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Climate Change and Water Supply Reliability

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Preface

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

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

The work described in this report was conducted under the Preliminary Economic Analyses of Climate Change Impacts and Adaption and GHG Mitgation contract, contract number 500-02-004, Work Authorization MR-006 by the University of California, Berkeley.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-4628.

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Abstract

This research is part of a spectrum of studies of the California water system to assess impacts of climate change on urban and agricultural water agencies. This report describes preliminary work on methods for measuring current water supply reliability and methods for projecting changes in supply reliability caused by climate change, including: (1) a review of recent climate change literature in California; (2) a summary of criteria for evaluating water resource models; (3) an assessment of CALSIM-II water supply reliability forecasts and (4) an assessment of the accuracy of April-June flow forecasts performed by the California Department of Water Resources (DWR).

The literature review showed that climate change will affect Californian hydrology in several ways, including an earlier start of spring snowmelt, an increase in winter runoff as a fraction of total runoff, and an increase in winter flood frequency. The study's evaluation of three models used to estimate the water supply impacts of changing climate scenarios—CALSIM-II, CALVIN, and CVMod—revealed each model strengths and weaknesses. The CALSIM-II studies revealed differences in water supply reliability among user groups and showed that supply reliability at the aggregate basin level differs markedly from reliability at the levels of Depletion Study Area (DSA) and other sub groups within basins. Additionally, the distribution of reliability is different between annual and monthly terms. Finally, analysis of DWR data showed a positive correlation between forecast accuracy and watershed elevation, and showed wet year forecasts to be significantly more accurate than dry year forecasts. This finding implies a strong correlation between snowpack and ability to predict streamflow, and thus a reduction in forecast reliability under most climate change scenarios.

Executive Summary

Climate change in California is a source of growing concern, and its impacts on the state's agricultural industry and economy are potentially significant. Major consequences are likely to be manifested through the state's water system. This project's objective is to assess the economic costs associated with potential changes in the reliability of water supply for users in various parts of the state. Previous research on water use in California has generally used data gathered from broad geographic aggregates. This research differs in that researchers gathered and analyzed data from individual water districts—which is necessary, because there is considerable heterogeneity among water districts in California with regard to source of water, nature and age of water rights, cost of operations, finances, price structures, and other terms of service. Also, unlike previous studies, this project focused specifically on measuring water supply reliability and the uncertainty that confronts water users at the time of the year when they need to make major decisions about water use. This approach was used because climate change is likely to affect these users primarily through its impact on supply reliability and uncertainty.

Important judgments about water use, such as crop choice or predicting the degree of water shortage, are made at the beginning of the high usage period (typically April) by both farmers and urban water managers, creating an inherent uncertainty in the decision process. Much of the water use that occurs in California between April and September is likely to be determined by expectations about the amount of water that will be available during the coming summer. Most of the existing hydrologic/economic models represent water supply through historical monthly deliveries, which represents the *ex post* outcome and obscures—and ultimately ignores—the underlying *ex ante* uncertainty. The timing of water use decisions by most agricultural and urban water agencies in California is such that the ex ante probability of obtaining water during the warm season has a large impact on these decisions.

To assess the impacts that climate change in California is likely to produce, with regard to the existing mismatches between both where and when rains falls and where and when people need to use water, researchers are conducting a broad spectrum of studies of the California water system. These studies include six main components: (1) determining the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state; (2) conducting an econometric analysis to measure the economic consequences of differences in supply reliability, which will ultimately be used to develop economic loss functions for changes in agricultural water supply reliability due to climate change; (3) conducting an econometric analysis based on cross-section and time-series data on urban water use in California to estimate demand functions for water, which will determine the demand elasticities that we will use to project future urban water demand in areas of new urban growth in California; (4) projecting future agricultural and urban water demand and supply in California in the absence of climate change; (5) assessing how climate variability and change will impact the reliability of water supply for urban and agricultural water agencies in California by evaluating alternative models to estimate the impact of climate change on water supply; and (6) assessing the economic consequences of the future changes in supply reliability for urban and agricultural water users in California due to climate change. The research reported here focuses on the first and fifth of these components.

The existing literature suggests that global warming is likely to have significant impacts on the hydrological cycle, which in turn will affect many aspects of the California water system. There is evidence that some changes have already occurred, such as an earlier beginning date of spring snowmelt, an increase in winter runoff as a fraction of total runoff, and an increase in winter flooding frequency. Depending on the model implemented, total runoff is expected to change, with the most significant impact from global warming on river basins located in medium altitudes. Other studies have suggested that shifts in runoff without accompanying operational changes will challenge the systems and perhaps reduce the reliability of the systems to meet current demands. Ultimately, the impact on California water resources will depend on the ability of human management system and infrastructure to cope with these changes.

To effectively assess these impacts, a water resources model is needed that represents the operation of the California water system. This model will use runoff derived from climate change impact studies of Central Valley hydrology to estimate water supply throughout the systems. The model needs to adopt a descriptive, rather than prescriptive, approach; it needs to provide hydrologic flexibility; and it should offer a good representation of the system in terms of comprehensiveness of coverage, spatial resolution, and validity in the characterization of operation policies and constraints. To date, researchers have analyzed three models: CALVIN, CALSIM-II, and CVMod. In addition, they have studied the RiverWare modeling system developed at the University of Colorado. At present, none of these models fully meets these criteria. The CALVIN model is prescriptive, rather than descriptive. CALSIM-II is a descriptive model with good representation of the system in terms of coverage, spatial resolution, and current operation rules. Its major fault is its inability to be run using a sequence of hydrologic inputs not strictly related to the 73 years of historical hydrologic data for which the model is validated. Also, CALSIM-II is non-uniform in terms of how water delivery settings for different geographic areas. CVMod is another good descriptive model, and can be run with any hydrologic inputs. CVMod's weakness is that some of the operations rules—and hence, the results—of using these models are far from how the system is actually run. At this point, there is no single model fully suitable for our purposes.

Using the results from the most recent runs of CALSIM-II, the Benchmark Simulation Runs, researchers found that: (1) water supply reliability is not the same among different water users in the Central Valley; (2) the distribution of reliability in *annual* terms is different than the distribution of reliability in *monthly* terms (they are quite similar when the overall measure of reliability is compared as deficits in supply are concentrated in only *certain months* in the year); (3) different project contractors have different reliabilities of water supply according to their water rights status; (4) the annual reliability curve for non-project users show that water supplies are mostly constant throughout the 73 years of different hydrologic conditions; and (5) and there are large differences in terms of reliability for different East San Joaquin users.

The report's final section discusses measurement of the *ex ante* uncertainty in water deliveries. The goal of this research on the accuracy of DWR water delivery forecasts is to measure the error bands that might be placed around these forecasts. The forecasts of water deliveries and streamflows, published weekly by the DWR from February through June, are likely to be a crucial input to water district managers' expectations regarding their warm-season water supplies, even considering their likeliness to contain some degree of error. This research determined that forecast accuracy not only improves over time as the period between the forecast date and delivery shortens, but it also seems to improve with watershed elevation; higher watersheds tend to have more accurate forecasts than lower watersheds. This correlation may be related to the dominance of snowmelt in the annual hydrograph of higher watersheds. If so, reduction of the snowpack due to climate change can have a substantial impact on future forecast reliability.

Researchers designated some areas of interest for future research, including:

- the accuracy of forecasts for higher elevation watersheds,
- the statistical correlation between snowpack and forecast accuracy,
- the difference in the range of forecasts between higher elevation watersheds and lower elevation watersheds,
- the faster and more uniform convergence of forecasts for higher elevation watersheds as compared to those for lower elevation watersheds, and
- the discrepancy in the 50% exceedance forecasts, which show that these forecasts tend to slightly underestimate actual deliveries for higher elevation watersheds and overestimate deliveries for lower elevation watersheds.

1. Introduction

A major pathway by which climate change will affect the California economy is through its impact on the California water system. Therefore, an economic analysis of the costs associated with changes in the reliability of supply for water users in various parts of the state forms a major component of the research being conducted at the University of California, Berkeley.

Compared to previous research, the approach we have adopted for measuring the economic impacts of climate change has two distinctive features.

First, our primary spatial unit of analysis is the service areas of individual retail water supply agencies—irrigation districts and urban water agencies—as opposed to broader geographic units such as depletion analysis areas. To the extent possible, our analysis will be disaggregated to the level of the individual water district. We wish to avoid any further aggregation because of the tremendous heterogeneity among different water districts even within the same county with respect to source of water, nature and age of their water rights, costs of operation, finances, prices charged to retail customers, and other aspects of their terms of service. Because of this diversity, aggregation is likely to be misleading and to introduce error into the analysis.

Second, unlike previous studies, we are focusing explicitly on supply *reliability* and the *uncertainty* over supply that confronts water users around the state at the time when they make important decisions regarding water use. We seek to measure these explicitly, both in the baseline situation and in climate change scenarios. We are doing this because we believe that climate change in California is likely to affect water users primarily through its impact on supply reliability and uncertainty. This has not been analyzed in the existing work on climate change in California.

In this context, it is important to note the uneven temporal distribution of water supply and water use in California: roughly 80% of the state's precipitation falls between October and March, but about three quarters of all water use in California occurs between April and September. What happens—or does not happen—during the water use period governs whether the state's economy is benefited or harmed by water supply that year. Moreover, many important decisions that determine water use during this period are made *at the beginning* of the period. Farmers decide which crops to plant (and whether or not to replace perennials) in the early spring, around March or early April. Once they have made that decision, they have limited ability to vary their use of water during the growing season: they can under-water their crops, or even abandon them, if they subsequently receive less water than they had anticipated at the time of planting, but they cannot switch to a different crop, nor is it practical to make major changes in irrigation technology during the growing season. With urban water use, the context is somewhat different but there is still a critical decision-making window around April. If urban water managers think there is a fair chance that they will experience some degree of water shortage during the coming warm season, they generally need to put out a call for voluntary (or mandatory) conservation by no later than the end of spring. This sets up a pattern of water demand for the summer that is likely to be, at best, only partially reversible if water supplies turn out to be more abundant than originally anticipated. For somewhat similar reasons, environmental water managers in California also face a key decision point around April: because of the time lags in securing water supplies and arranging for their transfer, if managers are to meet critical in-stream needs during the warm season they will need to take action by the end of spring. For these reasons, much of the water use that occurs in California between April and September is likely to be determined by water agencies' *expectation*s, as of the beginning of this period, regarding the amount of water that will become available to them during the coming summer. Supply reliability needs to be assessed with regard to these expectations.

Most of the existing hydrologic/economic models—both in California and elsewhere—deal with supply uncertainty by ignoring it. They represent water supply using the actual, historical monthly deliveries. This amounts to characterizing uncertainty by the *ex post* realization of the random variable, which effectively eliminates the uncertainty. However, as explained above, given the timing of water use decisions in California it is clearly the *ex ante* probability of obtaining water during the warm season (late spring and summer), as assessed some time around March or April, that has the most powerful influence on water users' decisions in California. Furthermore, it is reasonable to expect that these decisions will typically exhibit a significant degree of *risk aversion*. The important implication is that water use decisions are likely to depend not just on the mean of the *ex ante* probability distribution of warm-season water supply but also on other parameters of the distribution such as the semi-variance or the tail probabilities. In order to develop a linkage between changes in supply reliability and consequent economic impacts, one has to characterize supply reliability in terms of relevant parameters of the *ex ante* probability distribution of warm-season water supply. Given the observations above about the heterogeneity among water districts with regard to their water supply, these distributions generally need to be assessed for each district separately.

Implementing our approach, with its novel focus on measuring supply reliability at the level of individual water districts, is a major challenge because of the limitations in the data that are readily available in California. It is easy to obtain data on historical water deliveries for the two big projects (the Central Valley Project (CVP) and the State Water Project (SWP)) and for groups of irrigation districts combined into Depletion Study Areas (DSAs). Obtaining historical flow data for individual districts not served by the two projects is often difficult. Obtaining a representation of the likely expectations of district managers in the form of an *ex ante* probability distribution is a major research task that has not previously been undertaken in California.

To deal with problems caused by the limited availability of data, we are pursuing a flexible and iterative strategy. Under this approach, we iterate between data collection and data analysis. In our first year of research, we started by collecting the most readily available data and then conducted a preliminary analysis of these data. This was carried out to address as early as possible the many methodological issues that arise during the course of data analysis. While conducting the preliminary data analysis, we continue to work on expanding and filling in the dataset. After a second round of data collection, we will extend the preliminary data analysis, while continuing to complete the data collection, with a view to final data analysis. Thus, rather than working in sequence, we are conducting the various components of our analysis in parallel.

In California, climate change is likely to severely exacerbate the existing mismatch between where and when rain falls and where and when people need to use water. To assess these impacts, we are conducting a broad suite of studies on various aspects on the California water system. The overall research involves six main components:

> (1) Measure the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state, given their various sources of water supply and their water rights or water contract entitlements. To accomplish this task, we identify specific water users (agricultural and urban) who will be the focus of the study, and assemble a database of information on their water supply (e.g., contractual water entitlements, water rights, other sources of supply, within-district storage); their water demand (e.g., cropping pattern, population, number of industrial, commercial and residential customers); and the economic value of water to their customers (e.g., water costs and pricing, crop prices, other input prices, farmland values).
>
> (2) Conduct an econometric analysis based on cross-section and time-series data of the relationships between supply reliability and economic outcomes for irrigation districts in California, including consideration of agricultural practices, choice of crops, farm profit, and land values. These relationships measure the economic consequences of differences in supply reliability, and will be used to develop economic loss functions for changes in agricultural water supply reliability.
>
> (3) Conduct an econometric analysis based on cross-section and time series data on urban water use to estimate demand functions for water, for the use of urban water agencies in California. The resulting short- and long-run price elasticities of demand will be used to develop short- and long-run loss functions for shortages in urban water supply. The demand elasticities with respect to conservation variables will be used to assess the future potential for reducing urban demand via conservation. Finally, the demand elasticities with respect to climate variables, housing density, and housing vintage will be used to project future urban water demand in areas of new urban growth in California.
>
> (4) Project future agricultural and urban water demand and supply in California in the absence of climate change, based on economic and demographic scenarios as well as projections of land use conversion and patterns of future urban growth

in California. This analysis will incorporate results from the econometric analyses conducted in (2) and (3).

(5) Assess how climate variability and change will impact the reliability of water supply—the *ex ante* probability distributions—for urban and agricultural water agencies in California. In this task, we evaluate alternative models to estimate the impact of climate change on water supply and the factors that determine runoff forecasting and how they relate to climate inputs (e.g., how the amount of water stored in the snowpack affects the accuracy in forecasting).

(6) Assess the economic consequences of the future changes in supply reliability for urban and agricultural water users in California identified in (5) when applied to the future scenarios developed in (4), using the economic loss functions developed in (2) and (3).

The research conducted during our first year has focused on (1), (2), and (3). In addition, we have started to employ the results of the recent paper in the Proceedings of the National Academy of Sciences dealing with the effects of climate change on California hydrology as preparation for performing (5). We are also beginning to carry out (4) and (5), specifically looking at the different water resources models available for California that would be needed to assess future hydrologic conditions, and at streamflow forecast accuracy.

The research described here has four components:

1. a short review of California's water resources climate-change-related literature,
2. an overview of the ongoing process to choose the most appropriate water resources model to be used in tasks (4) and (5) as just described
3. an assessment of historical water supply reliability in California performed using CALSIM-II, and
4. an analysis of DWR flow forecasts.

2. Review of Climate Change Literature in California[1]

The latest 2001 Intergovernmental Panel on Climate Change (IPCC) report reaffirms that the climate is changing in ways that cannot be accounted for by natural variability and that "global warming" is occurring (IPCC, 2001). The IPCC reports that climate model projections with a transient 1% annual increase in greenhouse gas (GHG) emissions show an increase in the global mean near-surface air temperature. The temperature increase ranges from 1.4°C to 5.8°C, with a 90% probability interval of +1.5°C to +4.5ºC by 2100 (Wigley and Raper, 2001).

This global warming is likely to have significant impacts on the hydrological cycle, affecting many water resources systems (IPCC, 2001; Arnell, 1999). California water resources, especially, are expected to suffer from the effects of global warming. Moreover, there is evidence that some change has already occurred: increasing temperatures have changed the runoff pattern of several watersheds of the Sierra Nevada. The trend is toward increasing runoff in the winter season and less in the spring-summer season (Dettinger and Cayan, 1995). There have been a number of investigations of California hydrologic response focused on changes in streamflow due to climate change as Miller et al. (2003) pointed out in a summary of the first works in this subject. Again, as the historical record already indicates, these studies suggest that Sierra Nevada snowmelt-driven streamflows are likely to peak earlier in the season under global warming, as a result of increased atmospheric GHG concentrations.

The most recent work studying the effects of climate change on California hydrology was done by groups at the Lawrence Berkeley National Laboratories (LBNL) (Miller et al (2003), the Scripps Institution of Oceanography (Stewart et al., 2004; Dettinger et al., 2004) and the University of Washington (VanRheenen et al., 2004). Although these studies used different Global Circulation Models (GCM) and different methodologies for downscaling the GCM results to derive regional hydrologic changes (see Table 2-1), their results consistently show that climate change will impact Californian hydrology via:

- An earlier start of spring snowmelt
- An increase in winter runoff as a fraction of total runoff
- An increase in winter flood frequency
- Various changes in total runoff, depending on the GCM used. There are the two GCMs used in these studies: the PCM (Parallel Climate Model) and HadCM2. (Hadley model). The former generates results that are cooler and drier than the latter.

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[1] With special emphasis on the use of water resources models

- Varying results by basin, with the key parameter being basin elevation relative to the freezing line location during snow accumulation and melt periods. Basins located at medium altitudes will be most affected by climate change.

Table 2-1. Summary of some recent studies on climate change impacts on California hydrology

	LBNL (1)	*SCRIPPS-USGS (2)*	*U. of Washington (3)*
GCM used and GHG emission scenario	Two GCMs: A warm wet HadCM2 (run 1) and a cool dry PCM (run B06.06).	PCM with a business as usual (BAU) emission scenario (run B06.44), plus some control runs.	PCM with: 3 BAU scenarios with different initializations; a control (CO_2 at 1995 level); and a historical (CO_2 at pre-industrial level) run.
Downscaling method	Statistical downscaling plus Sacramento and Anderson Snow hydrological models for 6 basins distributed along the Sierra Nevada: Feather, Kings, American, Merced, Sacramento, and Smith.	Two methods: A statistical downscaling, plus a Precipitation–Runoff Modeling System for three basins: Merced, American, and Carson; and a regression analysis for snowmelt timing and Temperature and Precipitation Index (TI and PI).	Statistical downscaling, plus Variable Infiltration Capacity (VIC) model for a set of basins in the Sacramento River System and the San Joaquin River system.

Sources:

(1) Miller et al. (2003)

(2) Dettinger et al. (2004); Stewart et al. (2004)

(3) VanRheenan et al. (2004)

Most of the streamflow in the Sierra Nevada is regulated by large reservoirs. Changes in the streamflow that feeds these reservoirs will change their ability to serve all the functions for which they are designed: flood control, water supply, hydropower generation, navigation, and recreation. Reservoirs provide flood control during the wet winter season, when they have flood space requirements. These flood requirements limit the amount of water stored during the wet season. However, a substantial amount of winter precipitation is stored in the snowpack in the Sierra Nevada. During the spring (late March, April, and May), flood control requirements are eased, and the reservoirs fill from spring snowmelt. Reservoirs are operated through the year using rule curves that represent the desired storage levels according to these flood-space filling requirements. These rule curves have been derived from historical hydrologic conditions, and hence will not be reliable in the event of a change from the historical hydrology. The hydrology expected as a result of climate change includes an earlier and smaller spring runoff. This would make it more difficult to refill reservoir flood space during the late spring and early summer, thus reducing the amount of water supply that can be delivered (Roos, 2003).

The ultimate impact on California water resources will depend on the ability of the man-made infrastructure to cope with these changes. The performance of the California water system under climate change scenarios was first studied by Lettenmaier and Sheer (1991) and separately by Sandberg and Manza (1991), who examined the implications of climate change scenarios for the performance of the State Water Project and the Central Valley Project. According to a review by Gleick and Chalecki (1999), "both studies concluded that the shifts in runoff without accompanying operational changes will challenge the systems and perhaps reduce the reliability with which the systems could meet current demands." More recently there have been four studies on the impacts of climate change on California water resources. The following is a brief description of these works.

2.1 Lund et al. (2003), University of California, Davis

The first of these studies was performed by Lund et al. (2003) at the University of California, Davis as part of the PIER Research Program of the California Energy Commission (Energy Commission). Lund et al. (2003) used the results of the hydrologic modeling performed by Miller et al. (2001) as inputs for the CALVIN statewide water resources optimization model,[2] assuming that: (1) all changes in dry season inflows directly affect water deliveries (because water is most easily managed during the dry season); (2) increases in wet season surface inflows are lost because of low water demand and low surface storage flexibility resulting from flood control;[3] and (3) no new infrastructure is constructed. Lund et al. (2003) estimated the economic impacts of climate change for two GCM results: HadCM and PCM. These impacts are expressed in

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[2] See Appendix B for a description of CALVIN and other water resources models for California.

[3] Water available throughout the region was obtained by extrapolating the results for the six basins considered in Miller et al. (2001) to each of the rim flows considered in CALVIN, taking into account the constraints in reservoir operations just described. Groundwater supplies were also considered. The CALVIN model is an economic-engineering driven optimization model developed at the University of California, Davis that has 37 inflows into the Central Valley from the surrounding mountains, which are called *rim inflows*. Historically, these rim inflows average 28.2 million acre-feet per year (maf/yr), accounting for 72% of all inflows into CALVIN's California intertied water system (Lund et al., 2003).

terms of the outage (scarcity) costs under the assumption of optimal allocation of water among regions and user types in the year 2100, using an estimate of the statewide population expected at that time. The results, summarized in Table 2-2, show that the impact of climate change on urban users is comparatively small, while that on agricultural users is much larger. This situation comes about as a result of extensive water transfers that are assumed to occur on a month-by-month basis with perfect foresight, with no institutional constraints. Population growth is projected to have a much greater effect on urban water use than does climate change, because the model assumes that urban areas can purchase much of the water they need from agricultural areas under unfavorable climates. However, the effect of climate change on agriculture water deliveries is greater than the effect of population growth, especially for the dry climate change scenario (i.e., PCM) (Lund, et al. 2003).

