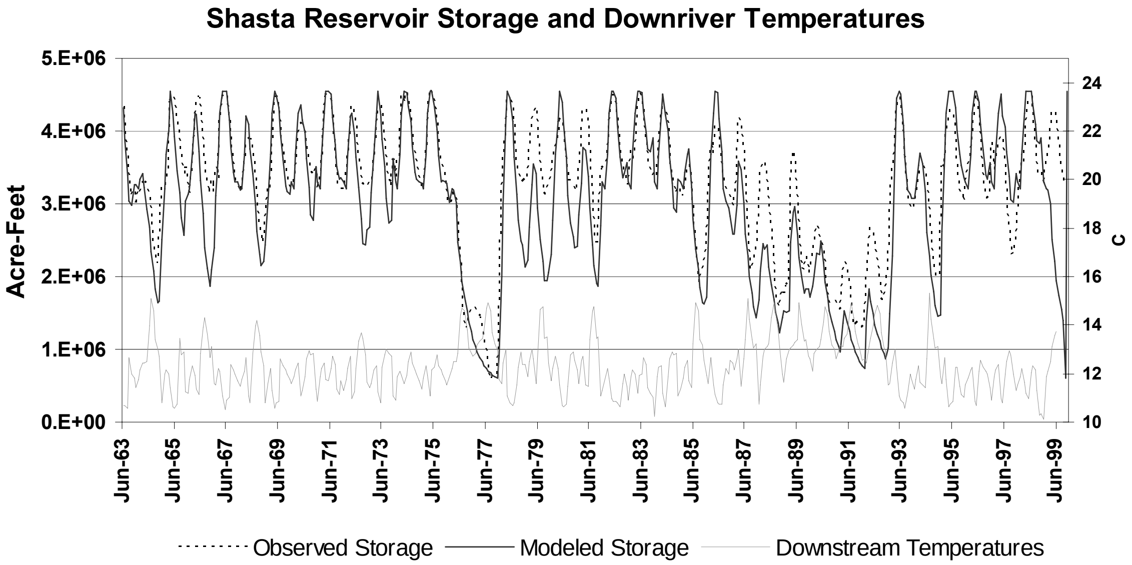



**Figure 7.4. Observed and modeled Shasta Reservoir storage for the historic period 1963 to 1999 (left scale) and the modeled temperatures just downstream of Shasta (right scale).**

For this study, the relevant model outputs included predictions of flow and temperature at specific locations and under assumed climate and water storage scenarios. The model was calibrated for the period 1961 to 1999 and consisted of historical reproduction of observed river flow and temperature regimes, water demands, irrigation requirements, reservoir storages and operations. Our model evaluation compared observational data against projections for Shasta storage volumes, Sacramento mainstream streamflows, and projections of river temperatures along selected reaches of the Sacramento mainstem (Figures 7.4 and 7.5).

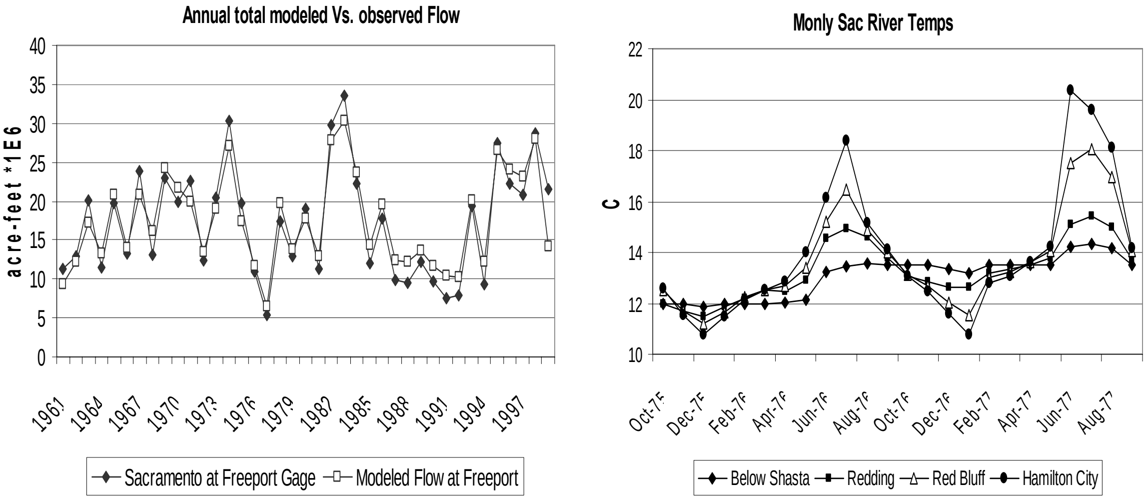



**Figure 7.5. Time series of historic and simulated river flows and simulated river temperatures along select reaches.**

Although a TCD helps control water temperatures released from the Shasta reservoir, as the reservoir's storage drops cold water availability is reduced and it becomes more difficult to release water with temperatures below 12$^o$C. Water temperatures in Shasta Reservoir were not explicitly modeled; rather, a monthly temperature release profile was prescribed based on the reservoir's storage state and estimates of water temperature near Keswick (DWR 1988). If the storage volume in the reservoir fell below 1 million acre-feet (a-f) in the summer, then the release temperature was prescribed at 15$^o$C in July, August and September. Subsequent Shasta release water temperatures according to the storage volumes were: 14$^o$C for volumes between 1 and 2 million a-f; 13$^o$C between 2 and 3 million a-f; ; 11$^o$C between 3 and 4 million a-f; and 10$^o$C for volumes greater than 4 million a-f.. Figure 7.5 illustrates the effects of this prescription, where estimates of the river's temperatures just downstream of Shasta were above 13$^o$C when reservoir storage volumes dropped below 2 million acre-feet. Note also in Figure 7.4, that the simulated Shasta Reservoir storages were in close agreement with those observed.

Recent observations of Sacramento water temperatures suggest that during normal hydrologic years, temperatures in the late summer have been about 13$^o$C downriver of the Shasta Dam, warming to about 15$^o$C at Red Bluff, and above 16$^o$C near Hamilton City (see Figure 7.2 for locations). In the lower reaches of the Sacramento River, where the flow slows as the river transitions into the heavily-levied Delta area, the water warms considerably in the summer, with Sacramento water temperatures climbing to nearly 25$^o$C below the City of Sacramento. Sacramento River water temperature data for severe drought years, such as 1976-1977, show that during the late summer/early fall of 1977, water temperatures ranged from around 18$^o$C to nearly 20$^o$C between Redding and Red Bluff (DWR 1998).

The left panel of Figure 7.5 shows that the model adequately reproduced the annual flow on the Sacramento and, importantly, the low flow conditions of 1977 above the confluence of the San Joaquin River. The right panel of Figure 7.5 shows the temperature regime from Shasta Dam down to around Hamilton City, for two water years (1975-1976; and 1976-1977) and shows the model's estimate of river temperature. The model captured the particularly warm temperatures during 1977 which neared 20$^o$C in these reaches, consistent with observations.

### 7.3.2. Historic and projected dam conditions

Because the flow of the Sacramento River is so heavily regulated, it is informative to consider what the water temperature regime would be under historic and climate change assumptions if the dams and diversions did not exist. To evaluate this, the WEAP's Sacramento River model schema was modified by removing all dams/reservoirs and all irrigation demands on the system. In essence, this returns the watershed to its *quasi* natural state, making it possible to evaluate the relative role of dams and irrigation on the river's hydrologic and temperature regimes. Watershed simulations without dams and irrigation should show how storages and diversions change the river's flow and temperature near and below Shasta Dam.

Figures 7.6 and 7.7 show modeled historic and future monthly mean water temperatures near Redding and Hamilton City, respectively (see Figure 7.2). The solid symbols in Figures 7.6 and 7.7 represent the model simulation of actual historic conditions, with water infrastructure (dams and reservoirs) in place and storage and diversions made in support of irrigated agriculture. The open symbols represent the scenarios where dams have been hypothetically removed and there is no irrigation taking place (e.g. a surrogate for "natural" watershed conditions).

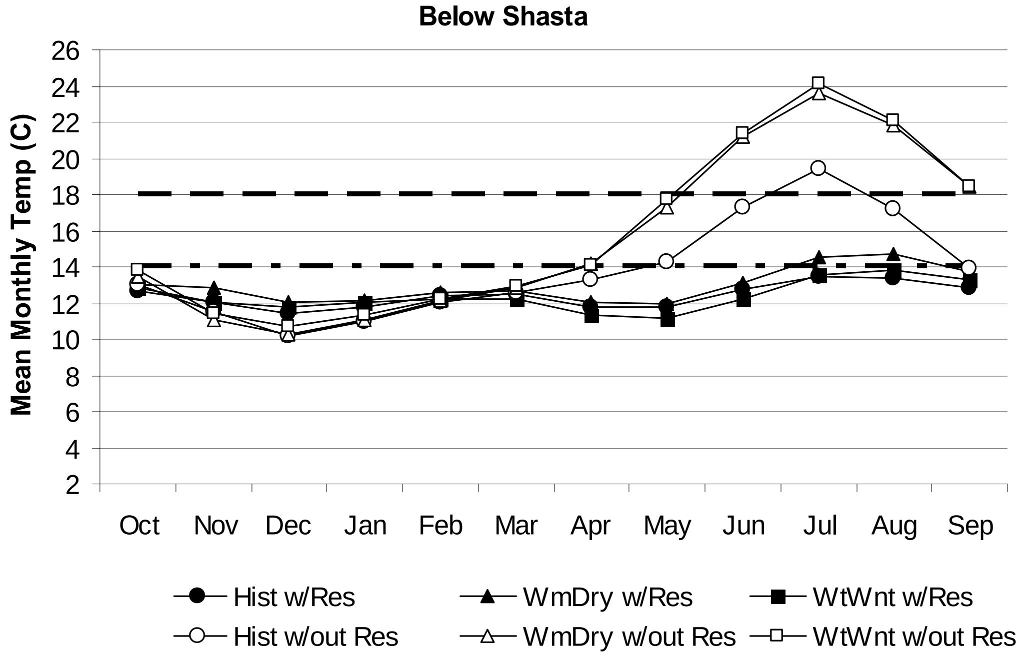



**Figure 7.6. Modeled historic and future (average for "2060 to 2100") mean monthly water temperatures in the Sacramento River near Redding. The top, horizontal dashed line represent the 18ºC for juvenile emigration and the bottom, 14ºC spawning and rearing threshold conditions**.