Table 2-2. Statewide scarcity costs for different climate change scenarios (million $/yr)

Cost	SWM2100[1]	PCM2100[2]	HadCM2100[3]
Urban Scarcity Costs	785	872	782
Agric. Scarcity Costs	198	1,774	180
Total Scarcity Costs	983	2,646	962

Source: Lund et al., 2003.

Notes:

[1] Optimized model for year 2100 without changes in water availability; scarcity costs mainly account for increasing demand

[2] Optimized model for year 2100 with water deliveries decreasing according to results of PCM scenarios

[3] Optimized model for year 2100 with water deliveries decreasing according to results of HadCM2 scenarios

2.2 VanRheenen et al. (2004), University of Washington

VanRheenen et al. (2004) also analyzed the impacts of climate change on Californian water resources. This group used their own runoff estimates as inputs for CVMod (see Table 2-1 for a description of their study parameters). CVMod is a monthly time step, water resources simulation model that incorporates the major projects and operational features of the Sacramento-San Joaquin basin. It was used to explore system performance and reliability given various operating policies and alternative climate and operating scenarios. Under the climate change scenario, the model depicted a decrease in inflows North and South of the Sacramento-San Joaquin Delta ("the Delta"), as well as a decrease in storage levels in reservoirs in both regions (see Figure 2-1). These decreases in available water affected hydropower production and the reliability of fish and other environmental targets. A series of mitigation strategies (e.g., changes in the rule curves of reservoir releases) were considered, but even with the most comprehensive mitigation strategy "achieving and maintaining status quo system performance in the future would be nearly impossible, given the altered climate (change) scenario hydrologies."

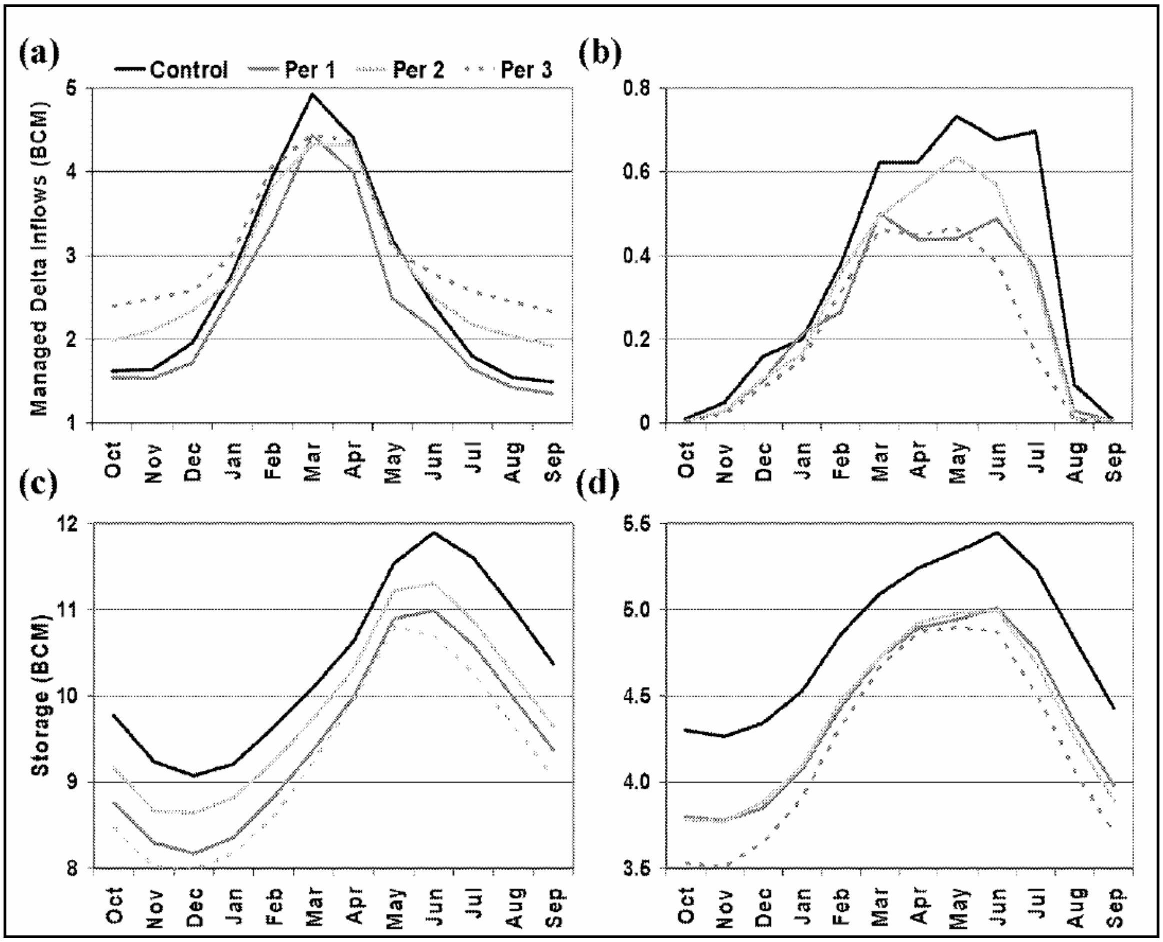


Figure 2-1. CVMod Predicted 2000–2098 mean monthly-regulated Delta inflows and Sacramento and San Joaquin total storages given current operating rules and year 2001 demands and hydrologic development.

Notes: (a) Regulated flows at the mouth of the Sacramento River and (b) at the mouth of the San Joaquin River; (c) total reservoir storage north of the Delta (i.e., Sacramento River System) and (d) south of the Delta (i.e., San Joaquin River System). The future scenario results (for the period 2000–2098) are partitioned into three 30-year periods, termed Periods 1, 2, and 3, respectively: 2010–2039, 2040–2069, and 2070–2098. Source: VanRheenen et al. (2004).

2.3 Brekke et al. (2004), University of California, Berkeley - LBNL

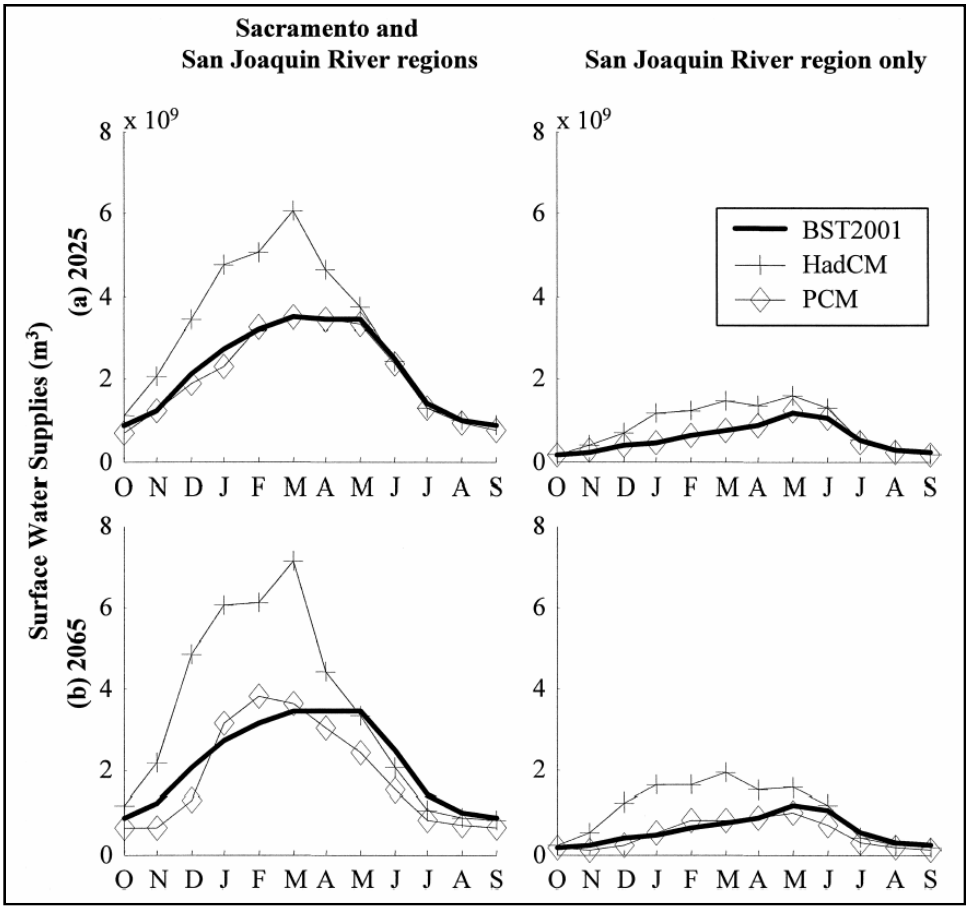
A third study was performed by researchers at the University of California, Berkeley, and the Lawrence Berkeley National Laboratories (Brekke et al., 2004). In this work, Brekke et al. used the runoff results derived by Miller et al. (2001) for two global projections of GHG increase (PCM and HadCM2) to derive mean monthly streamflow changes that were mapped onto 72 years of historical monthly reservoir inflows in the San Joaquin River region of California. Impacts downstream of the reservoirs were simulated using the California Water System Simulation Model (CALSIM) II 2001 Benchmark Study, which was developed by the California DWR in collaboration with the U.S. Bureau of Reclamation Mid-Pacific Region office. The results (shown in Figure 2-2) show a great dependence on the GCM used to derive runoffs. The HadCM2 model projects faster warming than the PCM model. The HadCM2 and PCM models project wetter and drier conditions, respectively, relative to present climate. In the HadCM2 case, there would be increased reservoir inflows, increased storage limited by existing capacity, and increased releases for deliveries and river flows. In the PCM case, there would be decreased reservoir inflows, decreased storage and releases, and decreased deliveries. The divergence in the results (both equally probable), are attributable to the divergence in the precipitation projections of the GCM models, as was mentioned before.

2.4 Yao and Georgakakos (2001)

The fourth study differs from the previous ones in that instead of looking at the climate change impacts of the California system as a whole, it focuses on just one reservoir—Folsom Lake on the American River. Yao and Georgakakos (2001) developed an integrated forecast-decision system for this study and used it to assess the sensitivity of reservoir performance to various forecast-management schemes under historical and future climate scenarios. The assessments are based on various combinations of inflow forecasting models, decision rules, and climate scenarios.

The climate scenarios are based on historical and potential inflow realizations generated by the Canadian GCM, assuming either no increase in CO_2 concentrations (control scenario) or a 1% annual increases of CO_2 concentrations. The results from this GCM (Carpenter and Georgakakos 2001) under the 1% CO_2 increase suggest that Central California will experience wetter and more variable climate. Table 2-3 summarizes the results of this paper. The results in this Table show that:

- A 1% increase in CO_2 concentrations will imply an increase in Folsom's energy generation and revenue of 20%–24%, spillage would increase by 65%–80% and flood damage would in some cases, increase by more than 4.3 billion dollars.
- Operating Folsom Lake under a combination of improved forecasting models and adaptive decision systems could effectively mitigate the effects of climate change and even improve reservoir response.



Note: BST stands for current climate CALSIM-II 2001 Benchmark Studies

Figure 2-2. CALSIM-II Simulated Surface Water Supplies for the Combine Sacramento and San Joaquin River Regions, and for the San Joaquin region only: (a) 2025 and (b) 2065

Table 2-3. Folsom Lake operation's assessments for future climate scenarios

Decision-forecast scheme	Reliability	Energy (GWh)	Energy value (million $)	Spillage (billion cubic feet)	Min. flow violations (days)	Max. flood damage (million $)
Future climate (control CO_2)						
Rule Curve						
Analog ESP	Deterministic	610.5	55.67	16.85	0	0
Perfect forecasts	Deterministic	610.72	55.69	16.83	0	0
DSS						
Hydrologic ESP	50%	654	59.4	16.436	0	0
	90%	678.878	61.595	10.368	0	0
GCM-Cond. ESP	50%	654.474	59.455	15.978	0	0
	90%	675.121	61.21	9.585	0	0
Analog ESP	50%	651.72	59.249	16.821	0	0
	90%	679.192	61.547	8.766	0	0
Perfect forecasts	Deterministic	706.256	64.15	7.789	0	0
Future climate (1% annual CO_2 increase)						
Rule Curve						
Analog ESP	Deterministic	745.24	67.87	27.98	0	0
Perfect forecasts	Deterministic	745.56	67.9	27.98	0	0
DSS						
Hydrologic ESP	50%	788.26	71.56	28.67	0	4275.2
	90%	839.48	76.08	18.06	0	219.9
GCM-Cond. ESP	50%	797.83	72.4	26.78	0	4275.2
	90%	833.78	75.54	17.87	0	841.44
Analog ESP	50%	786.41	71.43	29.22	0	4275.2
	90%	846.23	76.68	16.83	0	0
Perfect forecasts	Deterministic	868.92	78.77	15.09	0	0

Note: The results in this table were obtained using both heuristic rule curves and Folsom Decision Support System (DSS) and various forecast schemes including operational forecasts, analog Extended Streamflow Prediction (ESP), hydrologic ESP, GCM-conditioned ESP, and perfect forecasts. The reliability parameter indicates the type of forecast information utilized by the decision system. The "deterministic" and "50%" indications imply the use of a single sequence. For the ESP schemes, this sequence corresponds to the median trace. The "90%" indication implies the use of the full forecast ensemble and a probabilistic tolerance threshold of 90% for the reservoir level constraints. For a full definition of the decision tools and forecast models, refer to Yao and Georgakakos (2001).

3. Choosing a Water Resources Model for Climate Change Studies in California

3.1 Introduction: The need of a water resources model and objectives for this research task

The analysis of the performance the California water system under hypothetical hydrologic scenarios like the ones associated with climate change requires the aid of water resources models, also called *reservoir system analysis models*.[4] For this project in particular, there is a need for a water resources model that can be used to estimate both the existing reliability of supply for different users in the Central Valley, and how this might change under various climate-change scenarios. This reliability of supply is defined by the tail quantiles of a probability distribution where the random variable can be expressed in several ways, including the absolute quantity delivered or the ratio of the quantity delivered to some standard such as contract entitlement or the evapotranspiration requirements of crops typically grown in the area. We can employ historical data to assess what has happened in the past, but to assess what might happen in the future we need a water resources model representing the operation of the California water system. This model will use the runoff values derived from climate change impact studies on the Central Valley hydrology to estimate water supplies throughout the system. At a minimum, this model should have the following features:

- Descriptive, not prescriptive basis. There is a need for a model that will tell us how the system behaves under current operation policies, not how it ought to behave. Optimization can enter the analysis once we understand well how the system actually operates.
- Hydrologic flexibility. The model should run with any sequence of hydrologic conditions and not be bounded by any historical period hydrologic conditions.
- Good representation of the system in terms of coverage (including most of the main agricultural areas), spatial resolution (i.e., it should be possible to distinguish users with different set of water supply conditions, such as different water districts), and incorporation of current operation policies and constraints.

The following section presents a comparison of three currently available models that were analyzed for this research task.

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[4] There are several alternatives for these models. They can be mere descriptors of the water system that they represent (*descriptive models*), or they can prescribe the best rules by which a system should be operated (*prescriptive models*). They also may or may not have mathematical programming tools implemented. In Appendix A, there is a brief description of the differences between water resources models that could be used as a framework for the next section.

3.2 Comparison of water resources models available for California: CALSIM, CALVIN and CVMod

Models of the California water resources complex system have been developed by the U.S. Bureau of Reclamation (USBR), the California Department of Water Resources (DWR), and academic communities. The most prominent earlier attempts are the USBR's Project Simulation Model (PROSIM) and the DWR's Simulation Model (DWRSIM). Both were *descriptive* models that simulated the operations of the Central Valley Project (CVP) and State Water Project (SWP)—the major water projects in California. PROSIM was a traditional water balance approach with a monthly time step, to simulate a system represented by 50 nodes, including 11 reservoirs. Monthly streamflow data is input at 24 of the nodes for a 57-year (1922–1978) simulation period (Wurbs, 1996 and Sandberg and Manza, 1991). In comparison, DWRSIM evolved from a HEC-3, a U.S. Army Corp of Engineers (USACE) simulation model. It is a network flow programming model with a mathematical algorithm that assigns relative priorities to different demand points, and allocated storage within a reservoir to those demands, providing a better balance among the reservoirs in the system (Chung et al., 1989; Wurbs, 1996). More recently, three models of the California water system have been developed. These models are:[5] (1) CALSIM-II developed jointly by DWR and U.S. Bureau of Reclamation; (2) CALVIN developed at UC Davis; and (3) CVMod developed at the University of Washington. Appendix B presents a brief description of these three models. Table 3-1 compares the major features of these models.

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[5] Models not included in this analysis but that will be included in future steps are: the Natural Heritage Institute Water Evaluation and Planning (WEAP) model developed by David Purkey, the HEC-5 reservoir model developed by the U.S. Army Corps of Engineers for the flood control Sacramento and San Joaquin River Basins Comprehensive Study, and the CVP/SWP screening model implemented with OASIS (Meyer et al. 1999).

Table 3-1. Comparison between three water resources models for California (1)

	CALSIM-II	*CALVIN*	*CVMod*
Basic categorization	Descriptive Simulation with mathematical programming algorithm.	Prescriptive Optimization.	Descriptive Simulation without mathematical programming algorithm.
System Representation			
Coverage	All Central Valley plus SWP-CVP contractors in the San Francisco Bay, the Tulare Basin, and Southern California.	The same as CALSIM-II plus Colorado River, all the Tulare Basin and Mono Lake and Owens Valley.	Same as in CALSIM-II.
Demand Representation	Sacramento Valley: Demands are based on land-use and specified irrigation efficiencies for project and non-project users. Resolution is at the DSA(2) level with some specific ID(3) identified.(4) East San Joaquin: Demands are based on time-series of values for certain identified ID(5) SWP contractors south of the Delta: Time-series of values for each contractor CVP contractors south of the Delta: Time-series of values for groups of contractors	Agricultural demands are calculated with the Statewide Water and Agricultural Production Model (SWAP) based on land-use and irrigation efficiencies for different crops. The model includes 21 regions in the Central Valley and four regions in Southern California. Specific users are lumped into these regions. Urban demands are estimated separately and the model considers specific demand nodes for these.	Demands are time-series values obtained from CALSIM-II input files. However, there are the following differences with CALSIM-II values. Sacramento Valley: Demands are based only on project users' contracts. There's no representation of non-project users. East San Joaquin: Some specific users in CALSIM-II are lumped together in CVMod SWP contractors south of the Delta: Contractors are lumped together CVP contractors south of the Delta: Contractors are lumped together

Table 3-1. (continued)

	CALSIM-II	*CALVIN*	*CVMod*
Groundwater consideration	There is a representation of both groundwater pumping and groundwater-stream interaction. This representation is based on the results of CVGSM an integrated surface and groundwater model of the Central Valley.(6)	There is a representation of both groundwater pumping and groundwater-stream interaction. This representation is based on the results of CVGSM an integrated surface and groundwater model of the Central Valley.	There's no representation of either groundwater pumping or groundwater - stream interactions.
Water releases and allocation decision	Reservoir releases and water allocation decisions throughout the system are made based on a mathematical approach that attaches different weights to different water users (including environmental instream uses) and storage levels. Carryover and delivery decisions for the CVP-SWP system are made based on curves developed to mimic historical deliveries for the period 1922–1994.(7)	After some environmental and institutional constraints are met, reservoir releases and water distribution decisions are made in order to minimize the total cost associated with the final allocation of water.	Reservoir releases are based on detailed operation rules related to different levels in reservoirs (i.e., flood and conservation space) and environmental constraints. There's no further allocation procedure after water is released from the reservoirs.
Environmental Constraints	There's a very detailed representation of environmental constraints in the Delta and some stretches of rivers.	Environmental objectives are represented by time-series of minimum flow constraints on selected river locations and minimum flows to major wetlands taken from CALSIM-II studies results.	There is a representation of environmental constraints but not at the same level as in CALSIM-II.
Hydrologic foresight	The model does not have perfect foresight. It utilizes information about current monthly inflows and forecasts of future inflows to determine deliveries.	The model has perfect foresight of the whole time-series of inflows. Release decisions are made based on that knowledge.	The model has no foresight beyond current monthly inflows. The model does not use any forecast capability.

Table 3-1. (continued)

	CALSIM-II	*CALVIN*	*CVMod*
Hydrologic flexibility(8)	CALSIM-II is bound to a series of 73 hydrologic years (1922–1994) that determine: • Water allocation decisions and carryover storage(8) • Water deficits/gains that are used to determine the DSA level hydrology. An alternative to this would require a precipitation/ runoff model coupled to CALSIM-II	CALVIN is also bounded to the 73 time-series of hydrologic data because it uses as environmental constraints, output data generated with CALSIM-II.	CVMod is not bounded to any specific time-series of hydrologic data.

Notes:

(1) Sources of information to develop this table come from the models themselves, and documentation when available. In the case of CVMod, it also relies on personal communication with developers.

(2) DSA = Depletion Study Area

(3) ID = Irrigation District

(4) There's a proposed plan to update the Sacramento Valley demand representation, which is considered to have several flaws (DWR/USBR, 2004).

(5) Currently, the East San Joaquin region is being update to consider demands on a land-use basis as in the Sacramento valley (DWR/USBR, 2004).

(6) There's an ongoing effort to update the groundwater representation in CALSIM-II that is considered deficient (DWR/USBR, 2004).