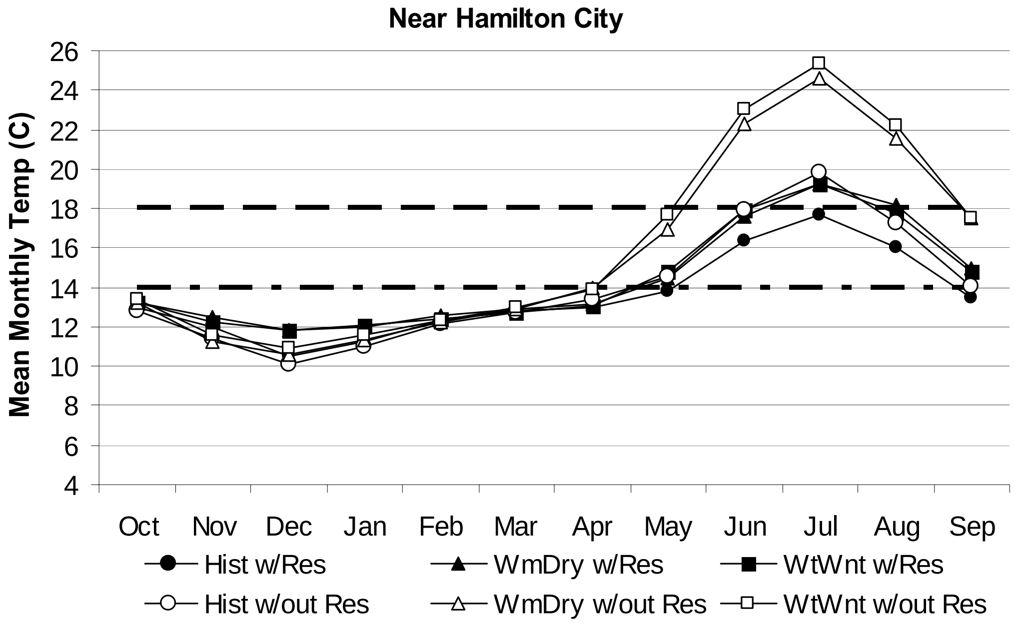



**Figure 7.7. Same as Figure 7.6, but for the Sacramento River reach near Hamilton City.**

### 7.3.3. Implications of Future Climate Change And Water Management Practices

Figure 7.6 shows modeled historic and future monthly mean water temperatures in the upper reaches of the Sacramento River but downriver of Shasta Dam where Chinook salmon now spawn, and their young are reared, before emigration to the sea. These projections show that in the recent past, with dams in place, seasonal fluctuations in water temperature in the reach of the Sacramento River below Shasta have ranged between 14°C and 11°C, which is at and below the temperature threshold for Chinook spawning and rearing. In contrast, the projections in Figure 7.6 also show that without releases from the dams, the May through September water temperatures would exceed this threshold by up to 6°C, illustrating the current utility of the dams in maintaining suitable spawning conditions.

Releases of cool water from Shasta Reservoir could keep water temperatures just below the spawning and rearing threshold for both climate change scenarios (Figure 7.6), with the exception of an approximate 1°C exceedence for the *wmdry* scenario in July and August. Comparison of Figures 1 and 6 indicates that the winter-run and spring-run Chinook young fish, now confined to this portion of the mainstem, may be the most threatened during this period by climatic changes. The fall and late-fall runs have already completed their rearing by May and most of the yearlings have moved downriver and would not be so affected.

In addition to modeling the relationships among dams and diversions, and climate change on water temperature changes, we also modeled the potential effects of climate change on the availability of thermally suitable chinook spawning and rearing habitat from Shasta Dam downriver. The approximately 100 kilometer stretch of the Sacramento River from below Shasta to Red Bluff is currently the main spawning reach of the river (Moyle *et al.*, 2002) and the critical reach to keep cool with reservoir releases. June-July and August-September are the key months that correspond to spawning and hatching of winter and spring runs, respectively (Figure 7.1), with concurrently high potential water temperatures in the mainstem.

With Shasta releases, simulations of water temperatures for the historic period suggest that August water temperatures were, on average, slightly above 14ºC near Red Bluff. Table 7.2 shows the distance downriver from Shasta where simulated average water temperature exceeded the 14ºC spawning and rearing threshold, suggesting a particularly large potential reduction in the spawning habitat under the *WmDry* scenario as well as habitat reductions in the *WtWnt* scenario. Although the warming is not as substantial in the *WmDry* scenario as compared to the *WtWnt* scenario, reductions in overall precipitation lead to a smaller Shasta cold pool and thus reductions in reservoir releases to support cooler downstream temperatures (Figure 7.8). For the *WtWnt* scenario, spring and summer warming and drying forces a more rapid drawdown of the reservoir to meet downstream irrigation requirements, yielding higher summer flows below the dam. Regardless, substantially higher air temperatures lead to greater water temperatures, reducing the cold water habitat below the dam (Figure 7.8 and Table 7.2).

**Table 7.2. Approximate river distances from Shasta Reservoir to the downstream locality on the river where average Sacramento water temperatures exceed 14$^{o}$C with reservoir releases. * Indicates temperature immediately downstream of reservoir, suggesting no available habitat with water temperatures at or below 14$^{o}$C habitat.**

| | June | July | Aug | Sep |
|---|---|---|---|---|
| Historic | 100 | 55 | 65 | 220 |
| *WmDry* | 55 | 14.5* | 14.9* | 50 |
| *WmWet* | 65 | 40 | 35 | 110 |

*WmDry* Warmer and drier scenario; *WtWnt* Wetter winters, drier springs and warmer summers scenario

The hypothetical scenario which assumed no dams or irrigation suggests that prior to these anthropogenic influences, the mean monthly water temperatures below Shasta would have been significantly elevated during the summer months, well above the egg and fry threshold of 14$^{o}$C, and near or above the juvenile and adult physiological thresholds of 18$^{o}$C and 19$^{o}$C, respectively. This illustrates why the chinook migration strategies evolved to enable fish to avoid the mainstem during these months.

The two climate change scenarios yield a disproportionate amount of river water warming below Shasta under the assumption of no dams or irrigation, with mid-summer temperatures increasing by nearly 4$^{o}$C for both scenarios (Figures 6 and 7). Note that the wet *WtWnt* scenario has higher mid-summer water temperatures than the *WmDry*. The *WtWnt* scenario implies exceptional drying and warming into the spring-summer transition and without water storage, the majority of the winter runoff is lost downstream, summer flows are low, and water temperatures become elevated.

If cooler water is not released, the projected water temperatures under the two future scenarios would exceed the Chinook spawning and rearing temperature threshold by up to 6ºC during May through September (the spawning and rearing period for the winter and spring runs). This would result in highly unsuitable spawning and rearing thermal conditions, particularly for the winter and spring spawning runs. Through their earlier spawning and rearing seasons, fall and late-fall fish are able to take advantage of the naturally cooler water temperatures during the winter months and are less dependent on dam releases.

### 7.3.4. The freshwater portion of the Lower Sacramento River

Cold water releases from the Shasta Dam currently reduce the average monthly summer water temperatures downriver near Hamilton City only by about 1-2$^{o}$C from June through September (Figure 7.7). Thus, the current downriver benefits of cold water releases are not as substantial as further upriver. Nevertheless, these releases keep the water temperatures below the 18/19$^{o}$C emigration and immigration thresholds throughout the summer. If releases of cool water from upriver dams were discontinued, the mean monthly water temperatures would exceed the thresholds by 1-2$^{o}$C during July and August.

Under the two climate change scenarios, and assuming that releases of cool water were continued, the emigration and immigration thresholds would be exceeded by 1-2$^{o}$C during July and August. However, if no releases occurred the exceedences during June through August would be as high as 6$^{o}$C. This would result in highly unsuitable migration conditions for chinook. Under both climate scenarios, modeled future water temperatures from June through August exceeded the modeled historic temperatures (with dam releases) by a modest 2$^{o}$C and the differences between the two future scenarios are relatively minor at 1$^{o}$C or less, despite the fact that the *WtWnt* scenario is about

1.5°C warmer in the summer. This is because the warmer summer conditions lead to greater irrigation requirements, and thus additional reservoir releases (Figure 7.8). More summer irrigation also tends to enhance baseflows, as water is applied to agricultural fields and slowly returns to the mainstem in the late summer.

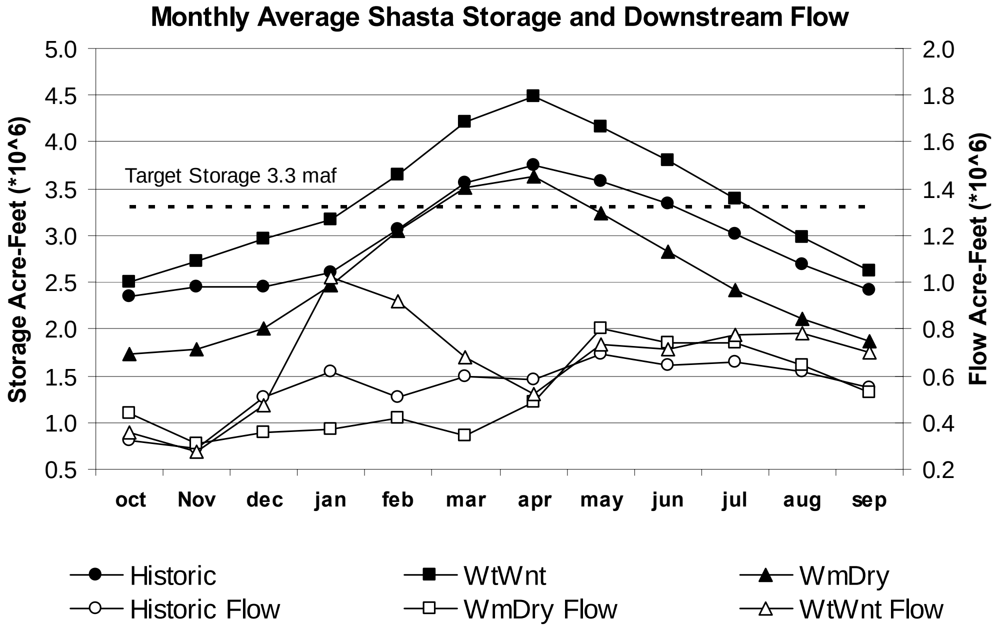



**Figure 7.8. Monthly average Shasta reservoir storage for the historic period and the two climate change scenarios (closed symbols) that might ensure adequate cold water in the upper river for the summer season from May to September. The open symbols are the Sacramento River flows just above Redding. The May targeted storage of 3.3 million acre-feet is also shown.**

A comparison of results in Figures 6 and 7 suggests that the reach from Redding to Hamilton City would, on average, not yield much additional warming, either under historic or climate scenarios. This is because the northern edge of the non-tidal portion of the SV is the warmest, and watershed accretions from tributaries like Battle Creek add relatively cool water downstream. Thus, for this portion of the mainstem, the water has nearly reached its thermal maximum around Redding.

The results in Figures 7.6 through 7.8 illustrate several major points. First, releases from dams play a role in maintaining suitable thermal habitat for chinook spawning and rearing and migration as far downriver as Hamilton City. Second, climate change will be a major determinant of the future viability of adult and juvenile reproductive and migration strategies, especially if releases from the upriver dams are discontinued. Third, in the upriver spawning areas and the downriver areas through which adults and juveniles migrate, adverse effects of climate change could be mitigated by continuing releases of cool waters. Finally, the two most vulnerable runs are likely to be the winter and spring runs (which are affected on both the spawning areas and during migrations). These results emphasize that releases of cool water are obviously critical to maintaining suitable thermal habitat in the future. However, the availability of cool water from reservoirs could be problematic.

Under moderate drying and substantial warming (e.g. the *wmdry* scenario), model results suggest challenges to reservoir operations (Figure 7.8). Average May targeted storage of 3.3 million acre-feet (maf) is tested, with greater spring and summer release requirements. Reduced winter releases allow the reservoir to rebound by February and March, but model results certainly indicate added stress to operational decisions. This could jeopardize the ability of the reservoirs to continue supplying cooler water for salmon under future climatic changes.

## 7.4. Discussion

In highly managed river systems, such as the Sacramento River, past human interventions have often been disastrous for fish populations and communities. Paradoxically, this study has shown that the very management structures and practices that adversely affected the fish historically may provide an opportunity to alleviate some of the future impacts of climate change. More "natural" and unmanaged systems may provide fewer opportunities.

Between May and September, the existence of suitable spawning and rearing habitat for Chinook in the upper Sacramento River is currently dependent on releases of cool water from reservoir hypolimnia (particularly from the Shasta Dam). Without these releases, the water temperatures would exceed the physiological tolerances of the eggs and juveniles of the winter and spring runs by three or more degrees Centigrade. It is unlikely that these populations could persist without these releases. By spawning later and earlier in the year, the fall and late-fall runs are able to reduce their vulnerability to this potentially critical period and are, therefore, less dependent on changes in water management practices.

Future climate change will increase the importance of controlled releases of cool water. We project that under either climate scenario and without releases of cool water, the water temperatures in the spawning and rearing areas immediately downriver of Shasta Dam may increase during the May-September period by up to 6°C, to monthly means as high as 23°C. Such conditions would be lethal for Chinook eggs or hatchlings, jeopardizing the viability of the winter and spring runs which spawn and hatch during this period. Our model projections show that releases from Shasta Dam could counteract this by maintaining spawning area water temperatures below physiological thresholds.

The availability of suitable thermal habitat for migrating adult and juvenile Chinook in the lower Sacramento River is also affected by releases from dams. The main determinants of the midsummer high water temperatures in the lower river are high ambient air temperatures and slow and low flows. Releases from dams, however, currently keep the river water temperatures below the physiological thresholds for migrating fish. Continuing releases under the two climate change scenarios would generally keep the river temperatures below the thresholds, except in July and August when the juvenile threshold would be marginally exceeded. However, if releases of cool waters from the dams were not continued under the two future climate scenarios the mid-summer monthly mean water temperatures in the lower Sacramento River would be about 6°C higher (approaching 25°C). Such temperatures could be lethal for adult and juvenile Chinook attempting to migrate in or out of the river system. Also, the period over which Chinook thermal tolerances would be exceeded would be extended from the current three months to five months. The runs most affected by this would be adults and juveniles of the winter, and spring runs.

# 8. Conclusions

There is an emerging consensus in the scientific community that climate change has the potential to significantly alter prevailing hydrologic patterns in California over the course of the 21st Century. This is of profound importance for a system where large investments have been made in hydraulic infrastructure that has been designed and is operated to harmonize dramatic temporal and spatial water supply and water demand variability. Recent work by the authors lead to the creation of an integrated hydrology/water management climate change impact assessment framework that can be used to identify potential tradeoffs between important ecosystem services provided by the California water system associated with future climate change and to evaluate possible adaptation strategies. In spite of the potential impact of climate change, and the availability of a tool for investigating its dimensions, actual water management decision-making processes in California have yet to fully integrate climate change analysis into the planning dialogue. This work has engaged a number of relevant decision-making processes that are well suited for climate change analysis based on the fact that their sector is climatically sensitive, their sector is socially and economically significant, and they expressed interest in incorporating the kind of decision analytic process that our proposed analytical framework could play in arriving at appropriate water management decisions.

We have developed an integrating framework for addressing the climate change implications on the freshwater ecosystem services provided by watersheds. The Water Evaluation and Planning Version 21 (WEAP21) Integrated Water Resource Management (IWRM) model seamlessly integrates water supplies generated through watershed scale hydrologic processes with a water management model driven by water demands and environmental requirements, governed by the natural watershed and physical network of reservoirs, canals, and diversions. This version (WEAP21) extends the previous WEAP model by introducing the concept of demand priorities and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches. WEAP21 introduces a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners through a scenario-based approach. These issues include climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives and available infrastructure.

Using the WEAP21 framework, the Sacramento Basin was subdivided into more than 100 sub-catchments, groundwater basins, irrigated areas, and urban demand centers in an attempt to completely characterize the forces that act on water in the basin. A 37-year, monthly climate time series from 1962 to 1998 forces a distributed hydrologic model, which simultaneously simulates runoff, groundwater-surface water interactions, and consumptive water demands. The water management infrastructure was superimposed across the physical watershed, and consisted of a multitude of reservoirs, canals and diversions, each with their own rules of operation as represented through WEAP21's allocation logic. Results show that the model was capable of reproducing both local and regional water balances for the 37-year period, including managed and unmanaged streamflow, reservoir storage, agriculture and urban water demands, and the allocation of ground water and surface water supplies.

Climate change clearly has serious implications for water management in the Sacramento Basin, with this study evaluating the impact of four future climate scenarios on agricultural water management in the region, and whether water management adaptation could reduce potential impacts. The four climate scenarios were derived by downscaling the output from two GCMs (Parallel Climate Model and Geophysical Fluid Dynamics Laboratory) and two emission scenarios (A2 and B1) combinations to a 1/8 degree grid over California. The Sacramento Valley WEAP application sampled these climate fields to provide input to a model of the Sacramento River Basin that disaggregates the basin into 64 sub-watersheds. The model was applied under two formulations, one where cropping and irrigation management patterns remained fixed over the course of a 100-year simulation and one where copping and irrigation management patterns evolved over the course of the 21st century along with the climate. Model runs under all four scenarios showed the largest impacts at the end of the 100-year simulations. In particular, the GFDL/A2 combination produced a downscaled climate series that included a major drought during the final 15 years of the coming century. With no adaptation, a lack of sufficient surface water to meet elevated evaporative demand for irrigated crops led to a dramatic increase in groundwater pumping and a coincident decline in simulated groundwater levels. All simulations also resulted in much lower reservoir levels in the late summer and early fall as simulated operations kept pace with the increases in evaporative demand associated with higher temperatures. When adaptation, in terms of shifting cropping and irrigation technology patterns, was allowed to occur, the amount of groundwater pumping between 2070 and 2100 was reduced. While the carryover reservoir storage was not significantly increased, deliveries to meet growing urban demand in the system became increasingly reliable when agriculture could satisfy evaporative demand with a reduced level of water input.

We also looked at the viability of the Chinook salmon (Oncorhynchus tshawytscha) under various climate change scenarios. These fish spawn and rear in the cold, freshwater rivers and tributaries of California's Central Valley. Historically, this river system has been home to four separate seasonal spawning runs: the fall and late-fall runs, a winter run, and a spring run. Dams and reservoirs have blocked access to most of the Chinook's ancestral spawning areas in the upper reaches and tributaries. Consequently, the fish increasingly rely on the mainstem of the Sacramento River for spawning habitat. Future climatic changes, particularly major shifts in temperature and precipitation patterns over extended periods, are projected to lead to alterations of the river's temperature regime, which could further reduce the already fragmented Chinook habitat. Specifically, increased water temperatures are projected to result in exceedences of critical spawning and rearing temperatures, thereby jeopardizing productivity. The winter and spring runs are shown to be most at risk, because of the timing of their reproduction. Paradoxically, water management could play a major role in maintaining spawning and rearing habitat in the future, as reservoirs such as Shasta are a key source of cold water. Our study showed that although reservoirs are already used to manage Sacramento water temperatures, they future management might be adaptable to counter the effects of climatic changes.

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**Appendix A- DWR Workplan**

**Evaluation of the WEAP Climate Change Assessment Framework for Use in the 2010 Edition of the California Water Plan Update**

**Partners:**
California Department of Water Resources (DWR)
The RAND Corporation

**Geographic Scope:**
The geographic scope of the effort will be coincident with the existing Sacramento Valley model, which is identical to the Sacramento River Valley Hydrologic Region as defined in the California Water Plan Update.

**Decision Context:**
The collaboration seeks to assist DWR in identifying the critical elements of the a climate change assessment framework that may be used to introduce quantitative considerations of climate change impacts into the next 2010 version of the legislatively mandated California Water Plan Update. Ideally this framework will also prove useful for supporting the portfolio analysis approach that DWR adopted for the 2005 version of the Water Plan Update and hopes to expand in subsequent versions. Potential refinements of the portfolio approach may also be driven by RAND's NSF supported research on Long Term Policy Analysis under deep uncertainty and it application to California water planning.

**Work Plan Tasks:**
Task 1: The collaboration will begin with a series of workshops designed to provide DWR staff with more detailed background on:

- The hydrology model included in WEAP and how it is used to internalize the simulation of reservoir inflows, evaporative demand, and accretions and depletions into the water resources planning model.
- The methodology used to downscale climate scenarios generated by GCMs into watershed specific climate time series needed to run WEAP.
- The water allocation logic used in WEAP with particular attentions being paid to user defined priorities and preferences, system and regulatory constraints, and the LP solver.
- The water quality routine used in WEAP, with a particular focus on the water temperature module.

The current Sacramento Valley model will serve as a working example for these workshops. A secondary goal of these workshops will be to build the capacity of DWR and RAND collaborators to manipulate the model so that the issue of appropriate model aggregation for used in the CARs framework can be addressed as part of the DWR-RAND collaboration.