(7) These are called the WSI:DI and DELCAR curves. The following is an explanation of CALSIM-II delivery procedure and the explanation of these curves according to Draper et al. (2004): "…The determination of annual delivery allocations is a two-step process based on water supply indices (WSIs) for the two projects and rule curves for carryover storage. The demand index (DI) represents the pool of water that is available for delivery or carryover storage and is determined as a function of WSI/DI curves that are established for each project. Subsequently a 'delivery versus carryover risk curve' is used to disaggregate deliveries and carryover storage from the DI pool. Generation of the WSI:DI curves has been automated in CalSim using an iterative process. The delivery versus carryover risk curve (DELCAR) is input by the user and, if necessary, subsequently manually adjusted to maintain minimum deliveries." Considering this delivery methodology within CALSIM, we find that the model lacks the flexibility needed to be run with different hydrologic conditions that do not represent historical sequence of drought-wet-normal conditions. This is not just our impression but also reflects one of the issues behind the current DWR/USBR's project to make the allocation decision module in CALSIM-II more flexible (CALSIM-II Allocation Model- CAM) so that it does not rely on past operation but is based instead on current reservoir operator's practices (DWR/USBR, 2004).

(8) By hydrologic flexibility we mean the ability of the model to perform studies with different time-series of hydrologic inputs. For example, a flexible model is able to use input data generated using synthetic streamflow techniques or streamflows derived from GCM models. An inflexible model is one that relies only on a fixed time-series of hydrologic data that at most can be modified applying constant (throughout the series) scaling factors.

Based on our analysis of the basic features of these three water resources models available and the needs of our research project, we have eliminated the use of the UC Davis-CALVIN model. The main reason for this decision is our current focus on assessing the performance (reliability) of the Californian water system as it is operated today, considering both historical and climate change driven hydrological inputs. The CALVIN model, being prescriptive, does not satisfy our needs because instead of describing the system as operated today it gives an optimistic view of how the system would be operated if several constraints and barriers were lifted.

Besides having the ability to "describe" the California water system, the model should have the following features: (1) Hydrologic flexibility to allow the assessment of future "climate-change" hydrologic conditions; (2) Coverage of at least the entire Central Valley and ideally areas in Southern California; (3) Spatial representation preferably at the Irrigation District level or at least a spatial resolution that allows one to distinguish between users with different water supply conditions (i.e., different water sources and water rights); and (4) Good representation of actual system policies and operations. Referring to Table 3-2, in which the strengths and limitations of CALSIM-II and CVMod are compared, we see that neither of them fulfills all of our requirements. However, both can be improved to achieve them, and in fact CALSIM-II is being enhanced in that respect.

Table 3-2. Strengths and limitations of CALSIM-II and CVMod

	Strengths	Limitations
CALSIM-II	• "Good" representation of current operations/ environmental constraints. Appendix C shows how the results of CALSIM-II and CVMod compare with historical operations of major reservoirs in the Central Valley.	• Hydrologic inflexibility • No statewide coverage • Resolution not at the irrigation district level • Allocation/release procedures and rules based on weights are not transparent for the user
CVMod	• Hydrologic flexibility • Transparent allocation/release procedure and rules	• Less Accurate representation of current operations/environmental constraints. See Appendix C. • No statewide coverage • Resolution not at the irrigation district level; resolution worse than in CALSIM-II

Considering the requirements of our research project, we can draw the following conclusions about the three models analyzed so far:

- CALVIN is not suitable for our needs, because it is prescriptive rather than descriptive.
- CALSIM-II is a descriptive model with relatively good representation of the system in terms of coverage, spatial resolution, and current operation rules. Its major fault is its inability to be run using a sequence of hydrologic inputs not strictly related to the 73 years of historical hydrologic inputs to which the model is bound.[6] Another limitation of CALSIM-II is the non-uniformity with which water demands and deliveries are set for different geographic areas.[7,8]
- Finally, CVMod is a descriptive model with flexibility to accept a variety of hydrologic inputs, including climate-change or synthetic generated inflows. The drawback of CVMod is that some of the operation rules embedded in the model do not reflect the real system operating rules and hence the results of using this model could be far from actual system operation. Appendix C contains a comparison of the performance between CALSIM-II and CVMod.

All of the models we have studied have some flaws that prevent us from using them without modification. Given that we do not have the resources to develop a new water resources model for California, we have the following options: (1) Study additional models. There are two more models we want to examine to determine whether they might be suitable for our use. These are the NHI WEAP model and the USACE ResSim model, developed for the Central Valley; (2) Wait for the next version of CALSIM-II and use that to estimate inputs; (3) Modify CVMod to better reflect actual system operations.

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6 This bound-ness is reflected in three areas of the model development:

- The DSA's water balance hydrologic setting that was performed to reflect history
- The carry over-delivery decisions for the two projects (CVP-SWP) that are represented in a "step-function" that again was develop to mimic history
- The forecasting procedure that in CALSIM-II is merely a time series of historical forecastings.

7 One example of such non-uniformities would be the different water demand/delivery methodology existing between the Sacramento Basin and the San Joaquin River Basin. In the former case, demands are set by land-use requirements, but in the later they are "*…generally set to fixed annual amounts rather than based on land use and hydrologic conditions*." (DWR/USBR, 2002, p. 76).

8 The good news for us is that inside DWR there is also concern about these two topics and there is an ongoing effort to improve both the "hydrologic flexibility" and the "system representation" of the model.

Specific studies that could be performed with the tools available are the following:

- Compare CALSIM-II reliability results (see Section 4) with real data for consistency of results (e.g., sources of groundwater and non-project reliabilities).
- Use CVMod to study the new PCM3 and HadCM3 inflow scenarios
- Use CVMod on a series of what-if studies for the California System. By systematically changing inflows parameters (e.g., average and dispersion from the current statistical distribution), we can gain understanding of the reliability of the system for different targets.

4. Assessing California Water System Reliability Using CALSIM-II

As we presented in the last section, there are two available models that represent the California Water System that partially satisfy our requirements for this project: CALSIM-II and CVMod. The ideal model should be able to assess system performance at the Irrigation District level, in terms of water supply reliability under different hydrologic scenarios (e.g., current climate and future climate-change driven conditions). The following is a preliminary analysis of the reliability of the Californian water system under historical hydrologic conditions as simulated by CALSIM-II. In the future we will duplicate this analysis using CVMod and compare the results between the models and against historical reliability of the system based on available data.

The most recent available simulations runs for CALSIM-II, known as the Benchmark Studies (DWR/USBR, 2002), contain monthly data of demands and deliveries for different water users in the Californian water system. Using this data, we calculated monthly and annual quantity-based reliability measures (equation 1) defined as the percentage of surface water delivered compared to a target delivery level represented by the water demand.[9,10] With both the monthly and annually reliability measures we constructed frequency curves of these values and calculated an overall reliability measure (equation 2).

Monthly/Annually quantity-based reliability is measured by:

$$R_{ij} = 1 - \frac{(Demand_{ij} - Delivery_{ij})}{Demand_{ij}} \text{ if } Demand_{ij} \geq Delivery_{ij}\text{; if not } R_{ij} = 1 \quad \textbf{(equation 1)}$$

---

[9] This definition is based on Hashimoto et al. (1982) and Bogardi and Verhoef (1995). A time-based definition of reliability would be the fraction of time that a system is under a no failure mode defined by a certain target. Other measures of system performance not included in this analysis are vulnerability and resilience (see Hashimoto et al. (1982).

[10] We are not considering ground water pumping as part of water deliveries. The main reason for not considering them is that CALSIM-II assumes that diversion requirements are always met for every DSA with ground water pumping when surface waters supplies are not sufficient. Thus, including ground water pumping as part of the delivery levels prevents any meaningful analysis of water supply reliability (i.e., demands are always met, and there is always 100% reliability).

The overall reliability measure is calculated as:

$$R_i = 1 - \frac{\sum_j \left(Demand_{ij} - Delivery_{ij}\right)^+}{\sum_j Demand_{ij}} \qquad \textbf{(equation 2)}$$

where *i* represents a certain user (or group of users) and *j* represents the corresponding timestep (month or year). The + sign denotes that only positive values are considered.

The analysis was done for different types of users according to geographic location, source of water and water rights status. These users were also aggregated into different levels. The first level provides the reliability estimate for the whole Central Valley system.[11] The second level compares reliability measures for broad geographic categories of users: North of the Delta (NOD) Project and non-project users; State Water Project (SWP) South of the Delta (SOD) users; Central Valley Project (CVP) SOD users and East San Joaquin users. Figure 4-1 shows a map of these broad categories of users.

The third and final level assesses the reliability of supply to more specific user groups.[12] An example of the analysis done at this step is the comparison of supply reliability among different CVP users (e.g., Between Exchange, Agriculture, Municipal and Industrial (M&I), and Refugee Contractors). Figure 4-2 shows a schematic of how the different users in the Central Valley are classified into these different types and levels of aggregation. The overall reliability measure for each of these steps and time periods is presented in Table 4-1. The reliability curves are presented in a series of Figures (4-3 to 4-14). These curves should be read first looking at a delivery target (say 50% of demand) on the y axis and then at the percent of time this target is equaled or exceeded in the x axis. Appendix D contains a detailed explanation of the sources used to perform this analysis.

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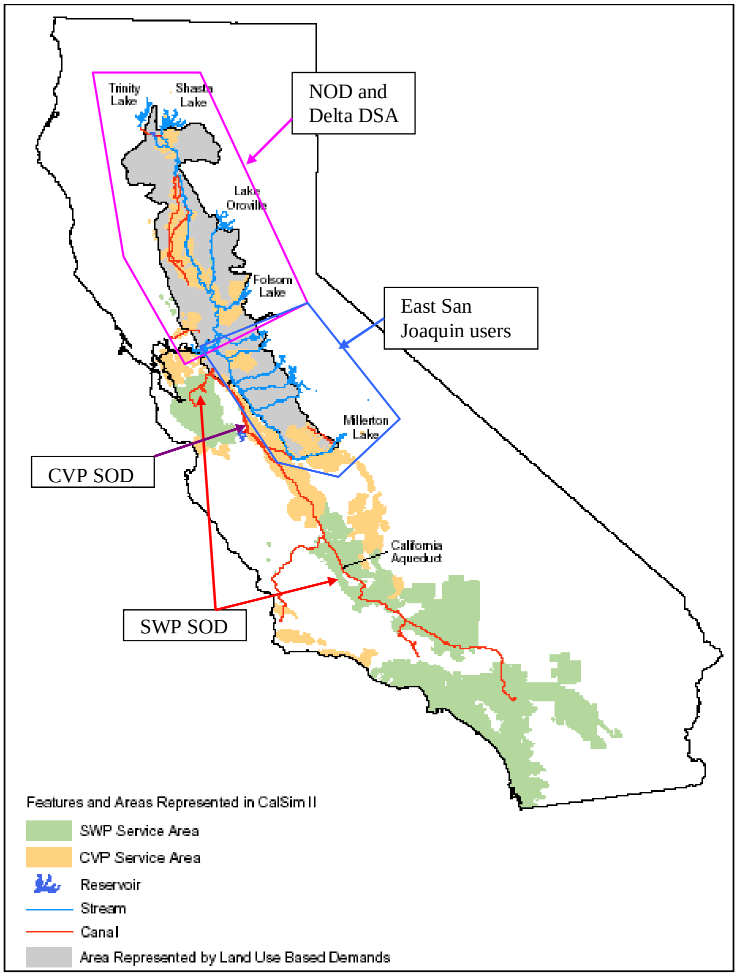
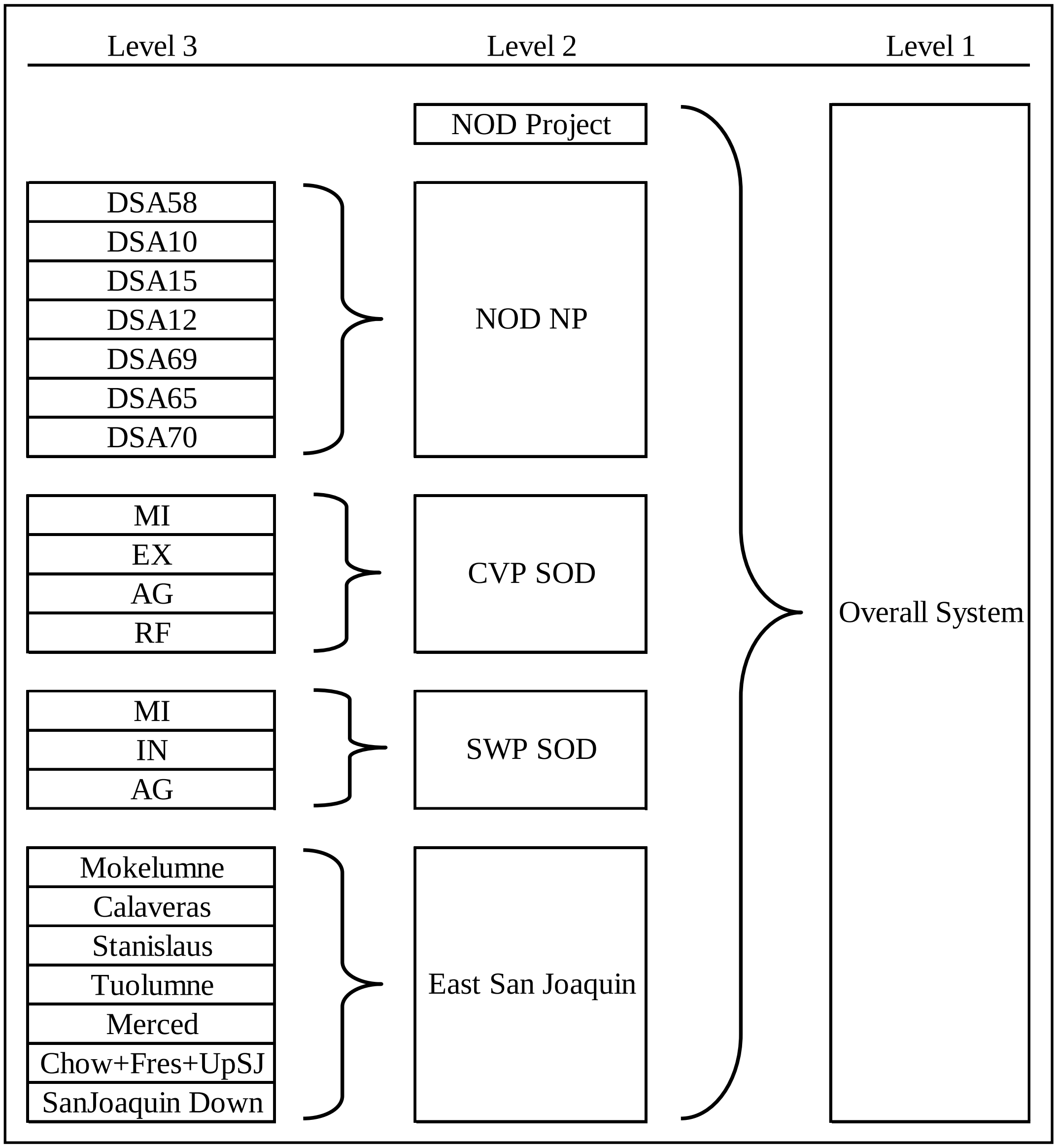
[11] Delta users were not considered in the analysis, because there are some concerns about the corresponding CALSIM-II results that need to be discussed with DWR.

[12] Using CALSIM-II it is possible to conduct a further step analysis of reliability at the ID district level, but there is not yet a good representation of these users so we preferred not to do it at this time.



Notes: NOD = North of the Delta; DSA = Depletion Study Areas;
CVP = Central Valley Project; SWP = State Water Project

Figure 4-1. Geographic location of users within CALSIM-II



Notes: NOD = North of the Delta; SOD = South of the Delta; DSA = Depletion Study Areas; CVP = Central Valley Project; SWP = State Water Project; AG = Agriculture Contractor; SC = Settlement Contractor; MI = M&I contractor; RF = Refugee Contractor; EX = Exchange Contractor

Figure 4-2. Schematic showing group of users within CALSIM-II

Table 4-1. Overall reliability measure of water supply deliveries for different water users in California

Analysis Performed	User	Annually	Monthly
Level 1:			
Overall System	NA	0.75	0.75
Level 2:			
Comparison of broad categories	NOD Project	0.80	0.80
	NOD NP	0.62	0.62
	CVP SOD	0.69	0.68
	SWP SOD	0.63	0.63
	East San Joaquin	0.84	0.84
Level 3			
Non-project users NOD DSA analysis	DSA58	0.87	0.87
	DSA10	0.48	0.48
	DSA15	0.94	0.94
	DSA10	0.33	0.33
	DSA69	0.83	0.83
	DSA65	0.33	0.33
	DSA70	0.85	0.85
CVP SOD	MI	0.87	0.87
	EX	0.97	0.97
	AG	0.65	0.63
	RF	0.97	0.97
SWP SOD	MI	0.81	0.80
	IN	0.12	0.12
	AG	0.80	0.79
Different East San Joaquin users	Mokelumne	1.00	1.00
	Calaveras	0.29	0.29
	Stanislaus	0.96	0.96
	Tuolumne	0.82	0.82
	Merced	0.87	0.87
	Chow+Fres+UpSJ	0.82	0.82
	SanJoaquin Down	1.00	1.00

Note: The numbers in the last two columns are very close because although the frequency of reliability values may differ as can be seen from the annual and monthly figures for each level of analysis (e.g., compare Figure 3-5 with Figure 3-6), the measure depicted in this table (1- sum of deficits/sum of demands) could still be the same for both cases. The analysis only considers surface water supplies.

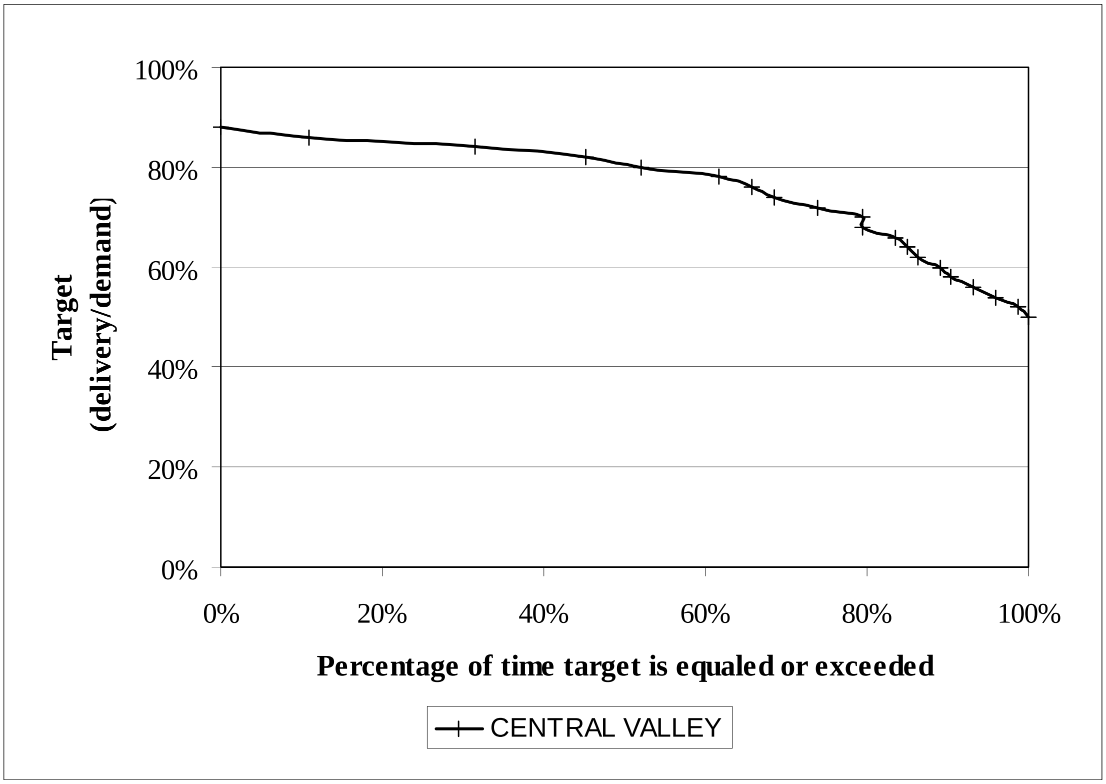


Figure 4-3. Annual reliability for all users in the Central Valley

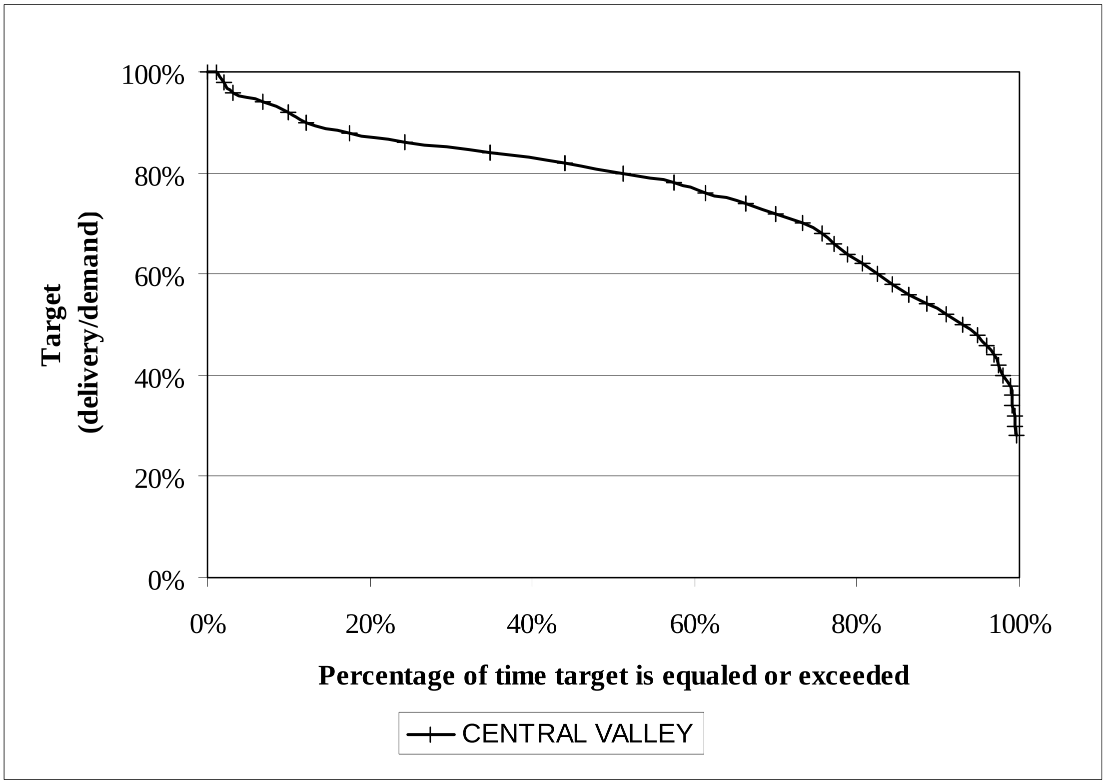


Figure 4-4. Monthly reliability for all users in the Central Valley

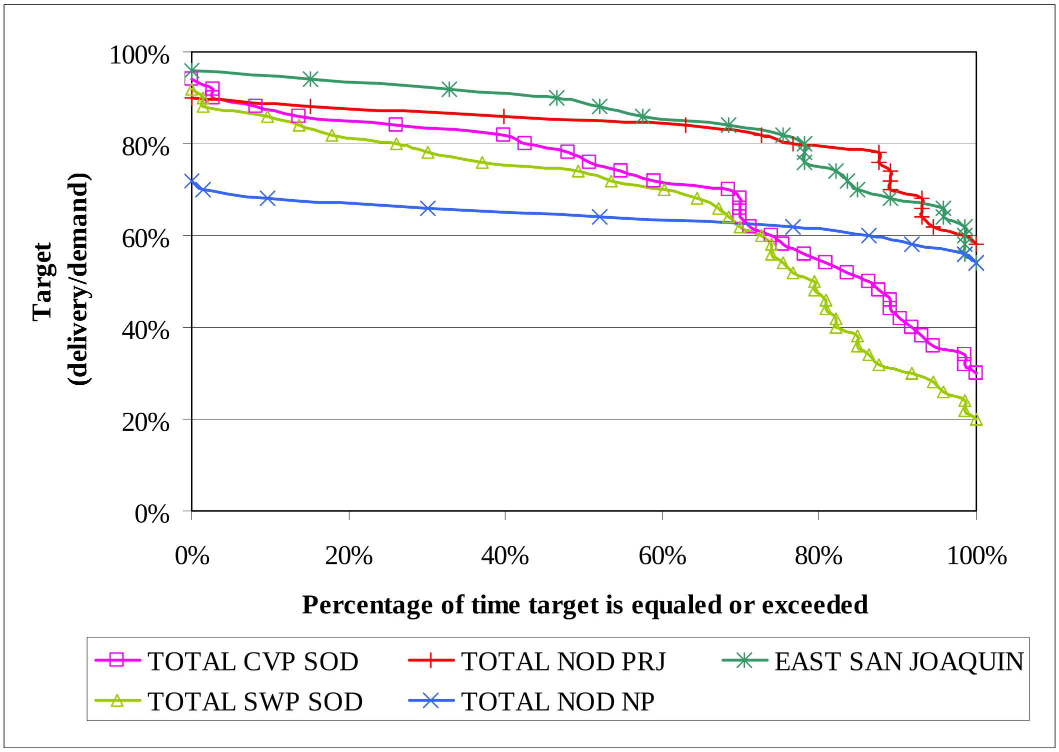


Figure 4-5. Annual reliability for broad categories of users in the Central Valley