Task 2: Find a HUC used in the Sacramento Valley portion of the existing model (e.g. Stone Corral) that is largely coincident with one of the mass balance computational units used by DWR in preparing the Water Plan Update. Compare the components of the simulated mass balance in this HUC to those estimated by DWR using available data. This comparison should focus both on the respective terms of the mass balance equation and their numeric correspondence. This task will also focus on how well the WEAP system can accommodate the output of other DWR models designed to provide insight about future water use patterns in the agricultural and urban sectors.

Task 3: Work with the DWR Delta Modeling Group to define and implement a strategy for considering the effects of sea level rise on system operations. This will require an extension of the current model in that the current Delta regulations are limited to flow based standards. To add salinity-based standards that will be impacted by sea level rise will likely require developing links to Delta hydraulic models. These might be statistical models or perhaps something similar to the ANN used in CalSim-II.

Task 4: Embed the model of the Sacramento Valley region into a skeletal representation of the California water system that includes all of the ten Hydrologic Regions used in Bulletin 160 and the appropriate links between them. The goal of this task will not be to develop detailed representations of the California water system outside of the Sacramento Valley but will be used instead to demonstrate how climate change impacts can be evaluated on a system wide basis. Positive results from this task may motivate an effort to add additional refinement to other regions of the California water system.

Task 5: Run various climate change scenarios through the aggregated model and report on how this approach might support both the climate change assessment and portfolio approach proposed for the 2010 version of the California Water Plan Update. As resources allow, this task may also include several attempts to define climate change adaptation scenarios.

**Appendix B- American Water Resources Association 2006**

**Understanding the Local Water Management Implications of Global Climate Change, in the South Fork of the American River, California**

David Yates, David Purkey, Melissa Gunter, Elizabeth Mansfield

## INTRODUCTION

To provide tools that water managers can use to assess the implications of climate change under their particular set of circumstances, the U.S. Environmental Protection Agency supported the development of an analytical framework that could seamlessly integrate climate change and others drivers that water managers commonly confront: population growth; land use change; and regulatory reform. This framework uses the Water Evaluation and Planning (WEAP) system to simulate different scenarios that emerge in response to different drivers (Yates et al. 2005a,b and Yates et al. 2006). Recognizing that such a framework it of little practical use unless it can support actual decision making, collaborations with water managers on the use of WEAP are underway. This article describes a collaboration with the El Dorado Irrigation District in California's American River Basin.

## CONCEPTUAL FRAMEWORK

The contours of the integration mentioned above are shown in Figure 7.1, which includes both the domain of watershed hydrology, representing water's natural flow though a watershed and the domain of the water resources planning. A planning model contains information on the physical characteristics of built features (dams, reservoirs, diversions, etc.) as well as the logic of their operations. By dynamically integrating the natural hydrology and built elements of the watershed, WEAP allows for robust analysis of future climate scenarios, associated hydrologic conditions, and appropriate management responses at a level relevant to local water managers.

While this integration gives WEAP creditability as a tool for the analysis of climate change (Purkey et al. 2005), the tool also needs to be relevant to the type of management scenarios that water planners would contemplate in response to climate change and other stressors. Finally, the model will be legitimate to the extent that it actually used by decisions makers. Through a pilot application in the American River system, conducted in collaboration with the El Dorado Irrigation District, the creditability, relevancy and legitimacy of WEAP for analysis by local water managers of the potential impacts of and adaptation to climate change is being assessed.

## THE EL DORADO IRRIGATION DISTRICT'S SOUTH FORK PROJECT 184

El Dorado Irrigation District (EID) is a water utility serving nearly 100,000 residents in northern California's El Dorado County, providing drinking water for homes, and businesses and irrigation water to agricultural interests in their service area. The EID facilities include a small hydropower facility and the District strives to meet or exceed increasingly stringent regulatory standards for water quality, environmental protection, and wildlife habitat. The rules that govern the operation of their infrastructure are daunting, and will become more so by 2008 when EID finalizes the Federal Energy Regulatory Commission (FERC) license to operate the hydro-electric facility.

This facility, known as Project 184, provides an important revenue source for EID through its 20 megawatt capacity powerplant that includes several reservoirs, and 23 miles of flume, canals, and tunnels. Project 184 represents nearly 35 percent of EID total water supply (Figure 7.2). Project 184 water supply is delivered to customers through a diversion from the South Fork of the American River at Kyburz. New guidelines in the FERC license will stipulate a conditional instream flow requirement (IFR) on the South Fork below Kyburz, which will vary between wet, above normal, below normal, dry and critically dry water years. The new requirements are an attempt to re-introduce some of the natural variability of the river system, with peak IFRs in April, May and June corresponding to the historical snowmelt season.

With regards to Project 184 the collaboration with EID seeks to discover whether the new regulatory requirements mandated by the up-and-coming FERC license will be attainable in the face of climatic variability and change and how often the system will fail to meet these requirements. The analysis also seeks to identify adaptation measures available to ameliorate these impacts.

## PROJECT 184 in WEAP

Figure 7.2 is a representation of EID's Upper South Fork of the American and the Project 184 system in WEAP. The hydrology module in WEP was forced with weekly time series of precipitation, temperature, relative humidity, and wind speed from 1982 to 2003 (Thornton et al. 1997). Four reservoirs (Echo, Aloha, Caples and Silver), with a total storage capacity of about 39,000 acre-feet (15% of the total annual discharge) were modeled according to their current operating rules. While more sophisticated climate change scenarios have been applied, the sensitivity of EID's Project 184 to climate change is illustrated by simply adding 2ºC to the 1982 to 2003 historical temperature time series with no change in the other climate variables, consistent with the warming suggested by General Circulation Models over the next 20 to 30 years.

## RESULTS AND ANALYSIS

The model was calibrated against the observed flow at the South Fork of the American below Kyburz (P184SFA IFR) and adequately reproduced both peak and low flows (Figure 7.3). Results for the +Δ2ºC scenario are also shown on the left-hand chart of Figure 7.3 along with the +Δ2ºC scenario with an adaptation whereby the reservoir rule curves are shifted to allow more over winter storage and to allow earlier summer releases. The results of the simple warming scenario suggests an increase in winter flows by about 40%, as more precipitation falls as rain. Spring peak flows are reduced and shifted earlier by about three weeks. Late summer flows are also reduced.

The ability to cope with the enhanced IFRs, particularly in May, June and July is detailed in the right-hand chart of Figure 7.3. This shows the average weekly unmet demand relative to the new proposed FERC IFR below Kyburz for the historic climate, the +Δ2ºC scenario, and this same climate scenario with an adaptation related to shifting reservoir operating rules. Even without climate change, this graph suggests that in some years EID will be challenged to meet these rather stringent new IFRs. With +Δ2ºC warming superimposed on the historic 1982 to 2003 climate record, meeting the IFR with current reservoir operations becomes increasingly difficult. With reservoir re-operation (which of course assumes new legal arrangements), there is greater ability to meet early spring IFRs, but less so in late summer. This adaptation also implies greater mid-summer reservoir releases with attending consequences on lake recreation.

## CONCLUSIONS

This targeted example of how the WEAP framework can be deployed to explore the implications of future climate and other stressors, in this case a new IFR regulation, demonstrates well how the tool can be of used by local water and aquatic ecosystem managers to understand the impacts of and adaptation to climate change. While only a simple climate scenario was presented here, WEAP flexibility accommodates single or multiple climate time series developed by any appropriate climate downscaling methodology. From these time series, WEAP can generate hydrologic responses that are characteristic of a watershed under consideration. These future hydrologic conditions, in turn, drive analysis of how a water system should be operated to meet multiple objectives. All of this analysis takes place within integrated, user-friendly, transparent, readily available software. Future work will entail further collaboration with water management decision making entities such as the El Dorado Irrigation District.

## ACKNOWLEDGEMENTS

This work was partially supported through a research grant from the United States Environmental Protection Agency Office of Research and Development Global Change Research Program (CX 82876601), and the Climate and Weather Assessment Program at the National Center for Atmospheric Research. The National Science Foundation sponsors the National Center for Atmospheric Research. The El Dorado Irrigation District graciously provided information on project 184 and its operations. The El Dorado National Forest provided information used to describe the watershed of the South Fork American River system.

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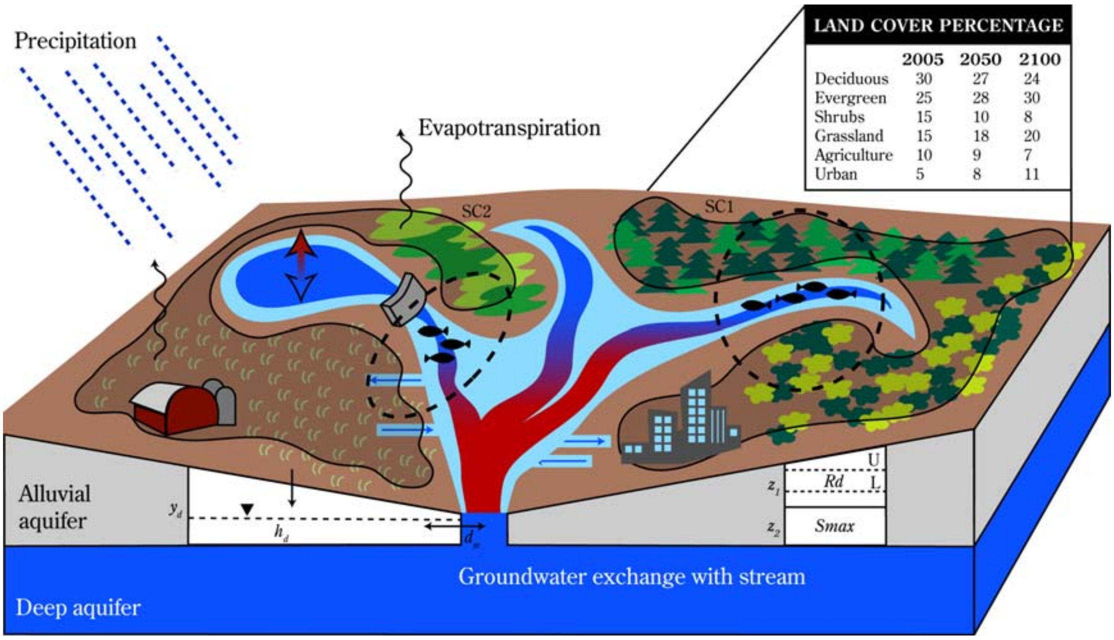


**Figure 7.1.** WEAP conceptual watershed/planning model. The river shading depicts water temperature gradients, with the vertical arrow in the reservoir reflecting the fact that there can be distinct temperature stratification. The two schematic diagrams imbedded in the figure are simplified representations of the WEAP21 hydrology module, with the left schematic the alluvial groundwater component ($y_d$ relative height of groundwater table; $h_d$ horizontal distance of aquifer extent, $d_w$ wetted stream depth) and the right diagram, the surface hydrology component ($R_d$ rooting depth; *Smax* deep holding capacity; $z_{1,2}$ relative storage; *U,L*-irrigation thresholds). In WEAP21, watersheds are sub-divided into sub-catchments (SC) as fractional land covers, which can change over time.

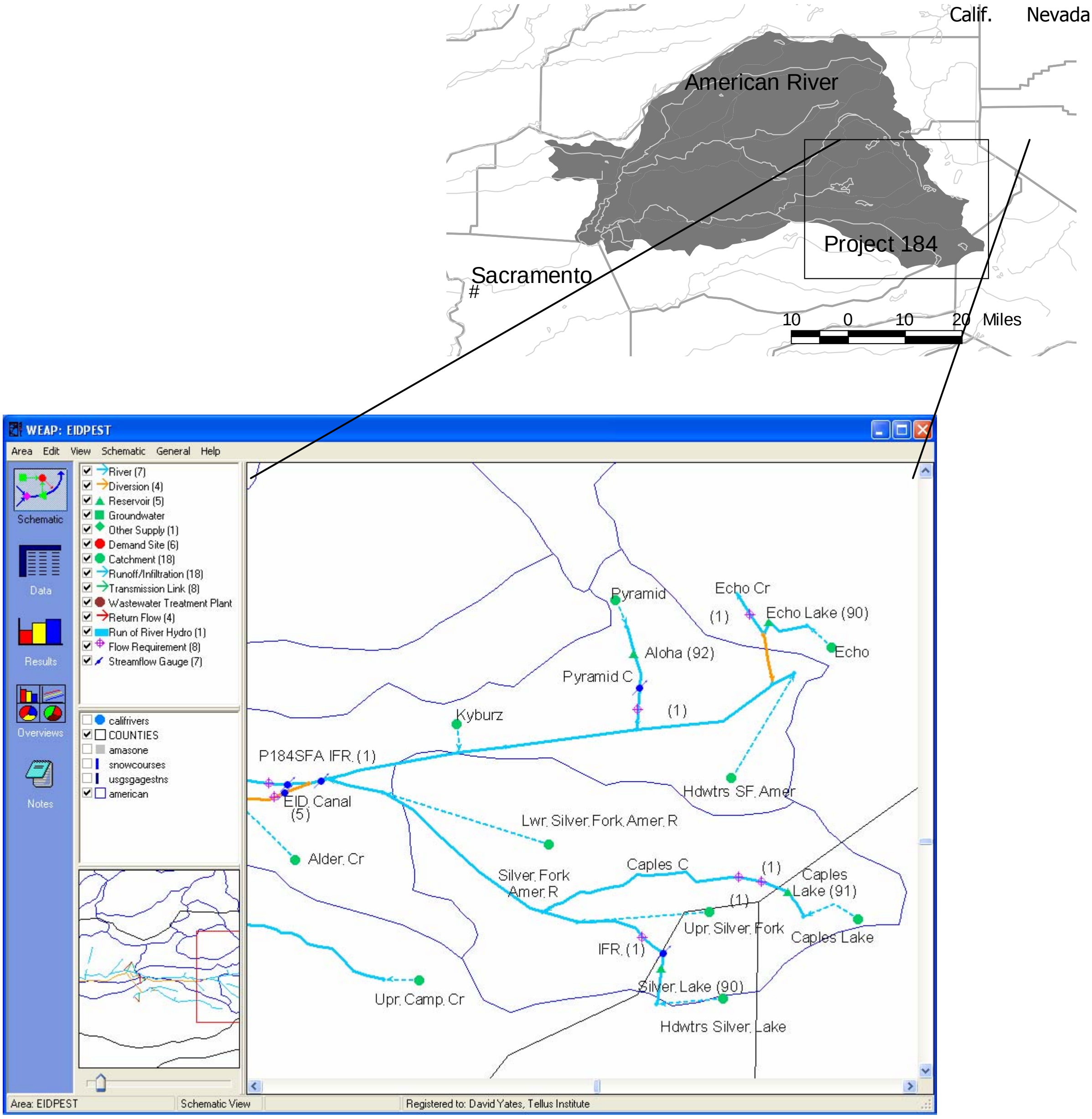


**Figure 2.** EID's Project 184 system as represented in the WEAP DSS. The 10 dots and their connecting dotted lines represent individual sub-catchments (Pyramid, Echo, Headwaters South Fork American, etc.). The four triangles are the reservoirs (Silver, Caples, Aloha and Echo), while the hatched circles are in-stream flow requirements.

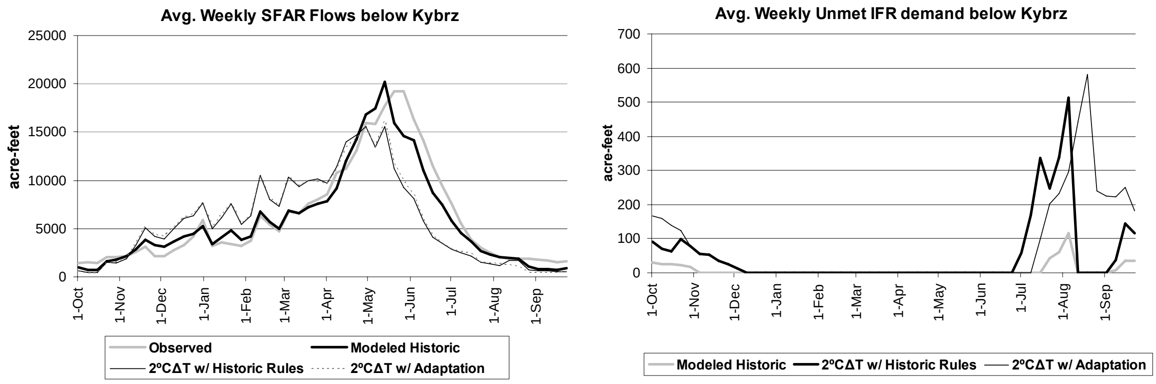


**Figure 3.** Observed and simulated streamflow values for the South Fork American River below Kyburz (left) and the unmet portion of the new FERC IFR for the South Fork American River below Kyburz (right)

**Appendix C: Development of Adaptation Strategies***

**(*This work was also funded under a grant from the California Energy Comission and the State of California- CEC-500-2005-194-SF, but would not have been possible without this EPA Grant)**

## C.1. Increased Irrigation Efficiency

As mentioned before it was assumed for the development of this project, that there are exogenous (not climate dependant) forces (regulatory pressure) that will increase irrigation efficiency over time on the $21^{st}$ century regardless of climate conditions. The assumption is that these increments of efficiency improvement occur gradually over the first half of the century until they reach a maximum level by 2050.

These improvements will be different for different crops as can be seen in Table C-1. The data in the table is estimated assuming orchard acreage to be entirely irrigated with low volume irrigation systems (e.g., drip) by 2050. Similarly, we assume 100% of row crop acreage, including vegetables, and 50% of field crop acreage will be served by low volume systems by 2050. Rice acreage, on the other hand, will be irrigated by gravity fed irrigation in 2050, as it is today. The resulting impact on applied water use of these changes in irrigation methods is indicated in Table C-1. For example, applied water to orchards is expected to fall to 84% of current levels. The drop in applied water in this case is relatively small, since most orchard acreage is currently irrigated with low volume methods.

In order to represent these improvements in the Sacramento WEAP model the parameters that determine the irrigation process in the model were modified. Under WEAP representation of hydrology and land use demands, a watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. The process represented in each fractional area (percolation, surface runoff, interflow, ET) have associated certain calibrated parameters such as the Leaf Area Index, that determines the amount of surface runoff or the root zone conductivity that determines the amount of water that percolates into the groundwater from the soil. All these physical parameters were previously calibrated (see Yates et al. 2005c) to represent current conditions in the Sacramento Valley. Two more parameters are used to represent irrigation practices when soil moisture is not sufficient to meet ET requirements. The first of these parameters called the lower irrigation threshold ($IrrThrLwr_j$) represents the soil moisture level at which irrigation will be required (i.e., any time the soil moisture is below $IrrThrLwr_j$ irrigation is called) to increase the soil moisture up until it reaches an upper irrigation threshold ($IrrThrUpr_j$). Considering that these two parameters were directly related to irrigation procedures they were chosen as parameters to be modified to represent improvements in irrigation efficiency.

Reducing $IrrThrLwr_j$ would lower supply requirements because holding all other parameters constant now irrigation is called less frequently, i.e., the level of soil moisture tolerance before external supplies of water are needed are increased. On the other hand reducing $IrrThrUpr_j$ also implies less water requirements because now every time an irrigation call is made, there will be less need of water to fill the bucket until we reached the soil moisture threshold level. However at the same time less irrigation is required, soil moisture is reduced (the bucket is filled to a lower level) and hence ET, percolation and surface runoff are reduced. The two later effects are expected under an improvement in irrigation efficiency but the former not anticipated. Modifying both parameters (allowing them to increase and decrease) created different water supply requirements holding ET at reasonable levels.

Using a reduced time period (1962-1980) of the original aggregated model of the Sacramento Valley, changes in these parameters were carried out to understand their impact on water supply requirements for each crop. The result from this experimentation was a collection of data points representing different changes in the parameters with their associated change in water supply requirements and change in ET. Based on this analysis the change in parameters that best represented the target improvement in water supply requirement for each crop is shown in Table C-1.

**Table C-1. Improvements in irrigation efficiency by 2050, associated parameter change**

| crop | Percent of original supply requirement by 2050 | Initial Lower Threshold | Initial Upper Threshold | Change in Lower Threshold | Change in Upper Threshold |
|---|---|---|---|---|---|
| cereals | 86% | 40% | 55% | -15% | 0 |
| oilcrops | 86% | 30% | 40% | -10% | 0 |
| orchards | 84% | 40% | 45% | -15% | 5% |
| pasture | 86% | 40% | 50% | -5% | -5% |
| rowcrops | 96% | 40% | 50% | -10% | 0 |

### C.2. Shifts in Cropping Patterns

The determination of cropping patterns is made each year prior to planting. WEAP supplies water for irrigation to several land use classes. Each land use class has its own irrigation demand pattern, which depends upon the time of planting, the crop coefficient, and reference evapotranspiration. In general, crops require water for irrigation between the months of February and October. As such, February 1st was chosen as the date for adjusting the cropping patterns for CVP contractors based upon an evaluation of water supply conditions in the Sacramento Valley.