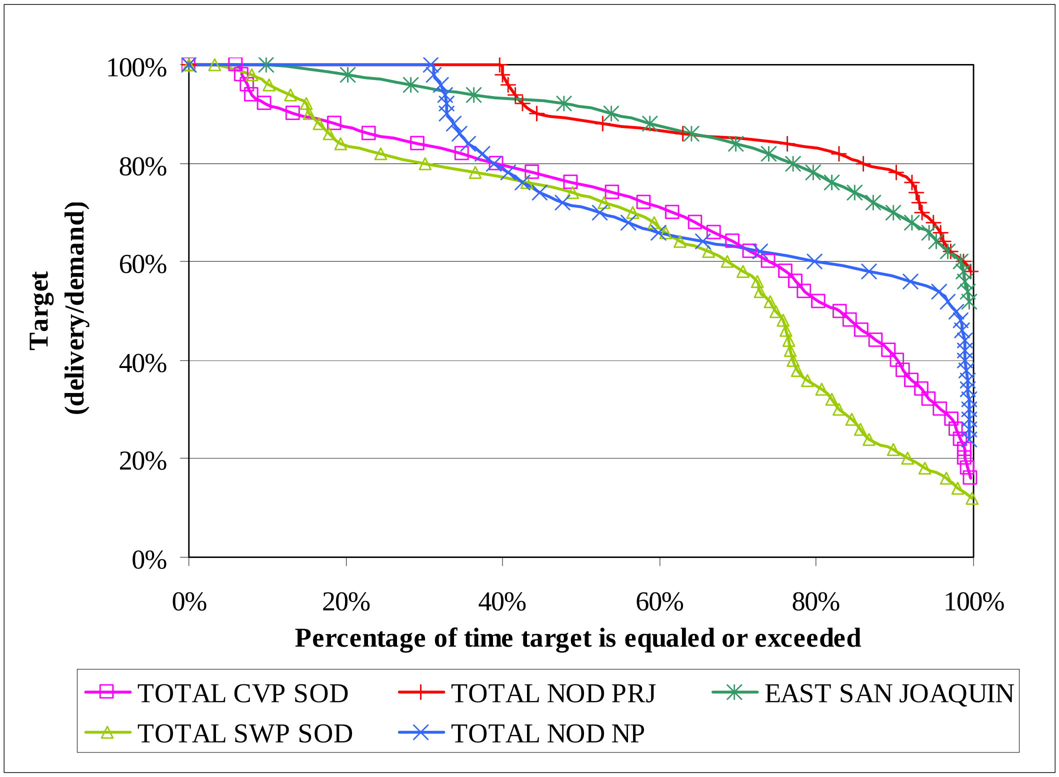


Figure 4-6. Monthly reliability for broad categories of users in the Central Valley