### C.3. Derivation of the Crop Adaptation Equations

The HUC's grow a mix of cereal, orchard, pasture, rice and row crop acreage. The share of crop acreage in each HUC varies as a function of changes in the supply of surface water and depth to groundwater. The function is derived from a multinomial regression analysis of synthetic data of crop shares generated by the Central Valley Production Model for regions 3, 3b, 4, and 5. These regions cover a portion of the northwestern Central Valley, very roughly coincident with Glenn and Colusa Counties.

The data were generated from CVPM model runs assuming the base water supply and groundwater depth, a 10% decrease from base water supply, a 20% decrease from base water supply, a 100 foot drop in the groundwater depth and a 200 foot drop in the groundwater depth. These model runs provided 408 synthetic estimates of crop shares across a range of different regional, water supply and groundwater depth assumptions. The multinomial logit analysis of this data was used to derive the following equation coefficients (Table C-2).

## Table C-2. Multinomial logistic regression results

**Coefficient output and z statistics**

| Crop | Cereal | | Orchard | | Pasture | | Rice | | Row | |
|---|---|---|---|---|---|---|---|---|---|---|
| | coefficient | z statistic | coefficient | z statistic | coefficient | z statistic | coefficient | z statistic | coefficient | z statistic |
| **depth** | **-0.004** | -22.4 | **-0.004** | -21.4 | **-0.005** | -20.8 | **-0.004** | -24.7 | **-0.004** | -20.7 |
| **percent supply** | **6.224** | 31.7 | **5.992** | 30.6 | **6.799** | 29.0 | **6.568** | 35.8 | **5.999** | 29.6 |
| **region 3** | **-1.287** | -27.2 | **-2.473** | -50.8 | **-1.569** | -31.2 | **0.609** | 12.1 | **-0.414** | -8.4 |
| **region 4** | **-0.130** | -2.6 | **-1.412** | -28.3 | **-2.201** | -37.9 | **0.681** | 12.8 | 0.111 | 2.2 |
| **region 5** | **-1.361** | -28.2 | **-0.405** | -8.8 | **-1.518** | -29.7 | **0.931** | 18.3 | **-2.074** | -38.1 |
| **constant** | **-2.683** | -14.4 | **-2.235** | -12.0 | **-3.481** | -15.6 | **-3.817** | -21.8 | **-3.074** | -15.9 |

**Combined Regression Coefficients**

| | Cereal | Orchard | Pasture | Row | Rice |
|---|---|---|---|---|---|
| | B1 | B2 | B3 | B4 | B5 |
| **depth** | -0.0044 | -0.0042 | -0.0048 | -0.0045 | -0.0042 |
| **persup** | 6.2245 | 5.9918 | 6.799 | 6.5681 | 5.9985 |
| **reg3** | -1.2872 | -2.4727 | -1.5688 | 0.609 | -0.4143 |
| **reg4** | -0.1303 | -1.4122 | -2.2013 | 0.6809 | 0.1112 |
| **reg5** | -1.361 | -0.4054 | -1.518 | 0.931 | -2.0739 |
| **cons** | -2.6829 | -2.2346 | -3.4806 | -3.8168 | -3.0742 |

Number of obs = 173597
Log likelihood = -259222.93
Pseudo R2 = 0.0790
(Outcome: Fallow is the comparison group)

The logit regression coefficients have the correct sign and are highly significant, with the exception of two regional dummy variables, as judged by the z statistics in Table C-3. The logit regression coefficients are manipulated to derive crop share equations (Table C-3).

In Table C-3, $P_0$-$P_5$ refer to the estimated crop shares, Β refers to the estimated vector of logit coefficients associated with each crop type, and X refers to the matrix of independent variables including the water supply and groundwater depth.

**Table C-3. Crop Share Equations**

| | | |
|---|---|---|
| Fallow | $P_0$ | $\Pr(y=0) = \dfrac{1}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |
| Cereal | $P_1$ | $\Pr(y=1) = \dfrac{e^{XB_1}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |
| Orchard | $P_2$ | $\Pr(y=2) = \dfrac{e^{XB_2}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |
| Pasture | $P_3$ | $\Pr(y=3) = \dfrac{e^{XB_3}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |
| Rice | $P_4$ | $\Pr(y=4) = \dfrac{e^{XB_4}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |
| Row | $P_5$ | $\Pr(y=5) = \dfrac{e^{XB_5}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$ |

The accuracy of the crop share equations in predicting changes in crop acreages was evaluated against changes in historical crop shares during the 1990-1992 period, the worst drought on record in the Sacramento Valley. The logit equations were calibrated to fit base 1989 Glenn and Colusa County crop shares, just prior to this drought. The calibration procedure involves changing the constant term in Table C-3 so that predicted crop shares matches base period crop shares. [2]

2. ** The constant term associated with each crop share (Pi) in the County in the base period is derived as follows (continued at the bottom of the next page):

3. $$\frac{1}{\sum_i e^{XB_i} + 1} = P_0$$

4. $$\sum_i e^{XB_i} + 1 = \frac{1}{P_0}$$

5. $$\frac{e^{XB_i}}{\sum_i e^{XB_i} + 1} = P_i$$

Relative surface deliveries to Glenn and Colusa Counties during the 1987-1994 period are assumed to match CVP north of Delta deliveries. This index suggests that surface deliveries to these Counties fell 30% between 1989 and 1992, and rose at the end of the drought after 1993 (Table C-4. Average groundwater depth in this region declined slightly according to DWR groundwater depth records (Table C-4).

**Table C-4. Water Supply and Depth to Groundwater Trends in Glenn and Colusa Counties**

| | Water Supply | | | Depth to Groundwater | |
|---|---|---|---|---|---|
| | CVP Deliveries, NOD | Total CVP, NOD | Total CVP NOD Index | Colusa and Glenn County | Reference to 85 feet in 1989 |
| 1987 | 1557692 | 1,900,569 | 1.03 | 36.68 | |
| 1988 | 1483088 | 1,834,060 | 0.99 | 39.14 | 85 |
| 1989 | 1500561 | 1,851,533 | 1.00 | 41.47 | 85 |
| 1990 | 1458159 | 1,770,766 | 0.96 | 43.23 | 87 |
| 1991 | 1189512 | 1,385,392 | 0.75 | 43.95 | 89 |
| 1992 | 1155254 | 1,276,833 | 0.69 | 38.98 | 87 |
| 1993 | 1241494 | 1,521,284 | 0.82 | 44.04 | 89 |
| 1994 | 1283860 | 1,486,920 | 0.80 | 37.03 | 85 |

**Source:**
Water Supply: CVP Deliveries in the Sacramento Valley. U. S. Bureau of Reclamation
Central Valley Operations Web site: http://www.usbr.gov/mp/cvo/deliv.html
Depth to groundwater averaged across Glenn and Colusa County. Department of Water Resources groundwater well depth records.

A comparison of historic and predicted Glenn and Colusa County crop shares suggests that the crop share equations provide only a rough approximation of drought period crop trends (Tables B-5 and B-6; FiguresB-1 and B-2). The drought precipitated relatively large declines in rice (4%) and cereal (-1.5%) shares accompanied by a large rise in fallowing (5%). Historic shares of other crops showed less pronounced trends. Interestingly, pasture tended to rise over the period rather than fall as predicted.

The crop share equations predicted the decline in rice and the rise in fallowing shares with some accuracy, somewhat under predicting both crop trends. The equations failed to predict the slight historic rise in pasture acreage; predicting a drop in pasture share instead. In addition, the crop share equations predicted land fallowing would peak in 1992 but the historical data indicate that land fallowing actually peaked in 1991 instead. The discrepancy between predicted and historical crop acreage trends may reflect an error in the historical water supply data used in our predictions.

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6. $$\frac{e^{XB_i}}{\sum_i e^{XB_i} + 1} = P_i$$

7. $$e^{XB_i} = \frac{P_i}{P_0}$$

8. $$XB_i = \ln(P_i) - \ln(P_0)$$

9. $$B_0 = \ln(P_i) - \ln(P_0) - XB_i$$

| Historic Crop Shares | | | | | | |
|---|---|---|---|---|---|---|
| **Year** | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegetables** | **Fallow** |
| 1989 | 24.0% | 21.5% | 17.5% | 33.9% | 3.1% | 0.0% |
| 1990 | 26.3% | 21.7% | 16.9% | 30.7% | 3.0% | 0.9% |
| 1991 | 22.8% | 22.6% | 18.7% | 26.1% | 2.3% | 5.5% |
| 1992 | 22.4% | 24.1% | 17.9% | 31.2% | 1.6% | 2.0% |
| 1993 | 25.5% | 25.2% | 20.0% | 37.8% | 2.0% | -7.6% |
| **Predicted Crop Shares** | | | | | | |
| **Year** | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegetables** | **Fallow** |
| 1989 | 23.7% | 21.2% | 17.4% | 33.6% | 3.1% | 1.0% |
| 1990 | 23.8% | 21.6% | 17.0% | 33.2% | 3.1% | 1.3% |
| 1991 | 23.7% | 22.5% | 15.0% | 30.8% | 3.2% | 4.7% |
| 1992 | 23% | 23% | 14% | 30% | 3% | 7% |
| 1993 | 24% | 22% | 16% | 32% | 3% | 3% |
| **Estimation Error, Predicted Minus Historic Crop Shares** | | | | | | |
| **Year** | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegetables** | **Fallow** |
| 1989 | -0.2% | -0.2% | -0.2% | -0.3% | 0.0% | 1.0% |
| 1990 | -2.5% | -0.1% | 0.0% | 2.5% | 0.1% | 0.4% |
| 1991 | 0.9% | -0.1% | -3.7% | 4.7% | 0.9% | -0.8% |
| 1992 | 0.9% | -1.5% | -3.7% | -1.5% | 1.6% | 4.9% |
| 1993 | -1.6% | -2.9% | -4.2% | -6.0% | 1.2% | 10.7% |

Source:
Historic crop shares from County Agricultural Commissioner Reports for Glenn and Colusa County.
Predicted shares from logit model crop share equations, calibrated to fit Glenn and Colusa Coutny 1989 crop shares

**Table C-5. Crop Adaptation Model: Predicted and Historic Crop Shares in Colusa County**

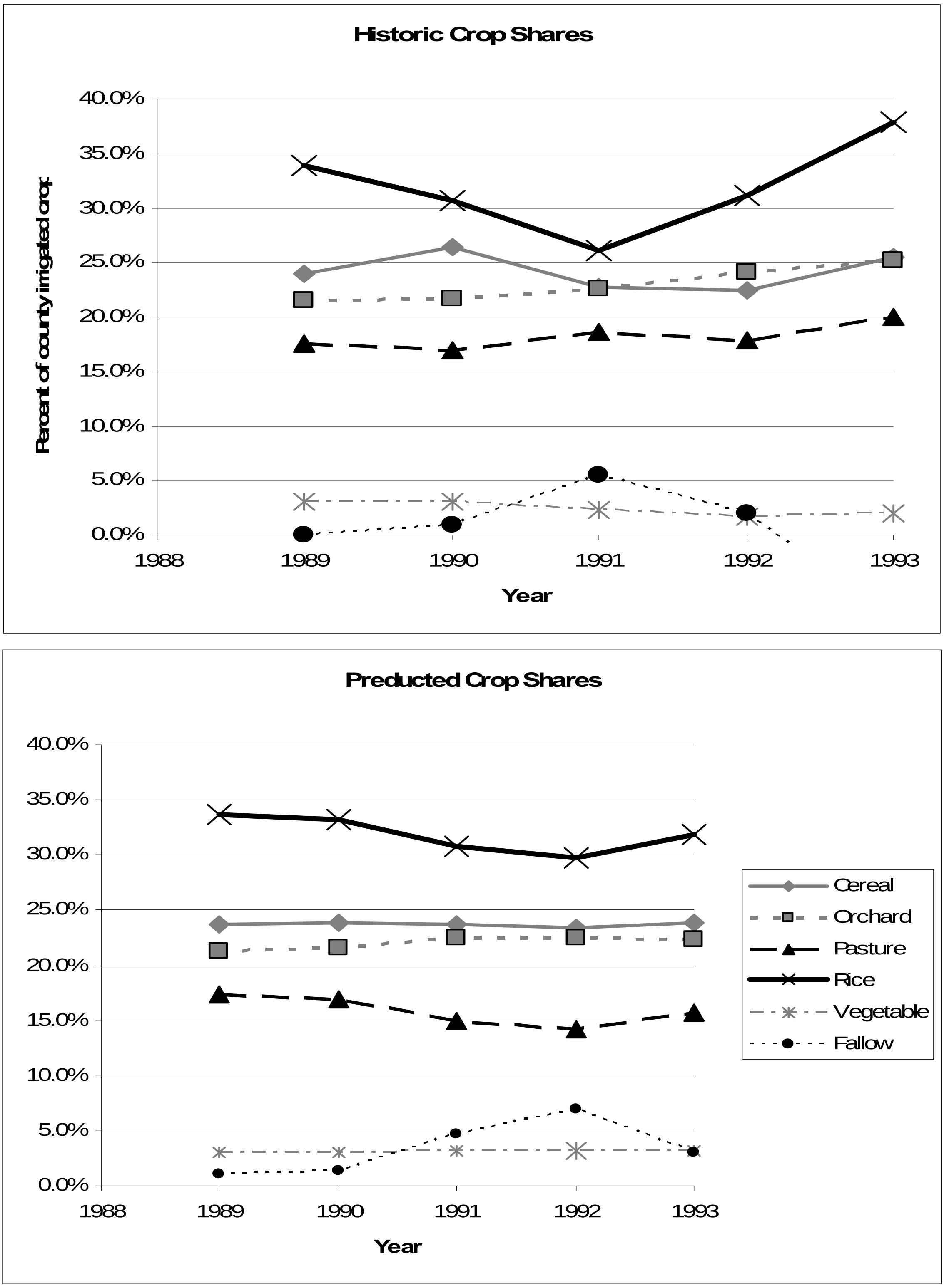
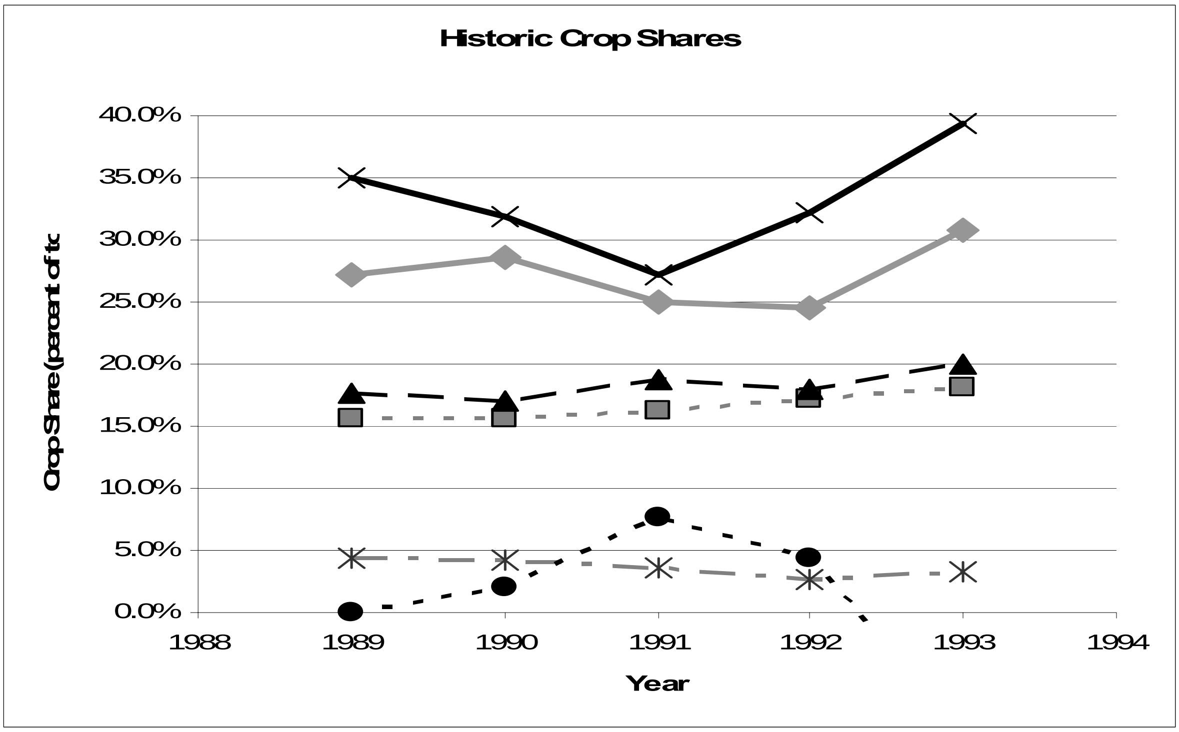



**Figure C-1. Historic and Predicted Crop Shares in Colusa County**

**Table C-6. Crop Adaptation Model: Predicted and Historic Crop Shares in Glenn County.**

| **Historic Crop Shares** | | | | | | |
|---|---|---|---|---|---|---|
| **Year** | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegitables** | **Fallow** |
| 1989 | 27.2% | 15.7% | 17.6% | 35.0% | 4.5% | 0.0% |
| 1990 | 28.6% | 15.7% | 17.0% | 31.9% | 4.3% | 2.1% |
| 1991 | 25.0% | 16.2% | 18.7% | 27.2% | 3.6% | 7.7% |
| 1992 | 24.5% | 17.2% | 18.0% | 32.3% | 2.7% | 4.4% |
| 1993 | 30.8% | 18.1% | 20.1% | 39.4% | 3.2% | -9.7% |
| **Predicted Crop Shares** | | | | | | |
| | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegitables** | **Fallow** |
| 1989 | 27.0% | 15.5% | 17.4% | 34.7% | 4.4% | 1.0% |
| 1990 | 27.1% | 15.8% | 17.0% | 34.3% | 4.5% | 1.3% |
| 1991 | 27.0% | 16.5% | 15.1% | 31.9% | 4.7% | 4.8% |
| 1992 | 27% | 16.5% | 14.4% | 30.8% | 4.7% | 7.0% |
| 1993 | 27% | 16.3% | 15.8% | 32.9% | 4.6% | 3.1% |
| **Estimation Error, Predicted Minus Historic Crop Shares** | | | | | | |
| | **Cereals** | **Orchard** | **Pasture** | **Rice** | **Vegitables** | **Fallow** |
| 1989 | -0.3% | -0.2% | -0.2% | -0.4% | 0.0% | 1.0% |
| 1990 | -1.5% | 0.1% | 0.1% | 2.4% | 0.2% | -0.8% |
| 1991 | 2.1% | 0.3% | -3.6% | 4.7% | 1.1% | -3.0% |
| 1992 | 2.1% | -0.7% | -3.6% | -1.5% | 2.0% | 2.6% |
| 1993 | -3.6% | -1.8% | -4.2% | -6.5% | 1.4% | 12.8% |



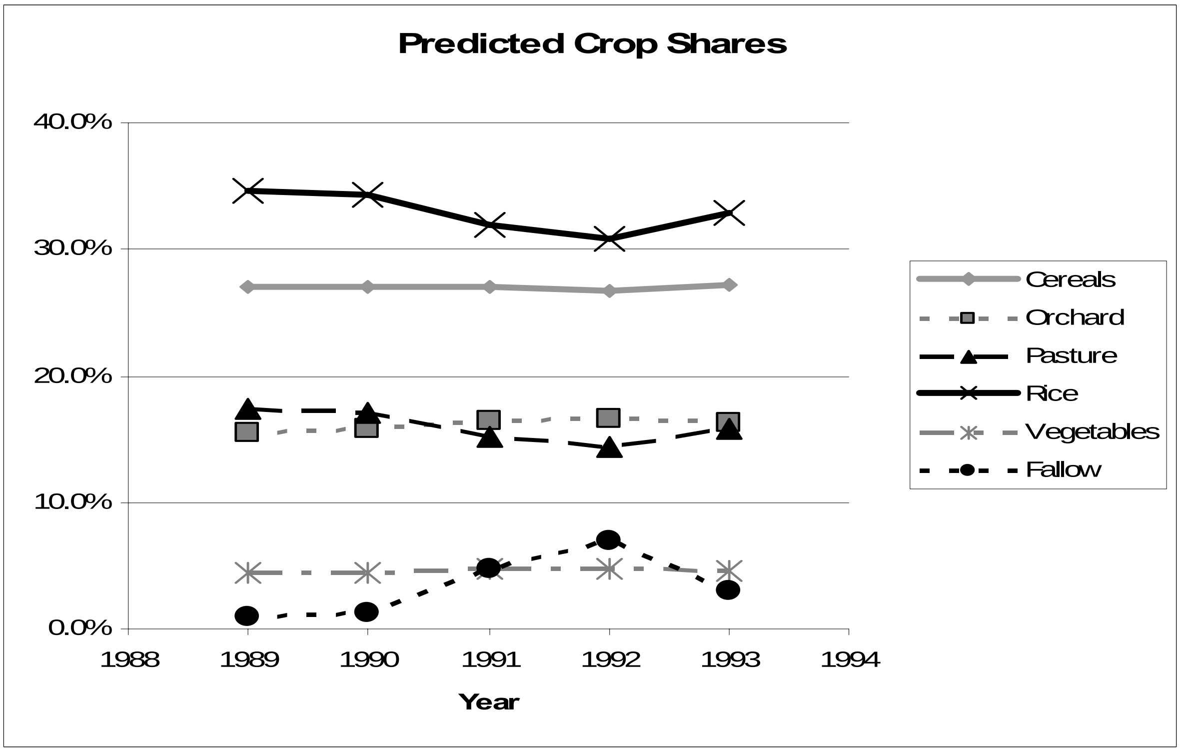




**Figure C-2. Historic and Predicted Crop Shares in Glenn County**

Crop share equations were developed to show changes in crop acreage and water use in the WEAP model over time. The share equations were developed from a multinomial logit analysis of simulated CVPM model crop share output. The equations were used to "backcast" historical crop trends in Colusa and Glenn Counties. The share equations predicted historical rice and fallow acreage trends during the drought with some accuracy, but delayed by one year. The "backcast" analysis suggests the equations provide a rough indication of crop shifts likely to accompany changes in water supply and groundwater depth in the Sacramento Valley.