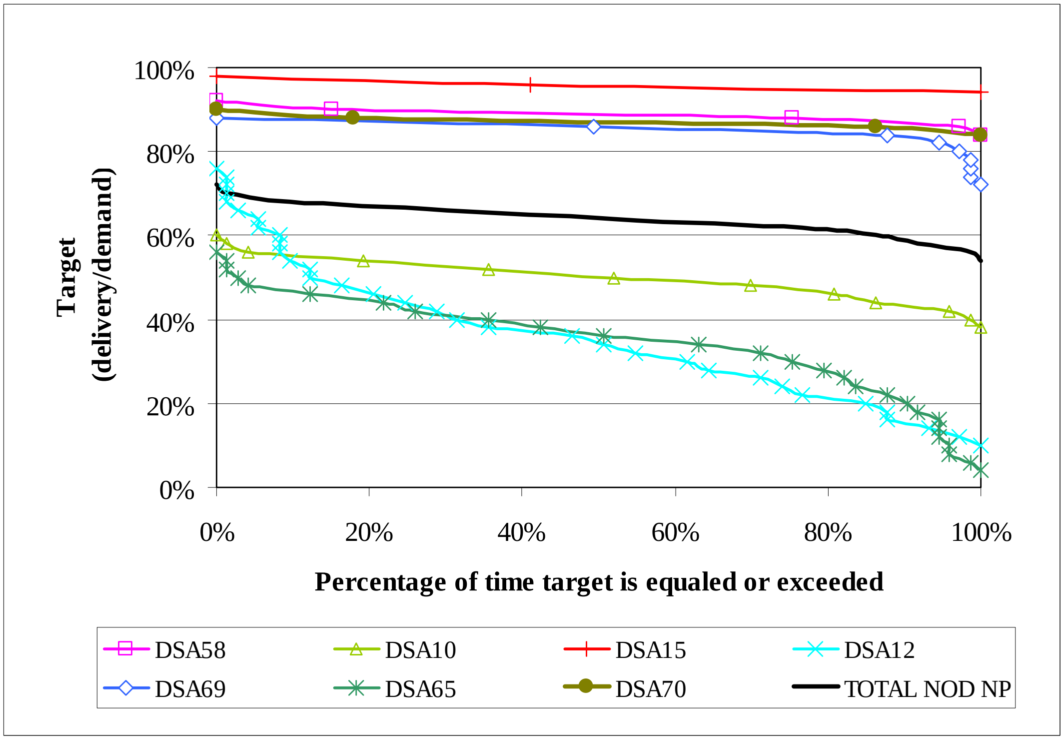


Figure 4-7. Annual reliability for non-project users north of the Delta

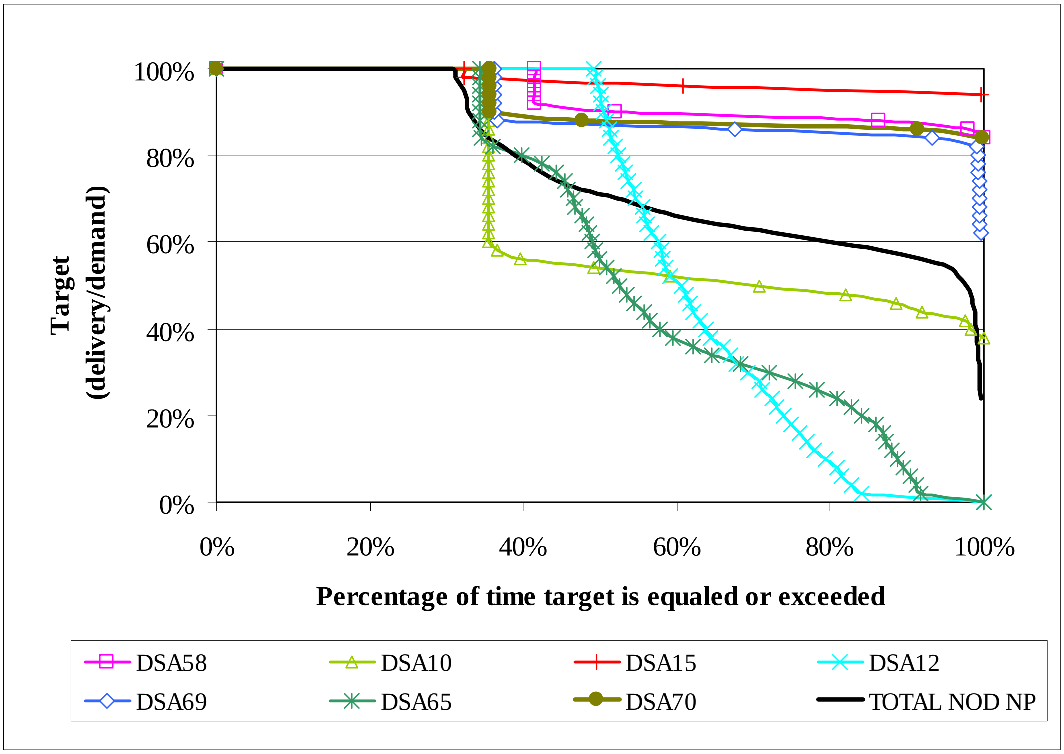


Figure 4-8. Monthly reliability for non-project users north of the Delta

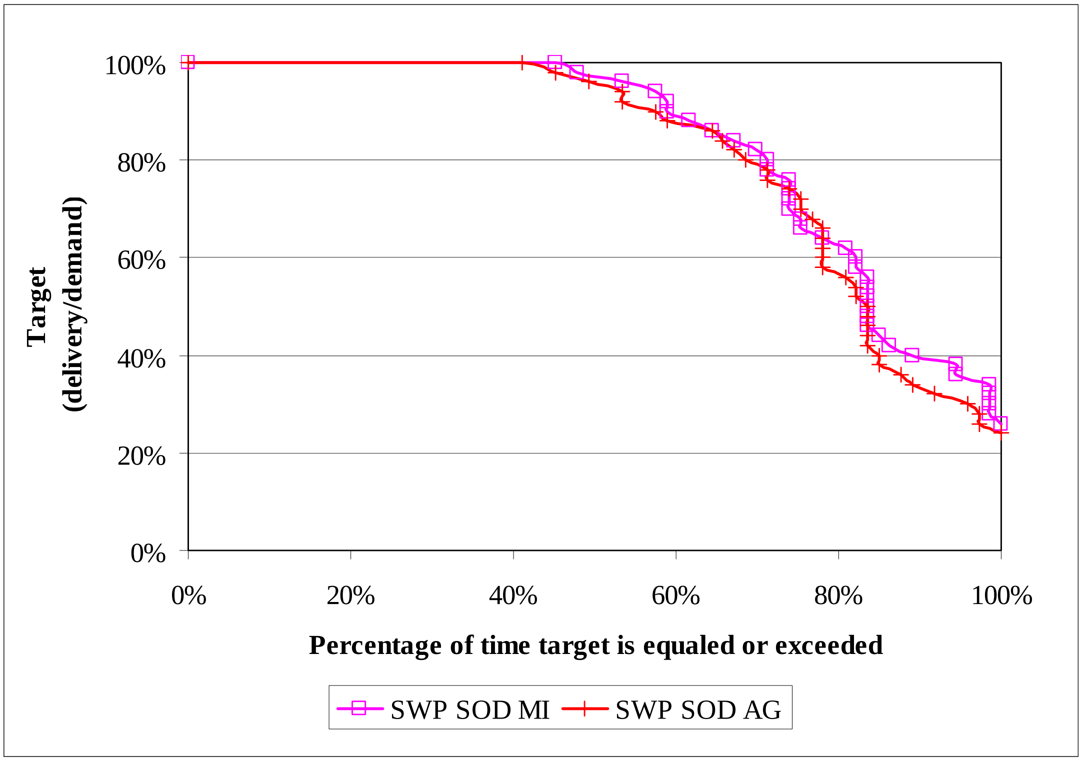


Figure 4-9. Annual reliability for SWP contractors South of Delta

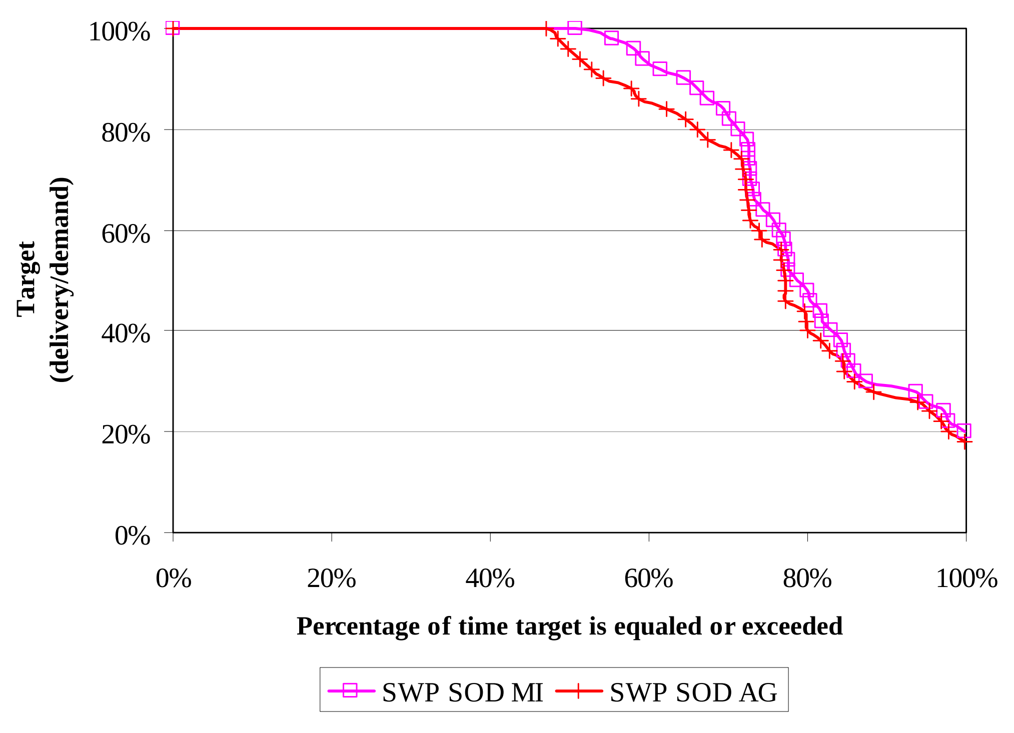


Figure 4-10. Monthly reliability for SWP contractors South of Delta

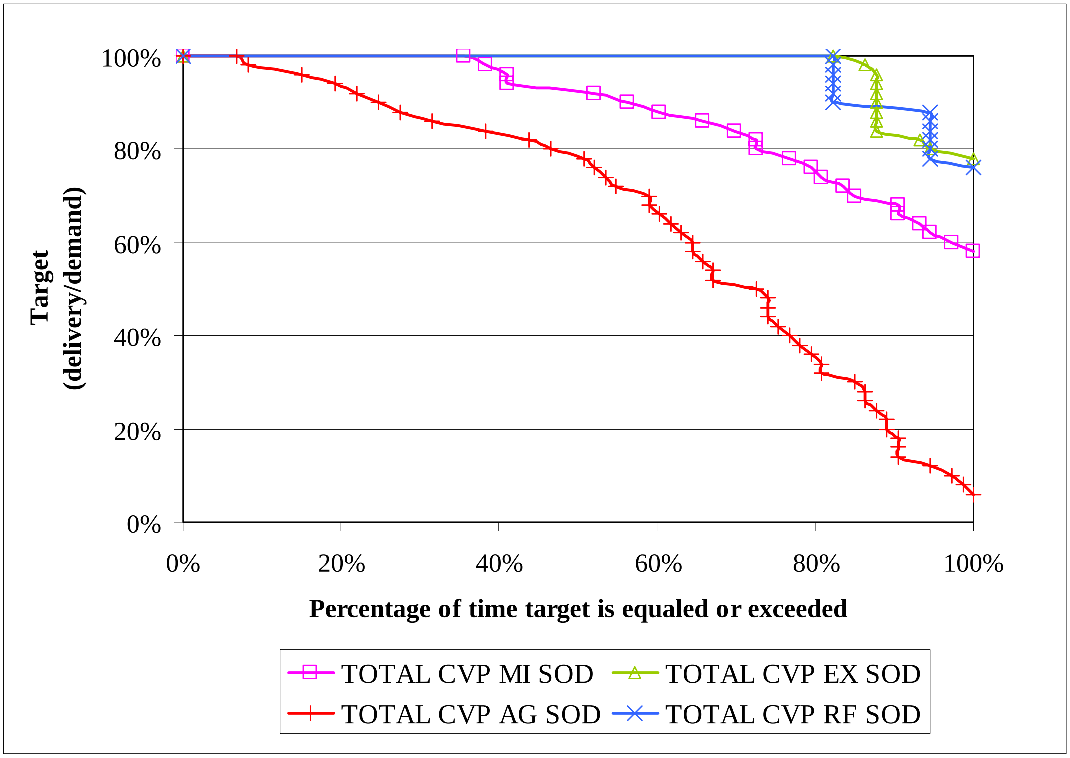


Figure 4-11. Annual reliability for CVP contractors South of Delta

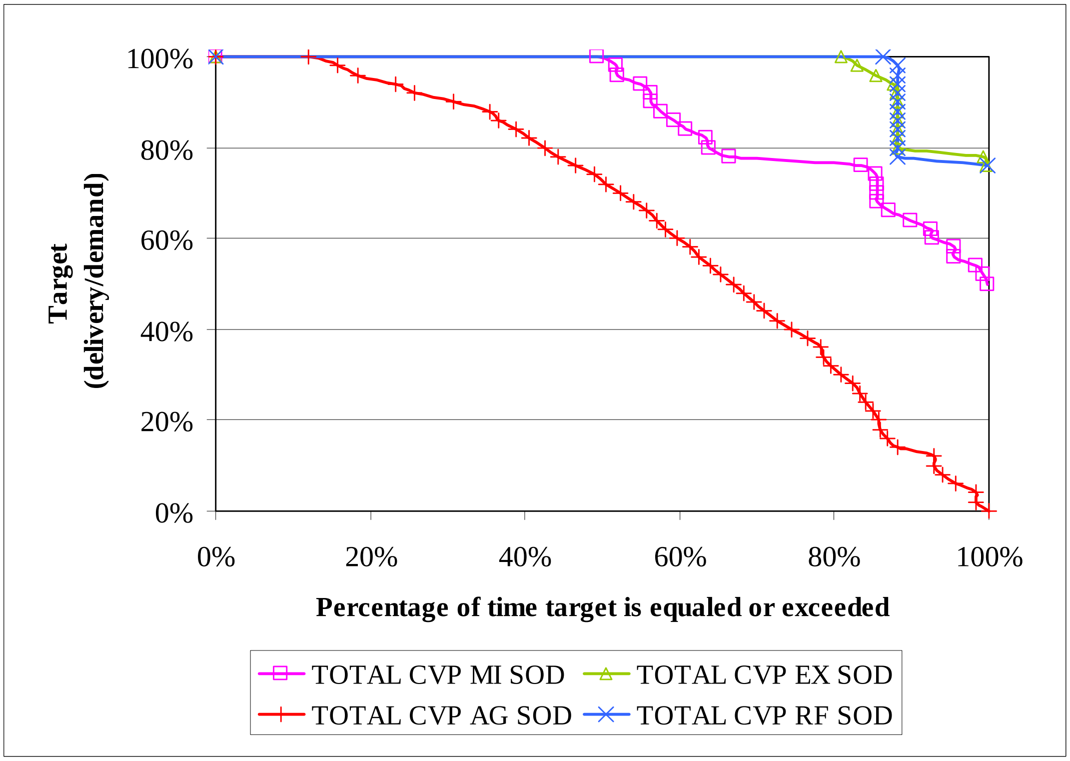


Figure 4-12. Monthly reliability for CVP contractors South of Delta

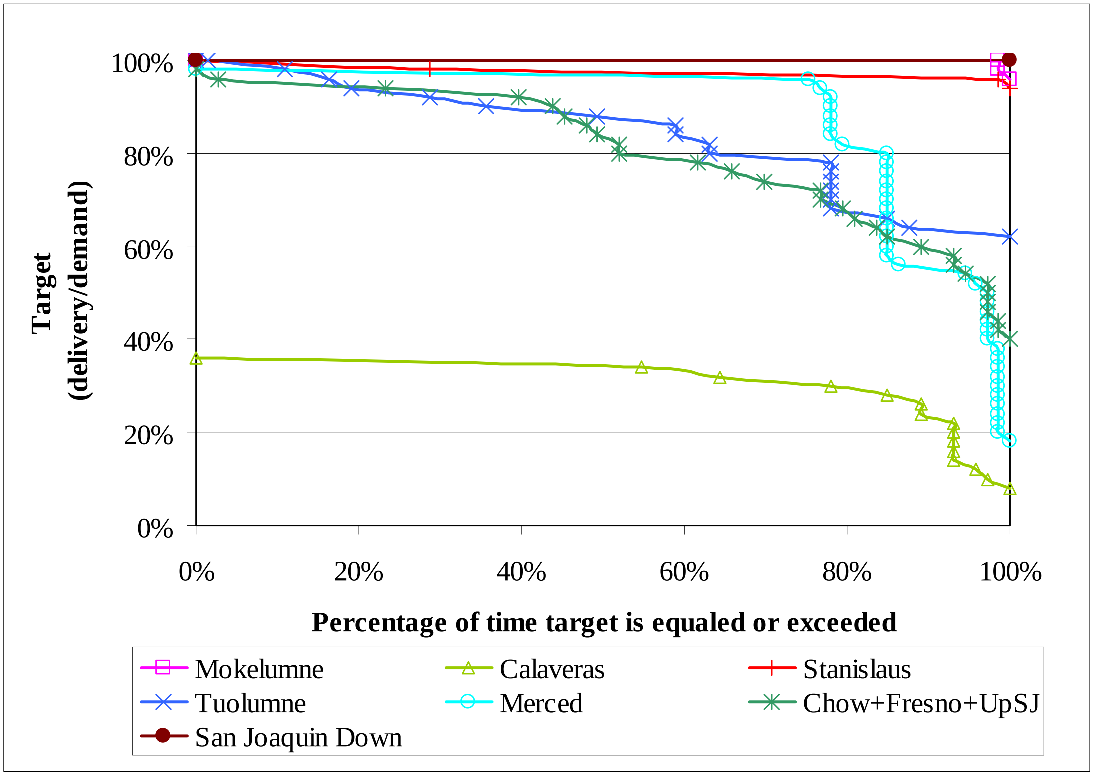


Figure 4-13. Annual reliability for different East San Joaquin streams' users

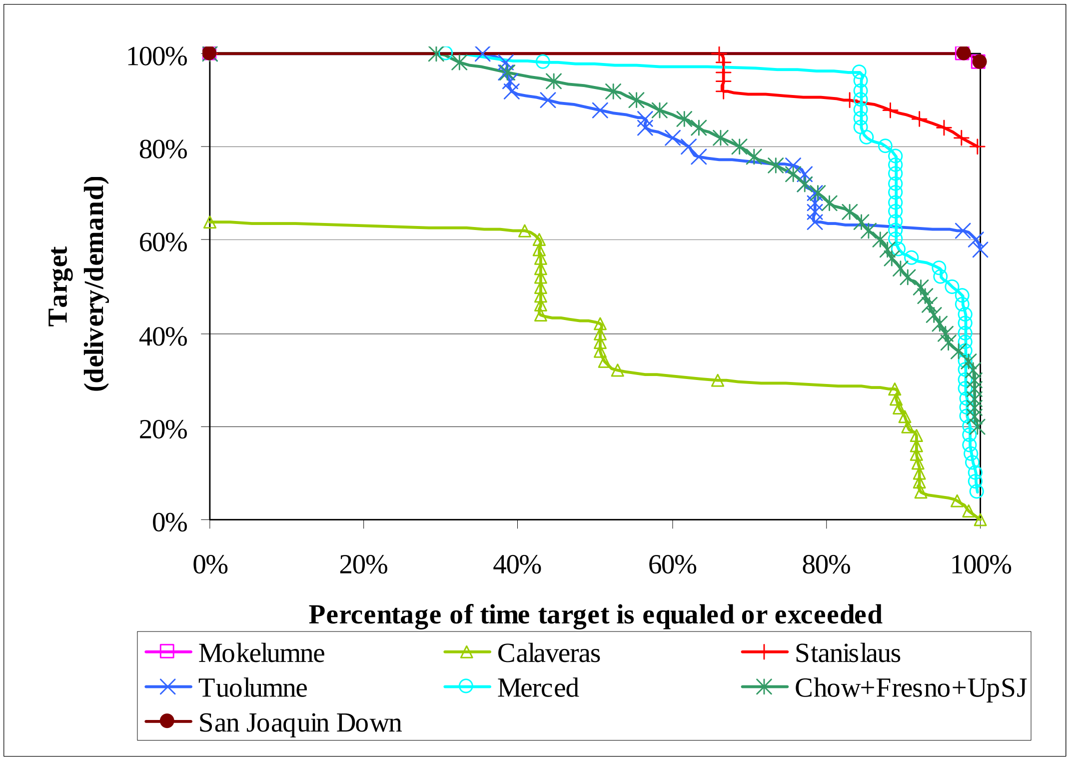


Figure 4-14. Monthly reliability for different East San Joaquin streams' users

From the results presented in the previous figures, we can derive the following conclusions about water supply reliability in the Central Valley calculated using the results of the Benchmark CALSIM-II runs:

- The first and most important conclusion is that water supply reliability varies widely for different water users in the Central Valley. This becomes clear when one compares the reliability for a group of users with the reliability of individual members within that group. Examples are the comparison between reliability for all users in the Central Valley (Figures 4-3 and 4-4) and reliability for the broad categories that constitute this whole group (Figures 4-5 and 4-6). A similar pattern of diverse reliability estimates is observed between NOD non-project user reliability (included in Figure 4-3 and 4-6) and the reliabilities of different DSAs where these non-project users are located (Figures 4-7 and 4-8).

- Another conclusion is that the distribution of supply reliability is different in annual terms than in monthly terms, but they are quite similar when the overall measure of reliability is compared (Table 4-1). The reason for this discrepancy is that the deficits in supply are concentrated in only *certain months* in the year, with the rest of the year (especially the winter months) having 100% reliability. In the end we are interested in monthly reliabilities—especially those in the growing season. The annual reliability measures could hide the possibility that even though supply matches demand on an annual basis, within particular months of the growing season there is a shortage. This does not happen very often though, as can be seen from the comparison of the monthly and annual results in Table 4-1. For the future, we might be interested in a monthly measure that takes into account the growing season portion of the year.

- As was expected, different project contractors have different reliabilities according to their water right status. For example, CVP SOD Refugee and Exchange Contractors have a higher reliability of supply than M&I Contractors, which have higher reliabilities than Agriculture Contractors (Figures 4-11 and 4-12). Something similar but more subtle arises with M&I and Agricultural SWP SOD Contractors (Figures 4-9 and 4-10).

- According to the results shown in Figures 4-3 and 4-4, when broad categories of users are compared, their order in terms of decreasing reliability is: North of Delta Project users, East San Joaquin users, CVP SOD, SWP SOD, and North of the Delta non-project users. An important caveat to this conclusion is that within CALSIM-II, demands are not estimated in a consistent way. Some places use land-use based estimates (all NOD users), while others consider pre-specified contract demands (e.g., SWP SOD).

- The annual reliability curve for non-project users NOD (Figure 4-3) shows that water supplies for this group are mostly constant (between 60%–70% of their demands) throughout the 73 years of different hydrologic conditions. The

CALSIM-II code assumes that the remaining 30%–40% of demand is satisfied by unlimited groundwater pumping. If we examine the breakdown of this data between different geographic areas in the Sacramento Valley (different DSAs, Figure 4-7) we see that some users have reliabilities on the order of 40%, while others have around 90% reliability. The reason for these differences in reliability is unclear at this point. One possible explanation could be the proximity of the respective DSAs (see Figure 4-15) to major sources of surface or groundwater (e.g., proximity to the Sacramento River). Another explanation might be the relative position of users in the basin (i.e., upstream users could have a more reliable supply than downstream users). The DWR places less confidence in CALSIM-II delivery estimates for non-project users in the Sacramento Valley than for project users. That is partly because some characteristics of non-project users, like irrigation efficiencies or sources of water, are less accurately measured than for project users (DWR/USBR, 2004, page 11-1).[13]

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[13] The lack of more accurate water use information about local/non-project water districts is one of the reasons why USBR/DWR recognizes the need to disaggregate the DSA structure in the Sacramento Valley to better represent the system (DWR/USBR, 2004). For this reason, this project will not pursue deeper analysis with these results at this time.

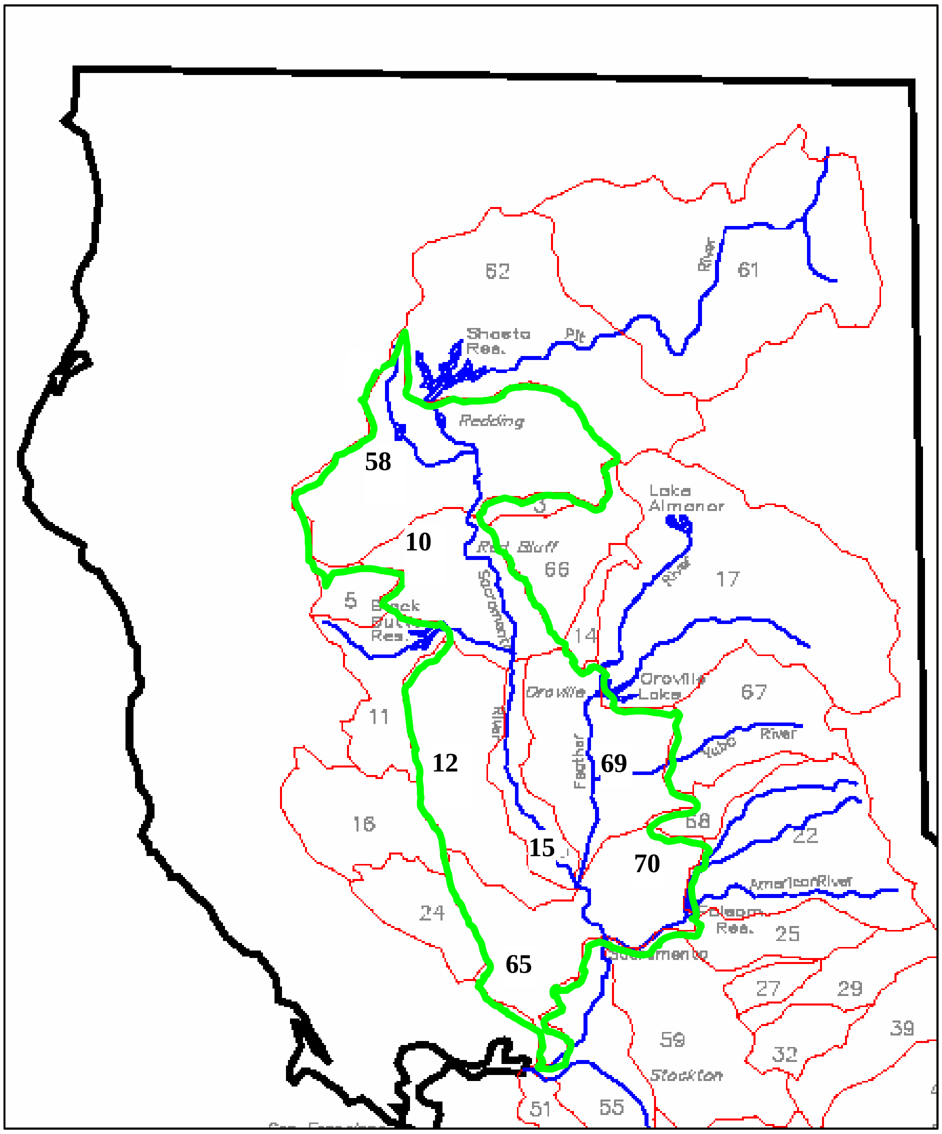


Figure 4-15. DSAs represented in CALSIM-II (enclosed by polygons)

5. Accuracy of DWR Water Flow Forecasts

The forecasts of April–July water flows and streamflows published by DWR at the beginning of each year are likely to be a crucial input to water district managers' expectations regarding their warm-season water supplies. However, since these are only forecasts, they are likely to contain some degree of error. The purpose of this research is to measure the error bands that might be placed around the DWR forecasts and predict the effects that climate change may have on those error bands.

Preliminary analyses of the DWR water flow forecasts have been performed on six California rivers for the period 1998–2003. Four rivers—the Mokelumne, Feather, Yuba, and American—drain medium-elevation watersheds (with an average elevation below 1,600 feet). Two rivers—the Kings and the San Joaquin—drain high-elevation watersheds (with an average elevation above 1,600). In addition, "wet year" and "dry year" forecasts were analyzed across all six rivers.

These forecasts have been assembled for different forecast dates, rivers, and water year type and have been graphed as a percent difference from actual flow. ("Actual" flow in this case is a reconstructed natural flow: the sum of real flow and upstream diversions.) For each river and water year type, percent difference between 10%, 50%, and 90% exceedance forecasts and actual flows were graphed vs. forecast date (Figures 5-1 through 5-6). The 10% exceedance forecast is interpreted as an upper-bound forecast, signifying a 10% chance that actual flows will exceed the indicated level. The 90% exceedance forecast is interpreted as a lower-bound forecast, with a 90% chance that actual flows will exceed the indicated level. The 90% and 10% exceedance forecasts bracket the most likely 50% exceedance forecast.

The accuracy of the forecasts is indicated by the vertical width of the spread between the 10% and 90% exceedance forecasts, provided at different points in time. As expected, forecast accuracy improves over time (moving from left to right), as the period between the forecast date and delivery shortens. There is a relatively wide spread in the January and February forecasts and almost no spread in the June and July forecasts. More interestingly, forecast accuracy also seems to improve with watershed elevation; higher watersheds tend to have more accurate forecasts than lower watersheds. To see this, compare the January forecast spread in the low elevation watersheds (Figures 5-1 to 5-4) and the high elevation watersheds (Figures 5-5 to 5-6). This correlation may be related to the dominance of snowmelt in the annual hydrograph of higher watersheds. If so, reduction of the snowpack due to climate change can have a substantial impact on future forecast reliability.

The largest correlation between forecast accuracy and a natural factor is apparent when considering only particularly wet and dry seasons (Figures 5-7 to 5-8). As expected, flow forecasts tend to be low for wet years. Error is almost entirely in the range of –50% to 0. In contrast, errors for dry years regularly ranges up to +200%. This correlation may also be due to the dominance and predictability of snowmelt during wetter years. Interestingly, errors tend to converge toward zero in a linear fashion when considering either wet or dry years, compared to the curved convergences seen in the river-based analysis.

Details of interest for future study:

- Forecasts for higher elevation watersheds appear to have more accurate forecasts in general.
- Forecasts in wetter years appear to have more accurate forecasts in general.
- The range of forecast errors for higher elevation watersheds is smaller than for lower elevation.
- Forecasts for higher elevation watersheds appear to converge faster and more uniformly toward actual flows than those for lower elevations.
- The 50% exceedance forecasts tend to slightly underestimate actual flows for higher elevation watersheds and, more significantly, overestimate flows for lower elevation watersheds.
- Forecast errors tend to converge linearly in analysis of wet and dry years, while per-river analysis yields curved error converges.

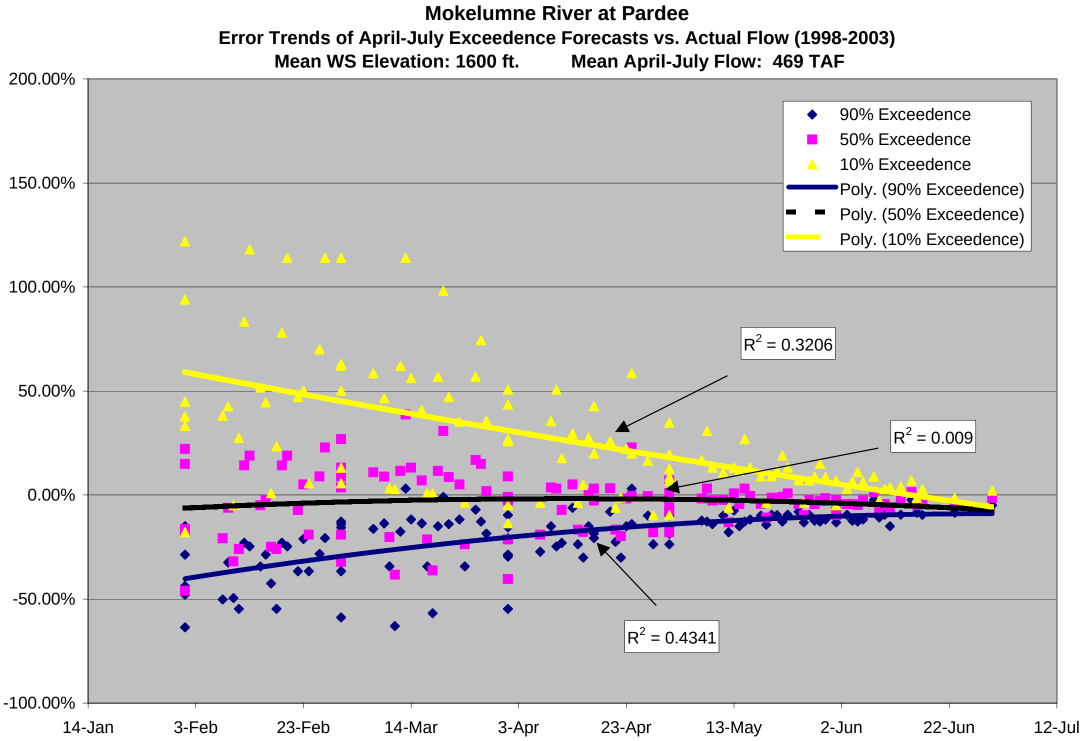


Figure 5-1. Mokelumne River Forecast Analysis

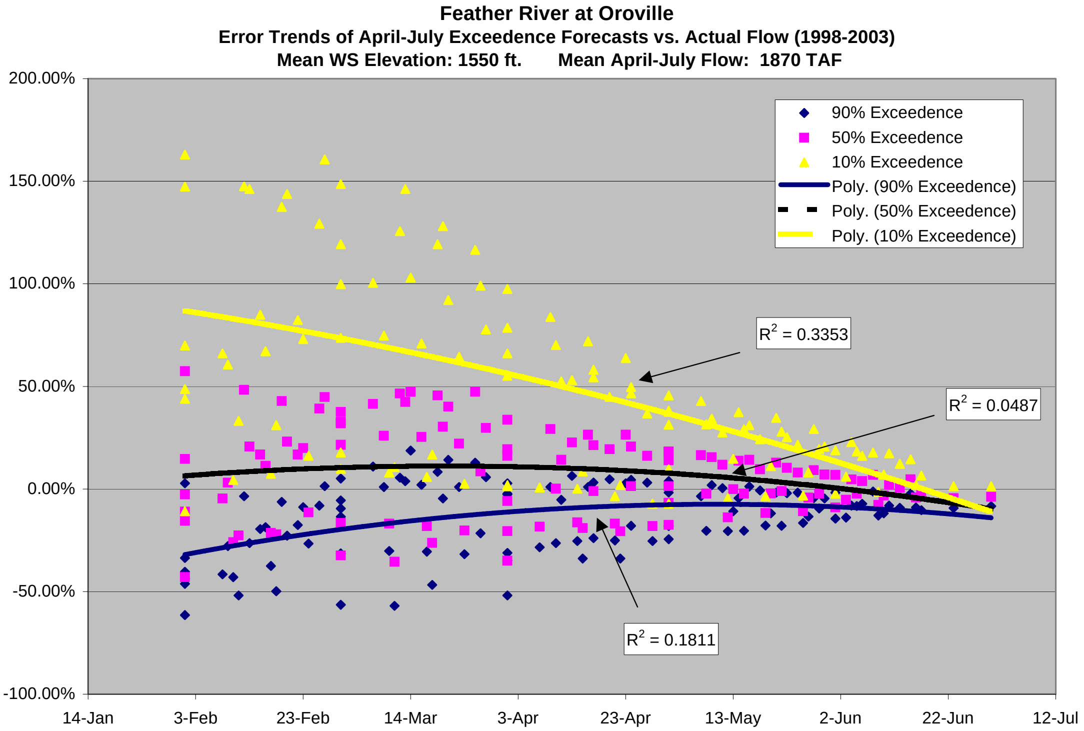
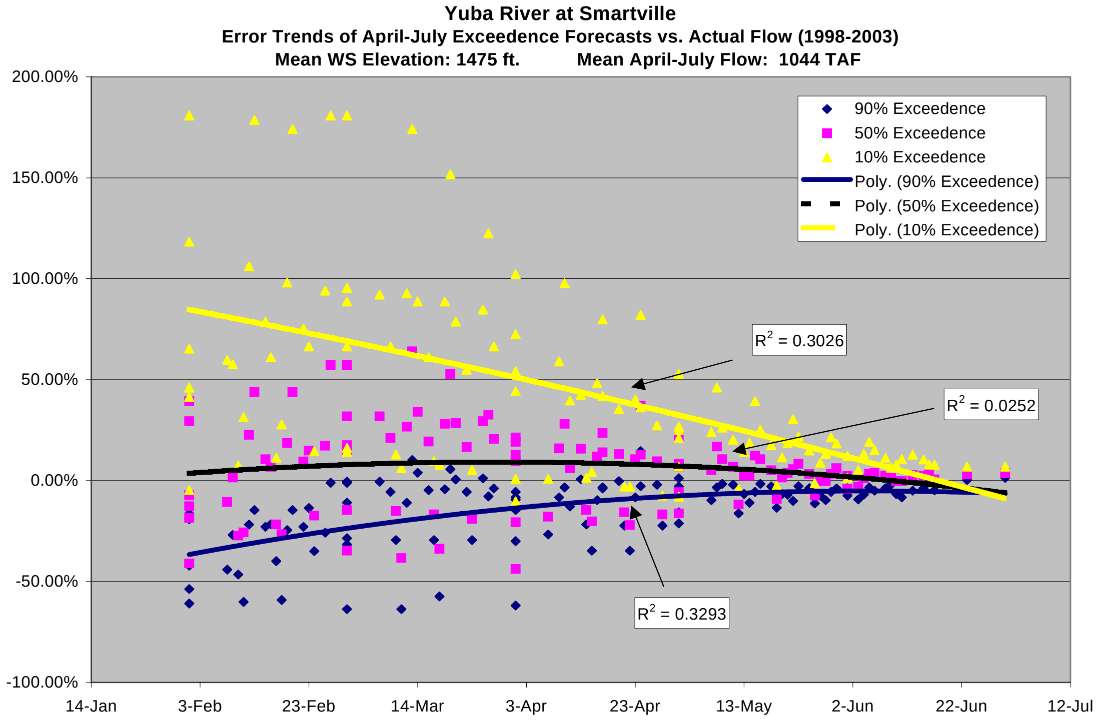
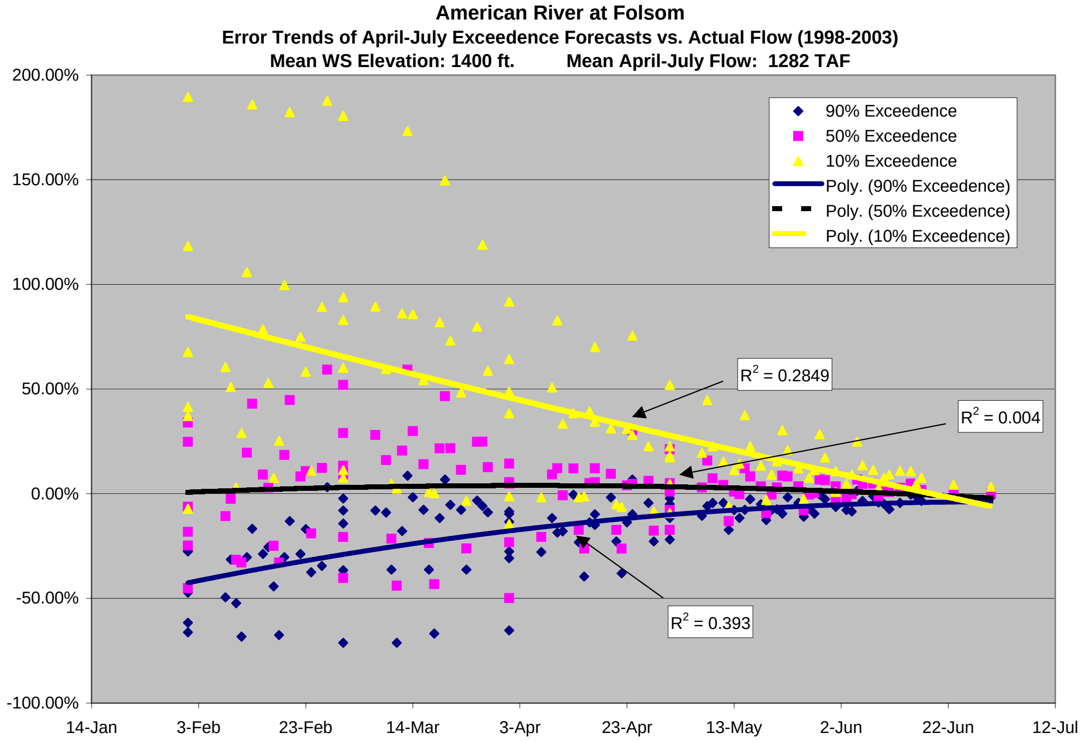


Figure 5-2. Feather River Flow Forecast Analysis



Yuba River at Smartville
Error Trends of April-July Exceedence Forecasts vs. Actual Flow (1998-2003)
Mean WS Elevation: 1475 ft. Mean April-July Flow: 1044 TAF

Figure 5-3. Yuba River Flow Forecast Analysis



American River at Folsom
Error Trends of April-July Exceedence Forecasts vs. Actual Flow (1998-2003)
Mean WS Elevation: 1400 ft. Mean April-July Flow: 1282 TAF

Figure 5-4. American River Flow Forecast Analysis

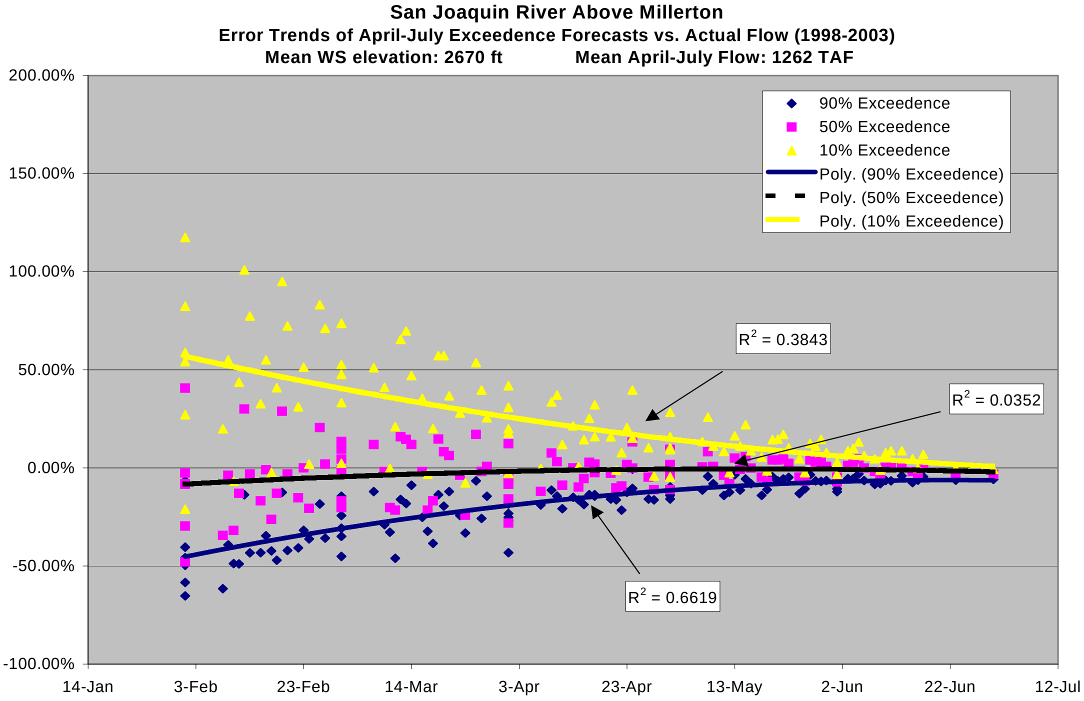


Figure 5-5. San Joaquin River Flow Forecast Analysis

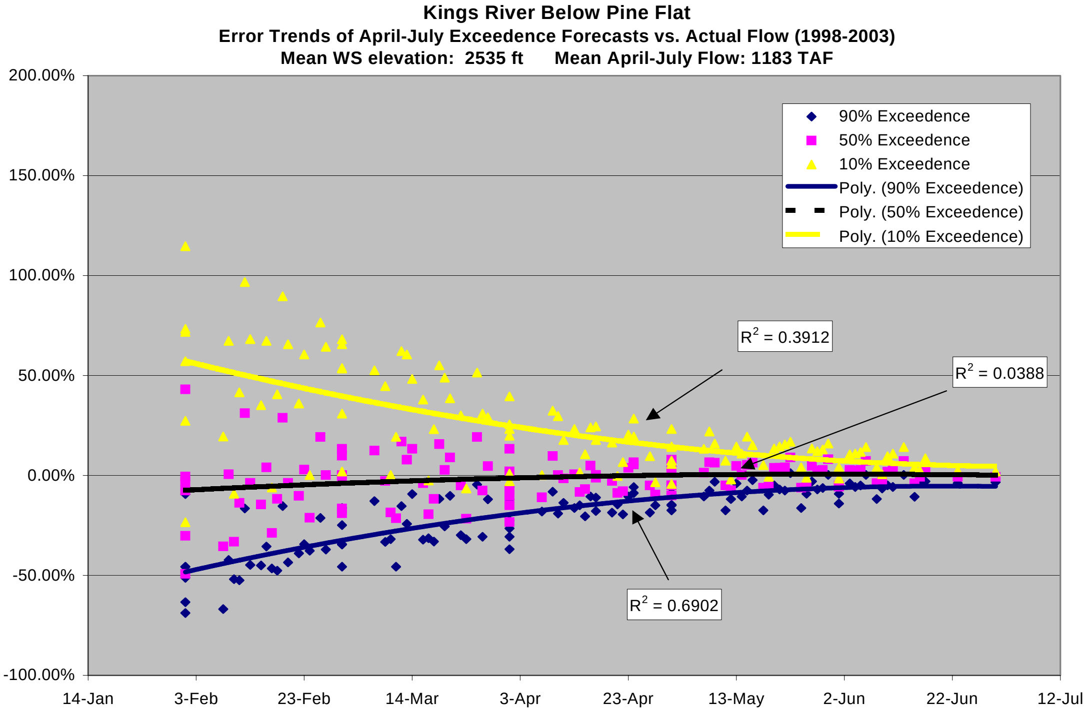


Figure 5-6. Kings River Flow Forecast Analysis

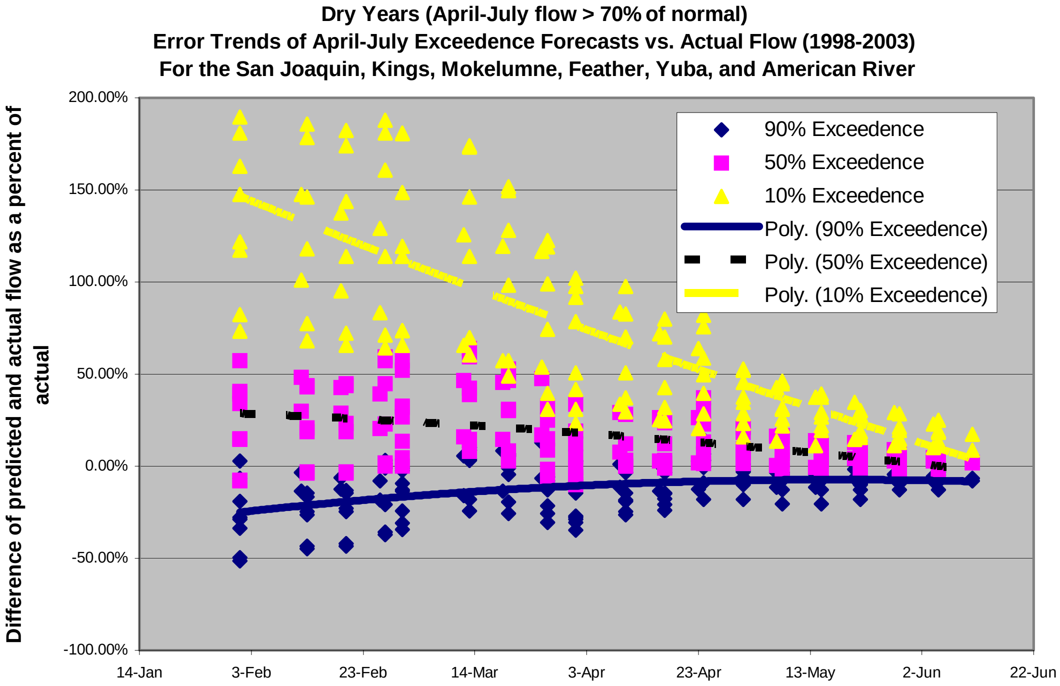


Figure 5-7. Dry Years Flow Forecast Analysis

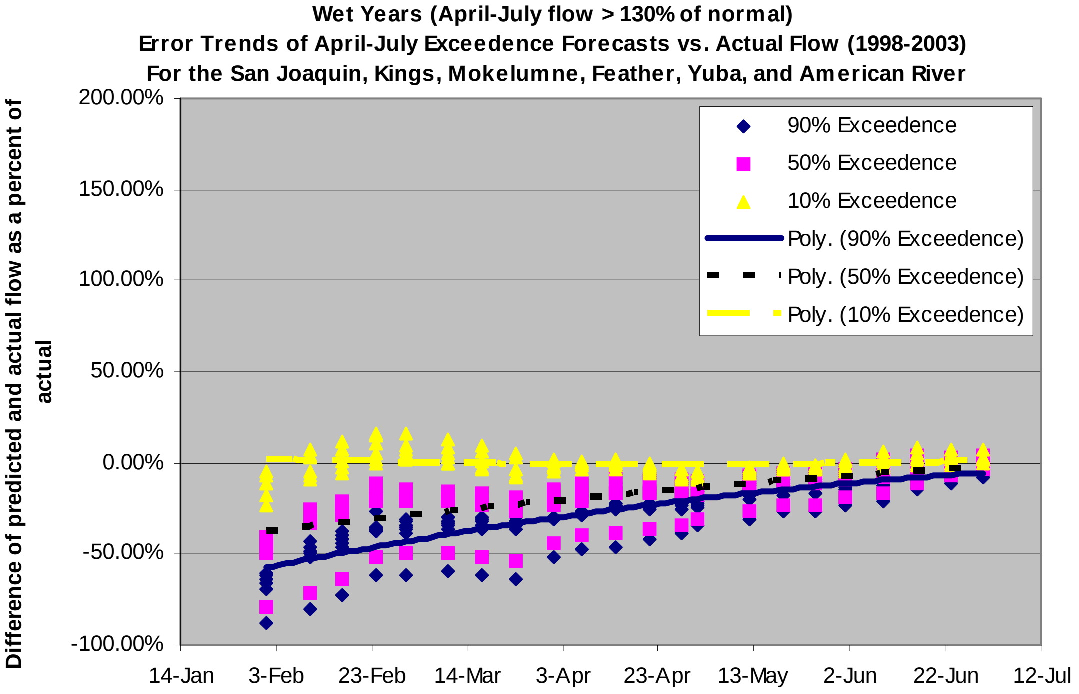


Figure 5-8. Wet Years Flow Forecast Analysis

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Appendix A. Brief framework on the differences of water resources models

The design, analysis, planning or operation of complex multipurpose, multiple-reservoir system like the California Central Valley System requires the aid of water resource models (also called *reservoir system analysis models*). There has been a significant amount of work on developing and applying reservoir system operation/analysis models during the past several decades. Yeh (1985), Wurbs (1985, 1993 and 1996), and Labadie (2004) provide a comprehensive, state-of-the-art review of these models. The following summary, based largely on those works, provides a framework for describing and comparing the different reservoir system models developed for California.

Reservoir system analysis models have traditionally been categorized as either *simulation* or *optimization* models. A *simulation* model reproduces the essence of a system in order to predict its behavior under a given set of conditions. From the perspective of reservoir system analysis, simulation models reproduce the hydrologic and/or economic performance of a reservoir system for given inflows and operating procedures (Wurbs, 1996). The models are based on mass-balance accounting procedures to: 1) track the movement of water through a reservoir-stream system, 2) compute storage levels and discharges at pertinent locations in a stream-reservoir system, considering various sequences of hydrologic inputs (streamflow, rainfall, and evaporation) and demands for releases. Physical constraints, such as storage capacities, outlet and conveyance capacities, and institutional constraints, such as maintenance of flows associated with downstream water rights, are also reflected in the models (Wurbs, 1985). Multiple runs of a simulation model are made to analyze system performance under varying conditions, such as for alternative operating policies (Wurbs, 1996). On the other hand, an *optimization*[14] model is based on a formal mathematical algorithm that computes decision-variable values that minimize or maximize objective functions, subject to constraints. For a reservoir system problem the decision variables are typically release rates, end-of-period storage volumes, and allocation of water. The objective function may be a mathematical representation of a planning or operational objective, or may be a penalty or utility function used to define operating rules based on relative priorities (Wurbs, 1996). The general method for setting the objective function (and thus the system's performance) has been economic. Either the total cost of the system is minimized or the total economic benefit is maximized. Constraints typically reflect mass balances, storage capacities or other physical characteristics of the reservoir-stream system, diversion or streamflow requirements, and mass balances (Wurbs, 1993). Optimization techniques can be divided into three distinct categories: (1) linear programming, (2) dynamic programming, and (3) nonlinear programming.

Simulation and *optimization* modeling approaches are compared in Table A-1.

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[14] The term *optimization* is used synonymously with *mathematical programming*.

Table A-1. Some differences between Simulation and Optimization models

	Simulation Models	*Optimization Models*
Operating rules	A simulation models needs detailed specification of operating rules	Many optimization models compute the releases that optimize an objective function without directly using detailed operating rules, rather than providing general mechanisms for the user to define the operating rules in greater detail.
System representation	A simulation model permits a more detailed and realistic representation of the complex characteristics of a reservoir/river system (e.g. nonlinearities) providing greater modeling flexibility and versatility.	An optimization model usually requires assumptions and simplifications (e. g. linearization) of model structure and system constraints for practical implementation
Major hurdle	Simulation studies are only useful if the operating policies incorporated in the simulation realistically reflect current or potential system operation.	Major areas of complexity in optimization model development are defining system objectives, developing criteria for quantitatively measuring system performance in fulfilling the objectives, and handling interactions and conflicts between objectives.
Finding the optimal policy	Within a simulation approach there is often a frustratingly large number of feasible solutions and plans. It takes enormous computational effort to select a solution, which might still be far from optimal.	Optimization models automatically search for an "optimum" set of decision variable values looking (implicitly) at all possible decision alternatives
Foresight	Simulation models perform computations period by period in such a way that future streamflows are not reflected in release decisions, except for some models that include features for limited short-term forecasts.	Optimization models typically make all release decisions simultaneously, considering all streamflows covering the entire hydrologic period of analysis.

Sources: Wurbs (1993), Yeh (1985)

Although optimization and simulation are two alternative modeling approaches with different characteristics, the distinction is somewhat obscured by the fact that many models contain elements of both approaches. All optimization models also simulate the system to some extent and some of the simulation models have mathematical programming algorithms that derive the operating rules, although the model still represents actual and not "optimal" operations[15] (Wurbs, 1996). Simulation and optimization models can also be used in combination to analyze specific reservoir systems.

Another useful way of categorizing reservoir systems models, which pertains more to general modeling, is to classify them as either *descriptive* or *prescriptive* models. A *descriptive* model is a representation of a system that predicts behavior under a given set of conditions, i.e. it will demonstrate what will happen if a specified plan is adopted. On the other hand *prescriptive* models determine the plan (e.g. operating policies) that should be adopted to satisfy decision criteria (e.g. cost minimization) (Wurbs, 1996). Simulation models are in essence descriptive models, but optimization models that incorporate mathematical programming algorithms to automatically search for an optimum set of decision variable values may be either descriptively or prescriptively oriented. An example of the former is the network flow programming models.[16]

Considering this two model classifications and based on Wurbs (1996) we categorize for future use reservoir system analysis models as:

- Descriptive simulation models that use no mathematical programming algorithms
- Descriptive simulation models based on mathematical programming
- Prescriptive optimization models

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15 Examples of this latter case are the network flow programming models that have proven to be useful in reservoir system analysis. In a network flow model, the system is represented as a collection of nodes (location of reservoirs, diversion points, stream tributary confluences, etc.) and arcs (river stretches, canals, etc.). Each arc (and storage level) would have an associated cost or penalty (specified by the user) and an optimization algorithm would distribute the flows in order to minimize these costs.

16 Ibid.

Appendix B. Brief description of CALSIM-II, CALVIN and CVMod water resources models

CALSIM-II [17]

CALSIM-II is a network flow programming model developed jointly by DWR and U.S. Bureau of Reclamation to represent the joint CVP–SWP water supply delivery system.[18] CALSIM-II routes water in the system on a monthly basis using an integer-linear-programming solver of operational decisions, which minimize a priority-based penalty function of delivery and storage targets. Calibration of the weights of these penalty functions trains the model to adhere to operating rules and constraints such as fish flow requirements, downstream water quality objectives and contract deliveries to agricultural and urban water districts. The end-of-period storages from each optimization step are used as initial conditions for the following month's optimization. Between months, nonlinear simulation-style adjustments can be made to reflect more complex environmental regulations, groundwater dynamics, etc. Model output includes monthly reservoir releases, river flows, reservoir stored water volumes, Delta export activities, and indicators of Delta water quality. A baseline version of the model, called Benchmark Studies (DWR/USBR, 2002), was set up to perform monthly operations decisions for a 73-year simulation period that is based on the 1922 through 1994 hydrologic years experienced in the Central Valley. Water demands and system infrastructure are modified to represent 2001 and 2020 levels of development. This Baseline model is available in several versions, representing different subsets of state and federal regulations. The model focuses mostly on the Sacramento and San Joaquin Valley systems with some representation of surface deliveries to the Tulare Basin and Southern California urban areas. It does not include sources of water like the Colorado River or the Mono Lake basin.

CALVIN [19]

The CALVIN (**Cal**ifornia **V**alue **I**ntegrated **N**etwork) model was developed at UC Davis. The model is a *prescriptive optimization* model that operates surface and groundwater resources and allocates water over the historical hydrologic record. It maximizes the economic values of agricultural and urban water use statewide, within physical, environmental, and selected policy constraints (Draper et al., 2003). The CALVIN

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[17] Description based on Munevar and Chung (1999), Brekke et al (2004), Draper et al (2004) and Quinn et al. (2004).

[18] CALSIM-II replaced the previous agencies models: PROSIM, DWRSIM and SANJASM.

[19] Description based on Draper et al (2003).

schematic includes the entire Central Valley; the Trinity River system reservoirs; parts of the San Francisco Bay; southern California SWP contractors; Californian water users of the Colorado River, the Owens Valley, and Mono Basin; and finally groundwater sources of water, making it the model with the broadest coverage of water users in California. This optimization problem is solved using the USACE Hydrologic Engineering Center's *HEC-PRM* software, which uses a network solver. Monthly operation and allocation decisions within the optimization problem are made for a 72-year period based on the 1922–1993 hydrologic period with perfect foresight of future inflows.

CVMod [20]

CVMod (**C**entral **V**alley **Mod**el) is a simulation model developed at the University of Washington. The model operates at a monthly timestep and represents the major projects and operational features of the Sacramento–San Joaquin basin. CVMod simulates the movement and storage of water within the basin given current operational policies. The primary hydrologic input to CVMod is monthly streamflow, which comes either from observed naturalized streamflow (for studies of past climate) or from VIC simulations.[21] The model's outputs are reservoir levels and releases, from which the predicted performance of the system can be calculated. CVMod runs on STELLA, a commercially available object-oriented modeling package designed to simulate dynamic (time-varying or otherwise changing) systems characterized by interrelated components (Wurbs, 1996).