### B.3.1. Estimating water supply for Sacramento Valley CVP contractors

Each spring the U.S. Bureau of Reclamation (USBR) and California Department of Water Resources (DWR) determine yearly allocations to CVP and SWP contractors based upon current storage in and forecasted inflows to their reservoirs (Shasta, Folsom, Clair Engel, and Oroville). CVP and SWP agricultural contractors are subject to reduced allocations each year, depending upon the anticipated amount of demand that their respective reservoirs can satisfy. CVP Settlement contractors, on the other hand, have their contracted water reduced only in years when the total annual inflow to Shasta is below 3.46 million acre-feet (MAF). In these dry (or Shasta critical) years, settlement contractors are guaranteed only 75 percent of their water contracts.

In order to adjust contract allocations within WEAP based upon water supplies, we must assess current reservoir storage conditions and estimate the expected inflows to reservoirs over the remainder of the water year. Reservoir storage levels can be easily read from previous time step results. Forecasted reservoir inflows, on the other hand, need to be calculated using other hydrologic indicators that the model has access to. For the purposes of this work, reservoir inflows for the period February through September are expressed as a function of the cumulative inflows for the period October through January.

Water supply conditions were estimated using reservoir storage and naturalized streamflow data obtained from the California Data Exchange Center (CDEC). Water supply for CVP settlement contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Shasta. Water supply for CVP agricultural contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Shasta, Folsom, and Clair Engel reservoirs. Finally, water supply for SWP contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Oroville. Figures C-3 through C-5 show cumulative reservoir inflows for the periods Oct-Jan and Feb-Sep for each of the groups of reservoirs used in calculating CVP and SWP water supplies. The regression equations shown were used in WEAP to estimate forecasted inflows. These forecasts were added to current project water storages to estimate the overall water supply for each project. Note that in each figure the water year 1997 was not included, because a large flooding event in January and a dry spring caused the data to be skewed.

Estimations of water supply were used as inputs to the logit regression equations developed to express changes in cropping patterns. For CVP and SWP agricultural contractors, water supplies were expressed relative to an average value (10,800 TAF for the CVP and 5,000 TAF for the SWP). For CVP settlement contractors, water supplies were reduced to 75 percent of full in years when inflows to Shasta were predicted to be below the Shasta critical criteria.

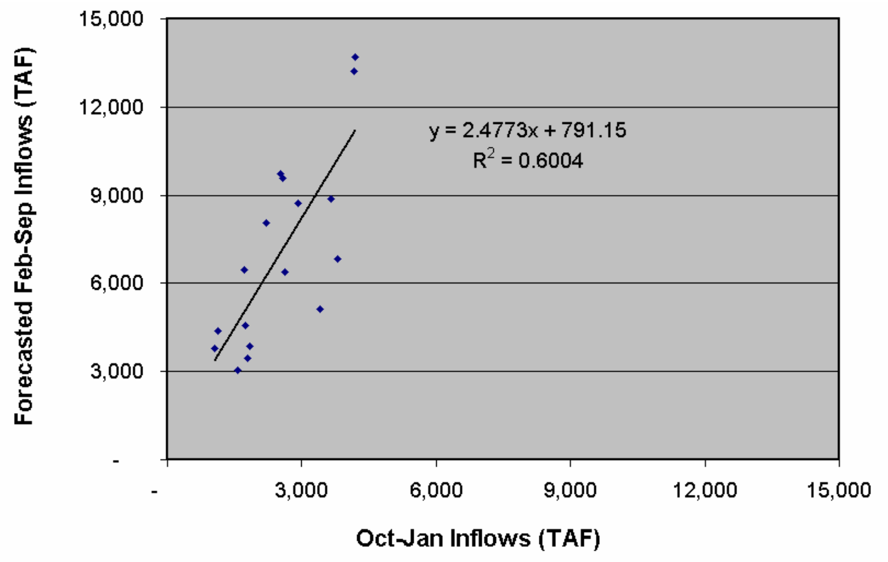
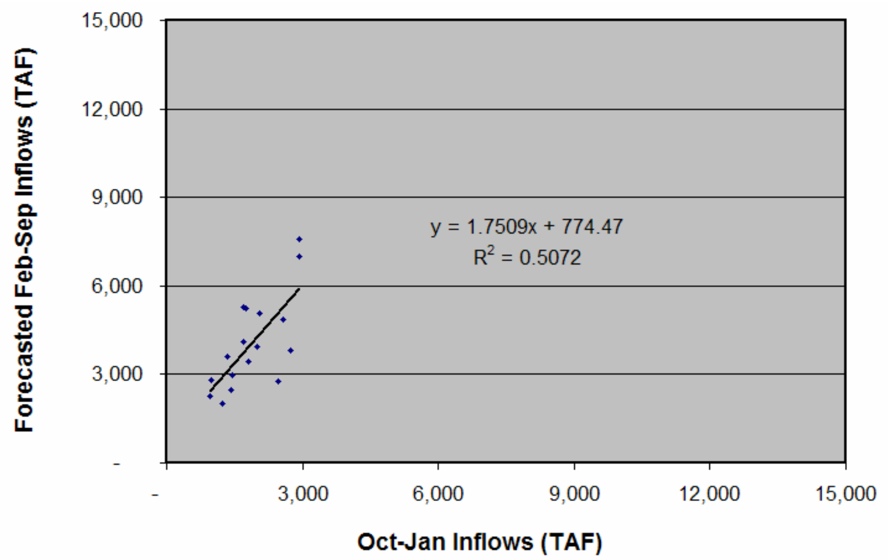



**Figure C-3. Total Inflow to Shasta, Folsom, and Clair Engel Reservoirs**




**FigureC-4. Total Inflow to Lake Shasta Reservoir**

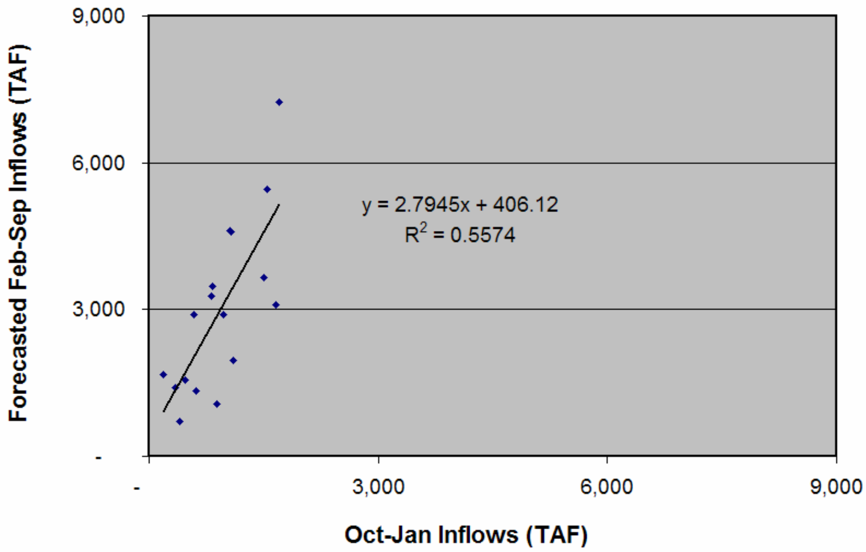



**Figure C-5. Total Inflow to Lake Oroville Reservoir**

### C.3.2. Economic Impacts on Agriculture

The economic impacts of different climate scenarios are estimated in WEAP from predicted changes to cropping patterns, crop revenues and crop production costs. The model predicts changes in cropping patterns and irrigation deliveries as described above. Changes in unit crop revenue and costs are estimated assuming current crop yield, revenue and production cost levels projected into the future.

The crop yield, revenue and production cost estimates in the model are taken from crop budgets, assembled by U.C. Cooperative Extension, and U.S.D.A. County Agricultural Commissioner yield and price data. Water costs are taken from unit pumping cost and surface delivery cost figures cited in the U.C. Extension crop budgets and other sources.

**Table C-4. Average net revenues for all users (2070-2099 for climate change conditions and 1962-1998 for historic conditions). (Figures in $10^6$ \$/year)**

| | Historic | Climate change scenarios with adaptation | | | |
|---|---|---|---|---|---|
| | | PCMB1 | PCMA2 | GFDLB1 | GFDLA2 |
| Farming net revenues (not including water costs) | 566 | 495 | 498 | 498 | 495 |
| Surface water deliveries costs | 10 | 8 | 8 | 8 | 8 |
| Pumping costs | 13 | 11 | 11 | 13 | 36 |
| Net revenues including water costs | **544** | **476** | **478** | **476** | **451** |
| *percent reduction* | | 12% | 12% | 12% | 17% |

This analysis provides a rough estimate of the decline in net revenue or farm profit resulting from climate change and decreased water supplies (Table C-4). All climate change scenarios show a reduction in net revenues, due primarily to increased land fallowing and shifts to water conserving crops. The decline is correlated with the predicted drop in water deliveries. For example, the model predicts that the PCM B1, PCM A2, and GFDL B1 scenarios, with moderate impacts on water deliveries, lower net revenue 12 percent. The model predicts that the GFDL A2 scenario, with a larger impact on water deliveries, lowers net revenue 17 percent.

**Appendix D- K-Nearest Neighbor (Yates et al. 2003)**

**(insert knn.pdf here)**