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20 Description based on VanRheenen et al (2004).

21 VIC (Variable Infiltration Capacity) is a regional hydrologic model implemented for the San Joaquin-Sacramento basins (VanRheenen et al., 2004).

Appendix C. Comparison of CVMod and CALSIM results with historical DWR data

The purpose of this Appendix is to compare the performance of the two water resources models analyzed in this project: CVMod and CALSIM-II. To assess the models' performance we compared the model estimates of end-of-month storage level in major Central Valley reservoirs with the historical storage. The period of analysis was 10/1979 through 6/1994.

In Table C-1 and Figures C-1 through C-22 we present the following results of this comparison, for each reservoir:

- average end-of-month storage derived from both models and the historical data
- average storage deficit/surplus from both models as compared to historical data
- standardized deficit/surplus (i.e. deficit/surplus divided by historical value)
- sum of squares of the deficits/surplus divided by average historical data (standardized)
- correlations between models and historical data

Examining these results it can be seen that CALSIM-II provides better estimates of storage overall than CVMod. CALSIM-II has both lower storage deficits, expressed as the standardized sum of square errors, and higher correlation with historical data (compare columns 7 with 10 and 11 with 12 in Table C-1) than CVMod for most of the reservoirs in the Central Valley. The differences between the outputs of the models and between the models and historical data are not entirely clear, but may be due to:

- The models are run considering a constant level of development (2001 in this case) rather than historical (variable) levels of development. This factor could explain why both models differ from historical data but not why they differ from each other. These differences could originate because CALSIM-II uses temporally variable demand while CVMod uses constant demands, or because they consider different representations of the regulations.

- CVMod may not match historical data as closely as CALSIM-II because CVMod's operations rules do not allow reservoirs to be drawn water below a conservation minimum level, which in actual operations does happen.

- A final possibility is the lack of any forecasting capability within CVMod, unlike CALSIM-II, which relies on the historical forecasting procedure to determine how much water to deliver or to store for carryover.

Table C-1. Comparison between CVMod and CALSIM results and DWR historical data on reservoirs storage in the Central Valley (1)

Reservoir	DWR data Average	CVMod Average	CALSIM Average	CVMod Average Deficit	CVMod Std Deficit (2)	CVMod Std Square deficits (3)	CALSIM Average Deficit	CALSIM Std Deficit (2)	CALSIM Std Square deficits (3)	CVMod Correl. (4)	CALSIM Correl. (4)
Shasta	3005	1605 (5)	2895	-1399	-0.47	***48***	-110	-0.04	***2***	0.59	0.94
Trinity	1739	1403	1391	-336	-0.19	***10***	-348	-0.20	***10***	0.89	0.90
Whiskeytown	220	223	224	3	0.01	***1***	4	0.02	***1***	0.79	0.80
Oroville	2456	2874	2371	418	0.17	***9***	-85	-0.03	***4***	0.82	0.88
Folsom	588	497	533	-91	-0.15	***21***	-54	-0.09	***9***	0.64	0.82
San Luis CVP	544	606	520	62	0.11	***29***	-24	-0.04	***29***	0.74	0.73
San Luis SWP	710	517	526	-193	-0.27	***41***	-184	-0.26	***52***	0.61	0.53
Camanche/ Pardee	421	422	444	2	0.00	***4***	23	0.05	***2***	0.90	0.94
New Hogan	117	95	109	-22	-0.19	***15***	-8	-0.07	***4***	0.93	0.98
New Melones	1039	926	1323	-113	-0.11	***55***	284	0.27	***69***	0.61	0.62
New Melones	1184	857	1231	-327	-0.28	***21***	47	0.04	***6***	0.89	0.94
New Don Pedro/ Lake	1872	1822	1929	-50	-0.03	***4***	57	0.03	***1***	0.92	0.97

Notes:

(1) For the period 10/79 - 6/94

(2) Equals the average of the deficits divided by DWR average data

(3) Equals the sum of deficits squared divided by DWR average data

(4) Correlation between model data and DWR data

(5) We are not confident at this point about the CVMod results for Shasta reservoir. We're checking with the model developers at U. of Washington about the large difference between CVMod and historical storage results. One possible source different run period used in this analysis and the one (much longer) used in the calibration of the model 2 years ago (Nathan VanRheenen, University of Washington, personal communication).

(6) Most of the deficits for New Melones come from the first two years where both CVMod and CALSIM reservoirs start with considerably more water stored than DWR historical data. These results are consistent with the fact that New Melones was built in 1978 and that CVMod is initialized by output from a longer-period run of CALSIM-II. This is why we present a separate set of results only including data after 3/82, when the reservoir was filled.

Sources:
CVMod results: 03-04 version, CALSIM Historical run, 2001 LOD
CALSIM results: Sep 01, Benchmark Studies D1641, 2001 LOD
DWR data: CDEC website, http://cdec.water.ca.gov/misc/resinfo.html

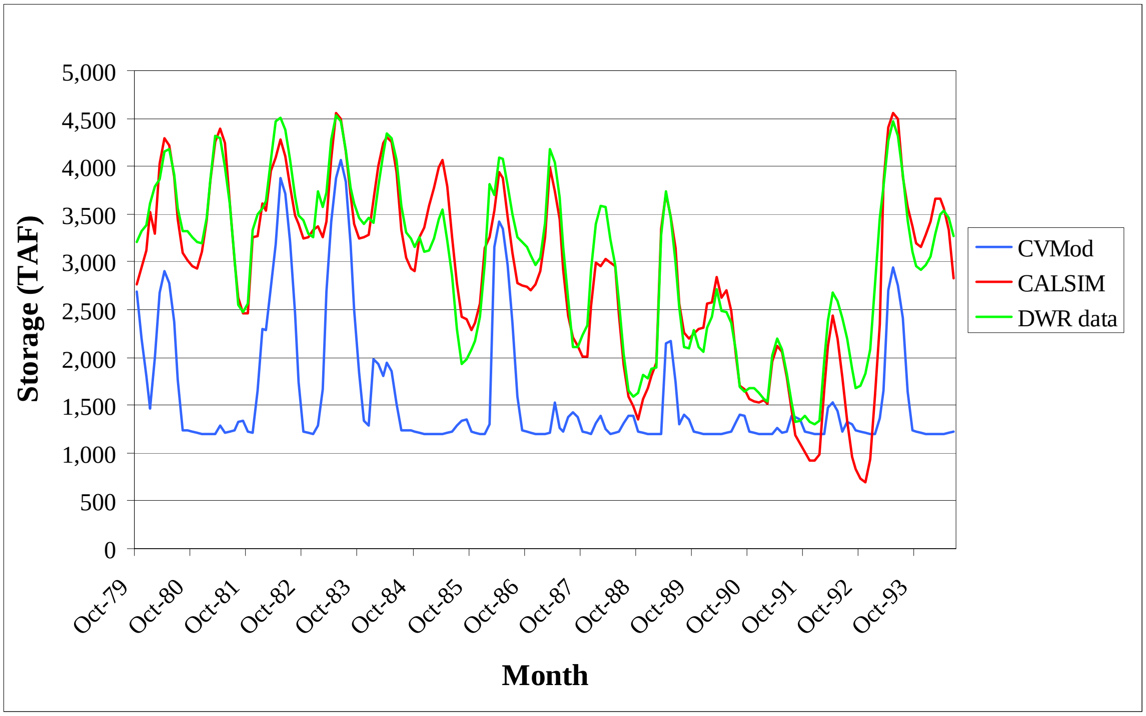
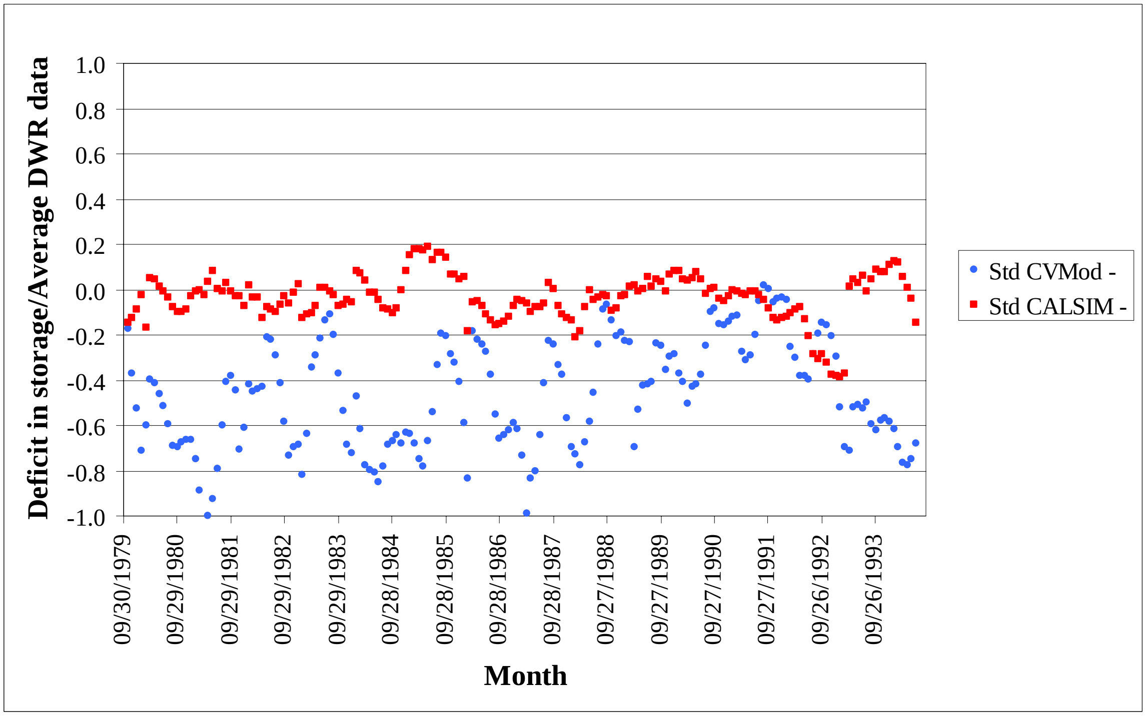


Figure C-1. Comparison of end of month Shasta storage levels



Standardized Deficit/Surplus = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-2. CALSIM-II and CVMod standardized deficit/surplus in Shasta storage level compared to historical data

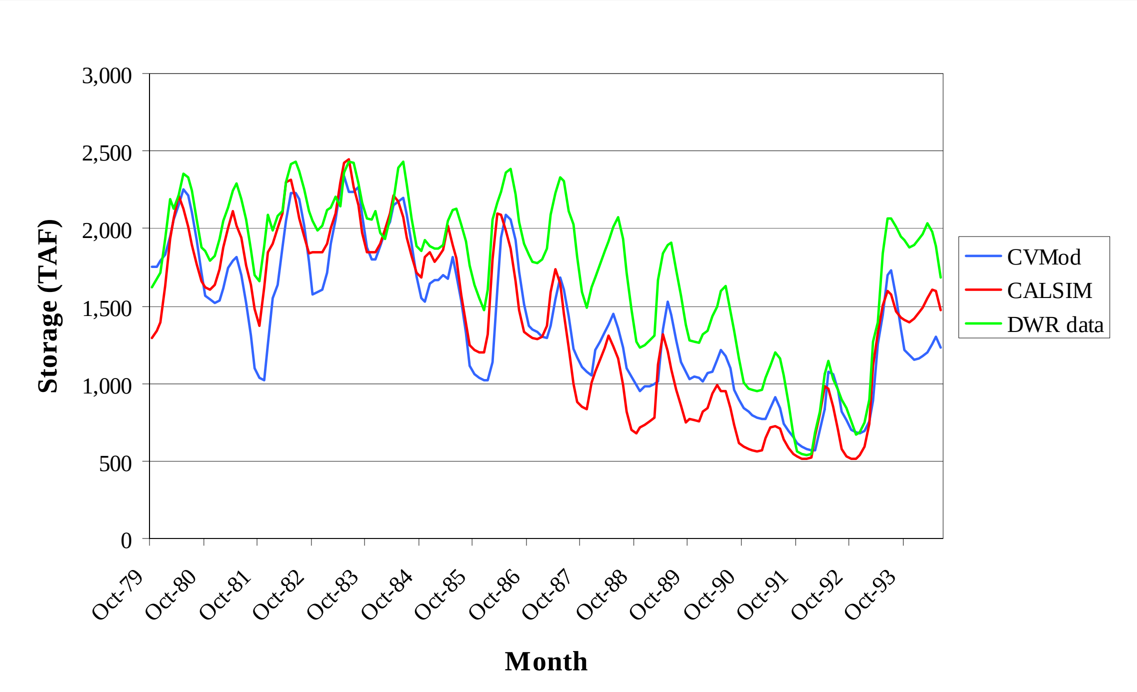
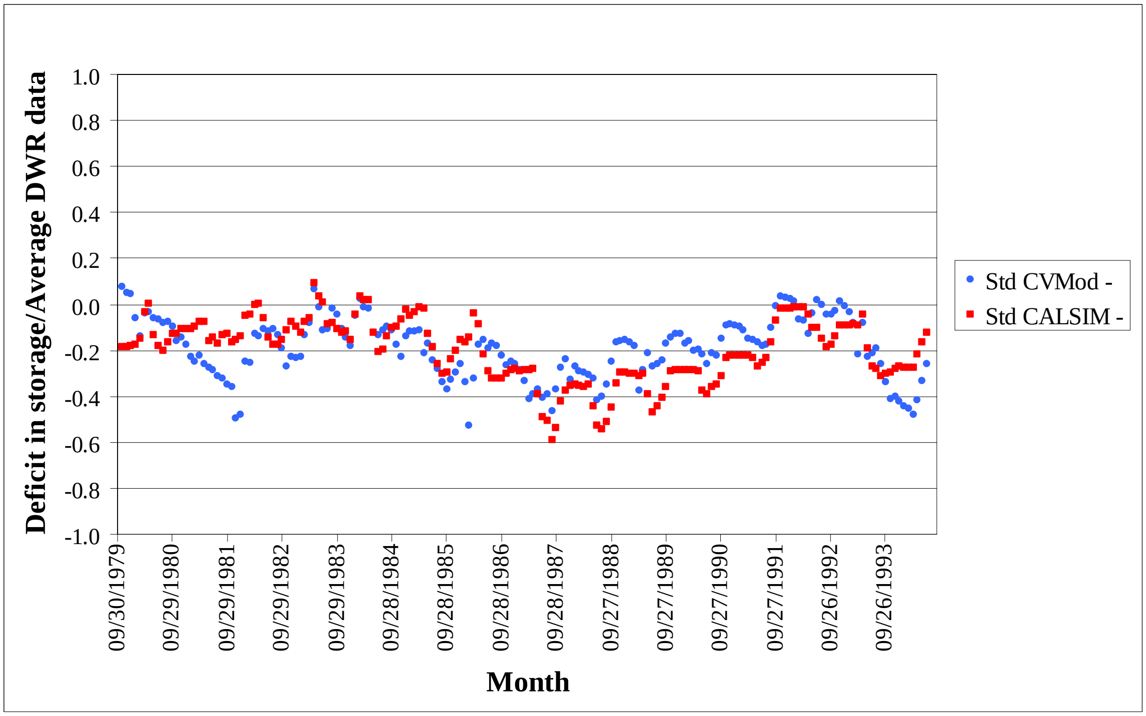


Figure C-3. Comparison of end of month Trinity storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-4. CALSIM-II and CVMod standardized deficit/surplus in Trinity storage level compared to historical data

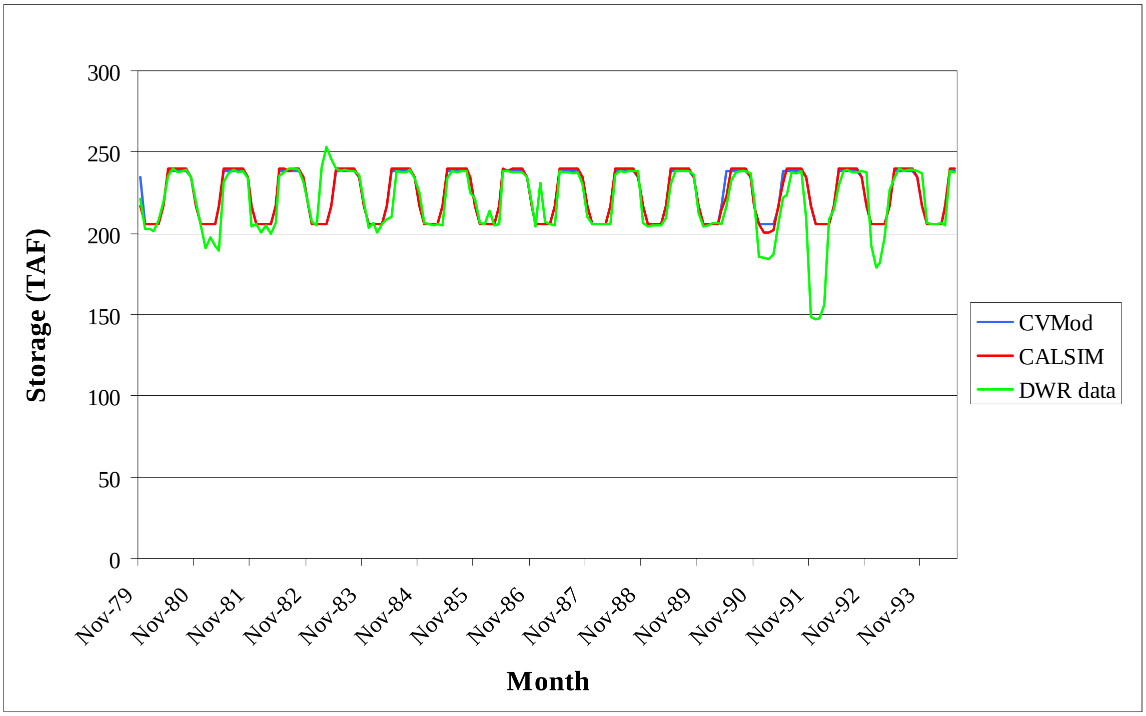
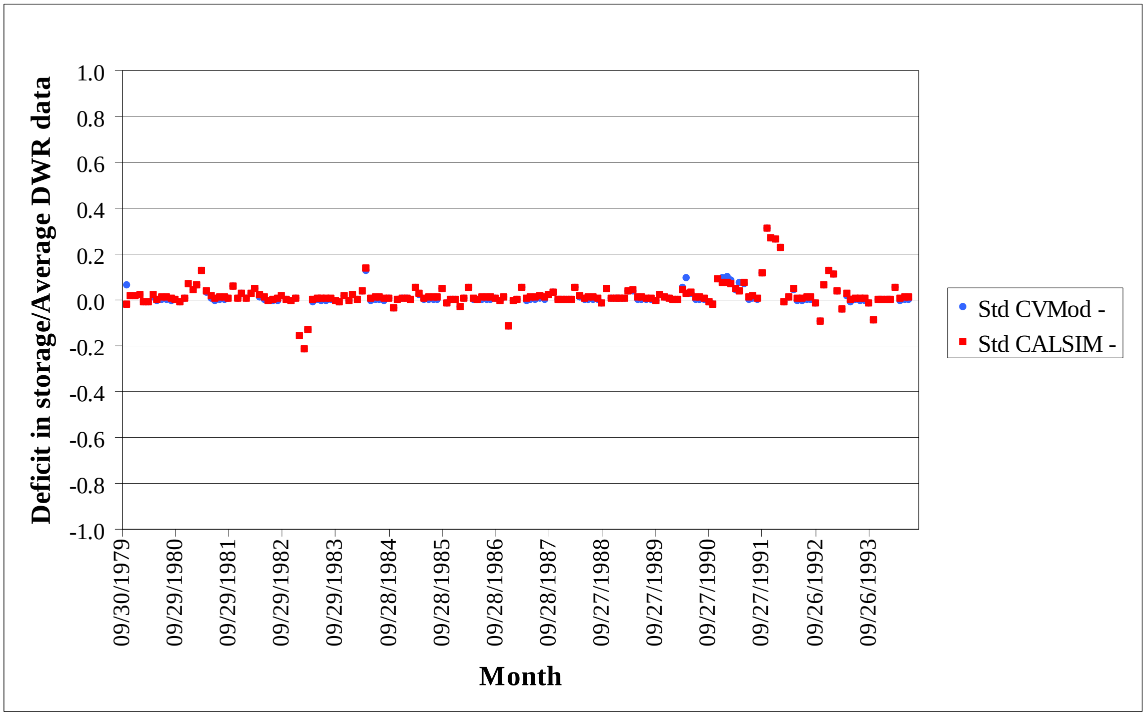


Figure C-5. Comparison of end of month Whiskeytown storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-6. CALSIM-II and CVMod standardized deficit/surplus in Whiskeytown storage level compared to historical data

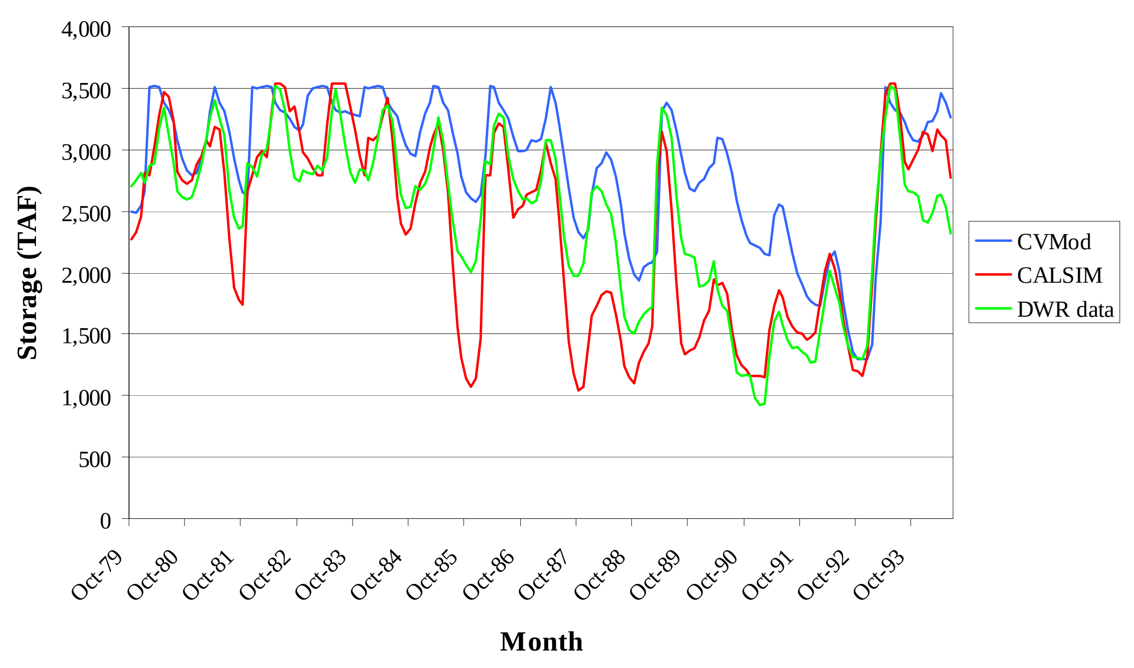
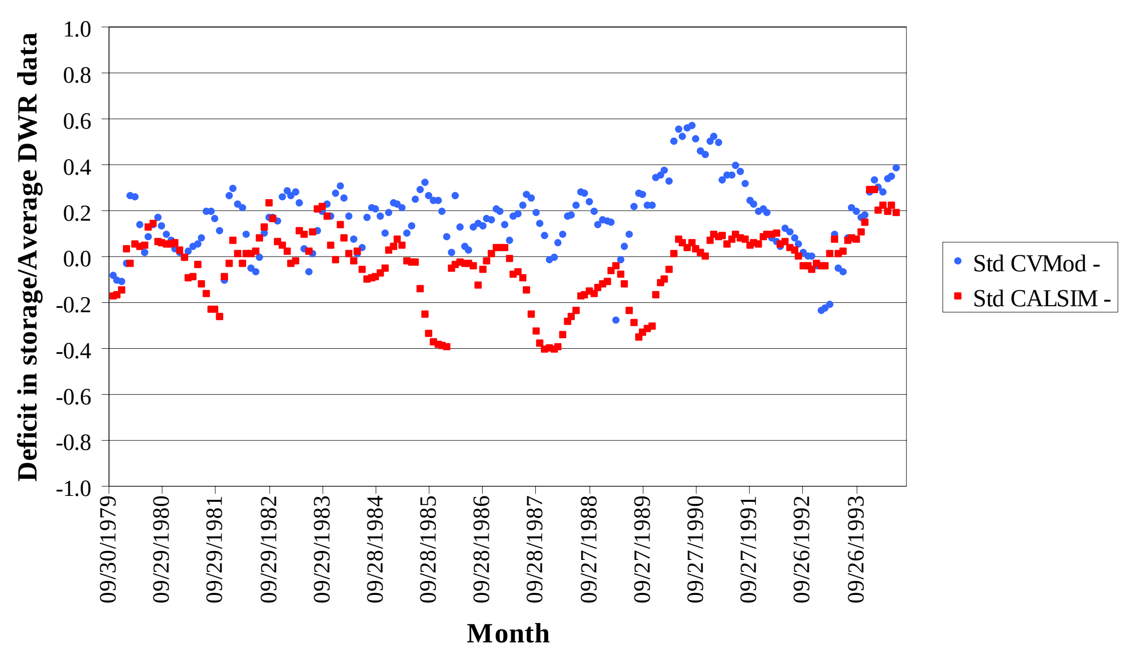


Figure C-7. Comparison of end of month Oroville storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-8. CALSIM-II and CVMod standardized deficit/surplus in Oroville storage level compared to historical data

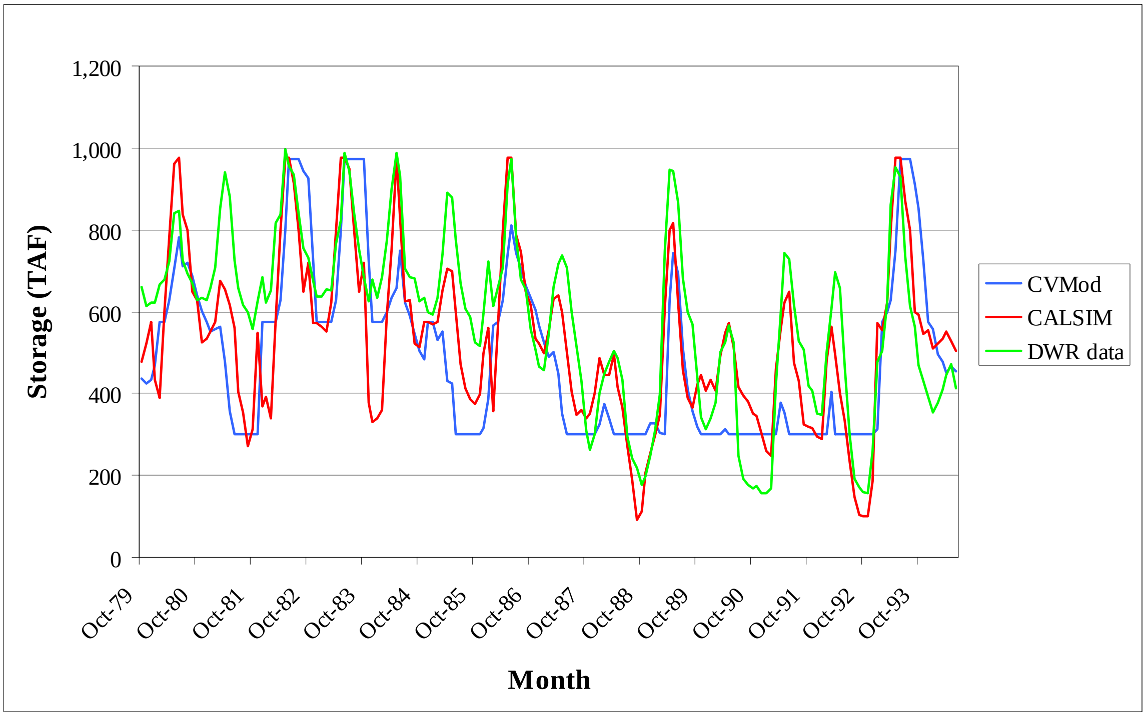
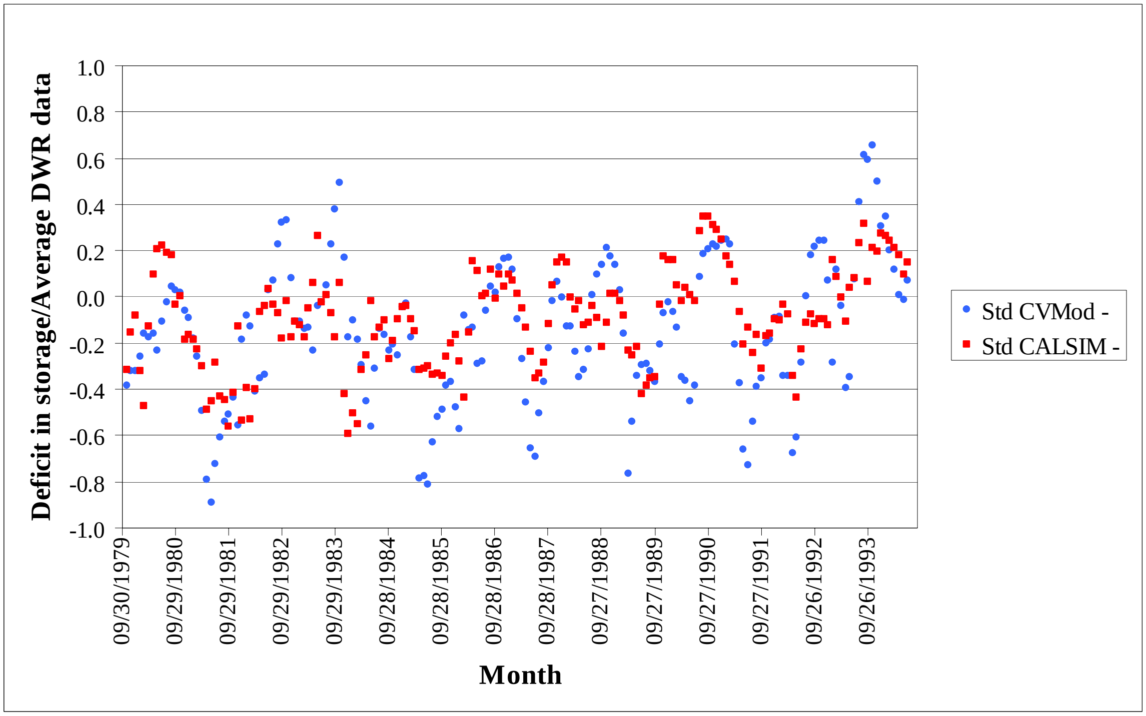


Figure C-9. Comparison of end of month Folsom storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-10. CALSIM-II and CVMod standardized deficit/surplus in Folsom storage level compared to historical data

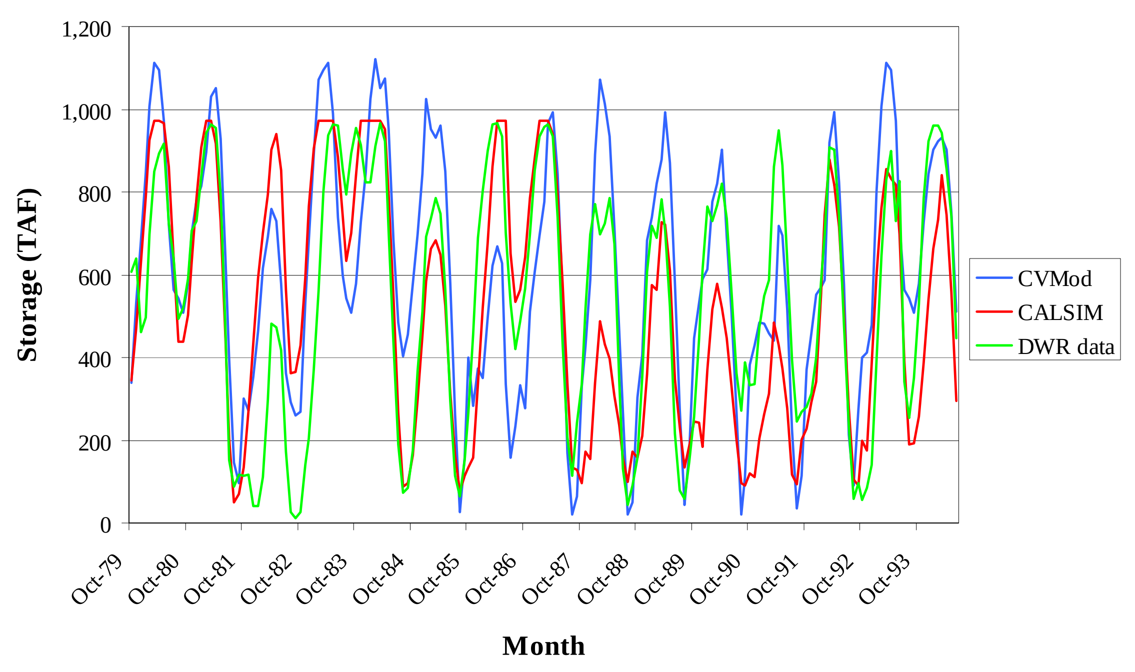
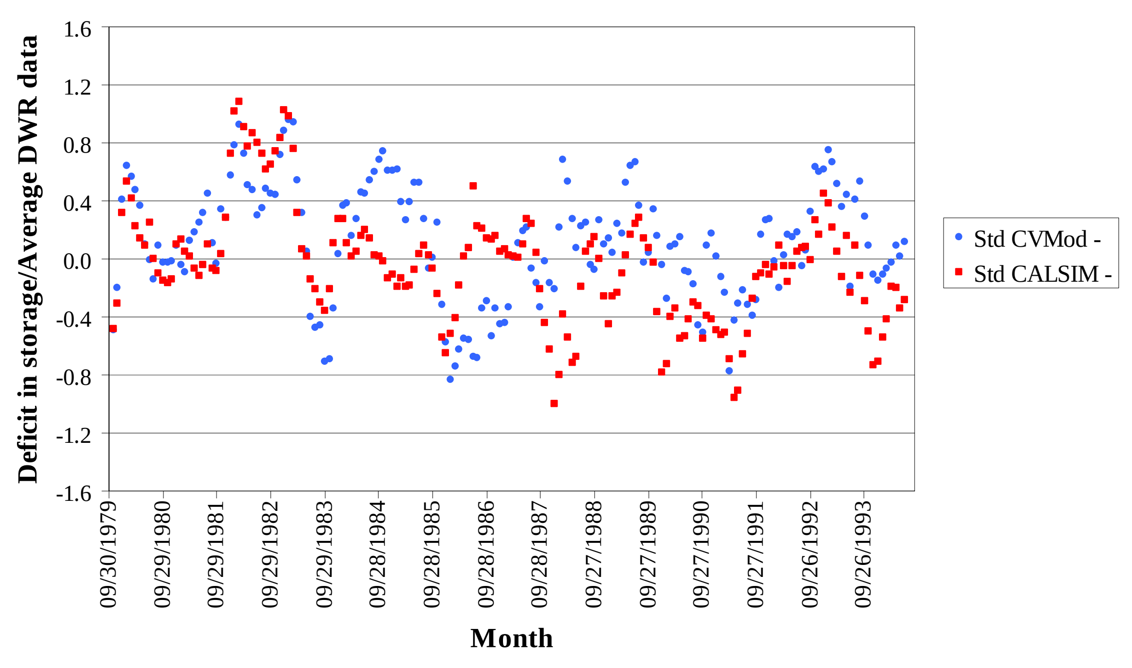


Figure C-11. Comparison of end of month San Luis CVP storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-12. CALSIM-II and CVMod standardized deficit/surplus in San Luis CVP storage level compared to historical data

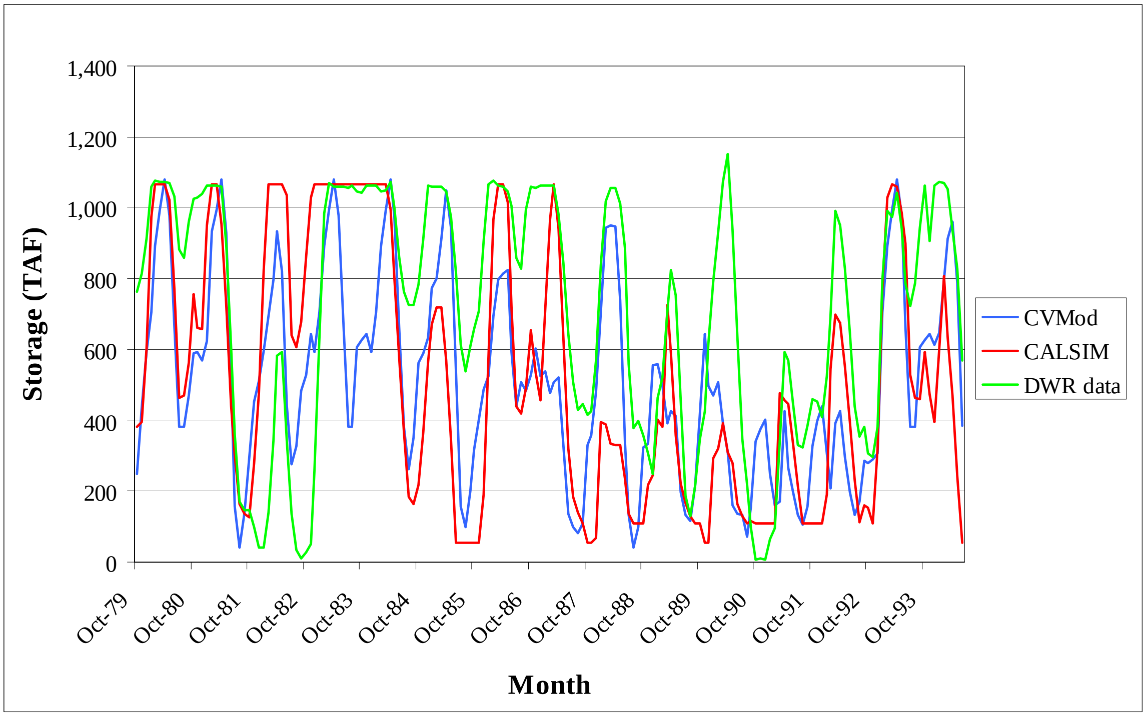
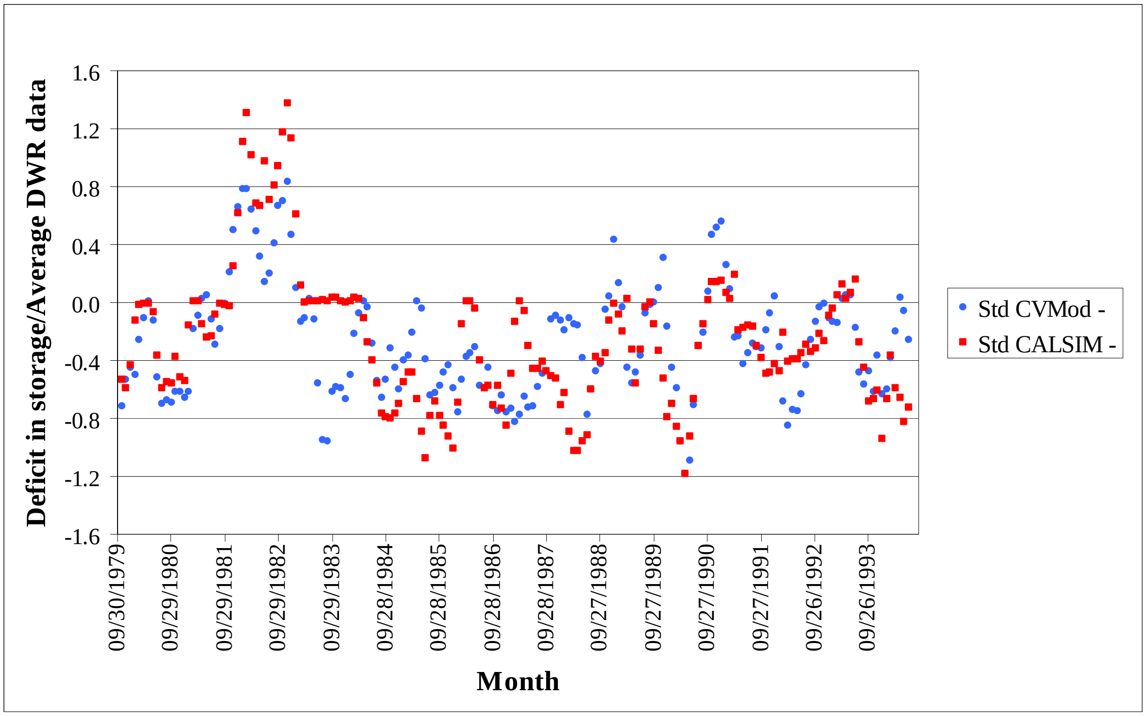


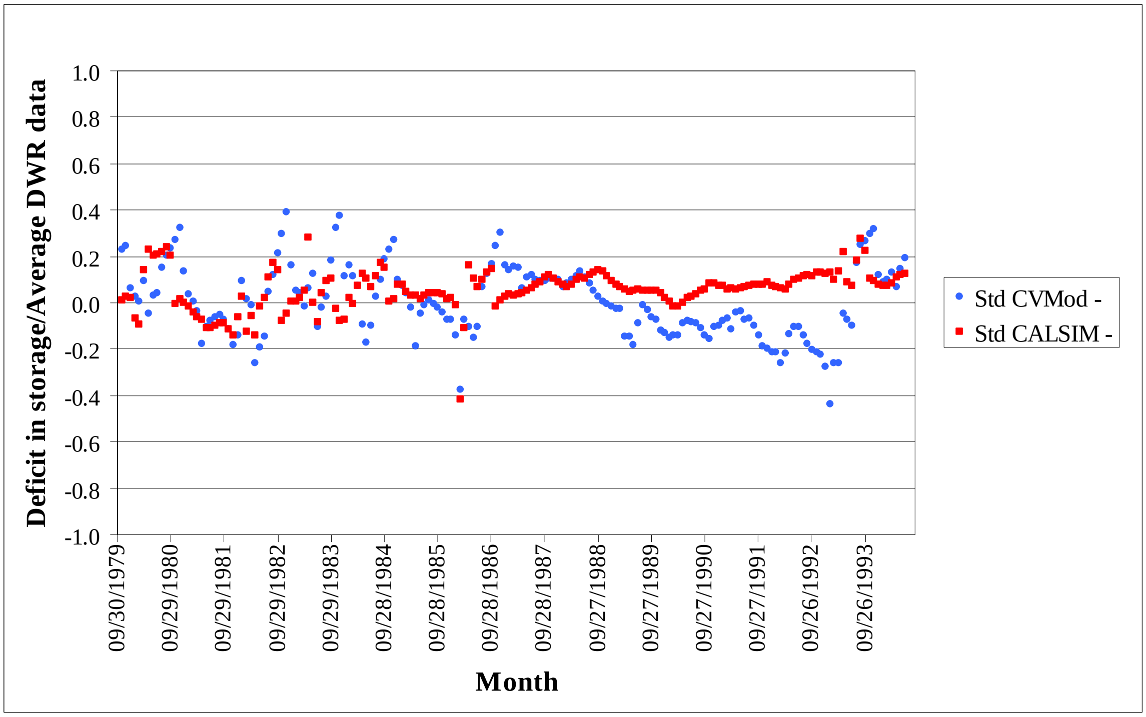
Figure C-13. Comparison of end of month San Luis SWP storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-14. CALSIM-II and CVMod standardized deficit/surplus in San Luis SWP storage level compared to historical data

Figure C-15. Comparison of end of month Camanche + Pardee storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-16. CALSIM-II and CVMod standardized deficit/surplus in Camanche + Pardee storage level compared to historical data

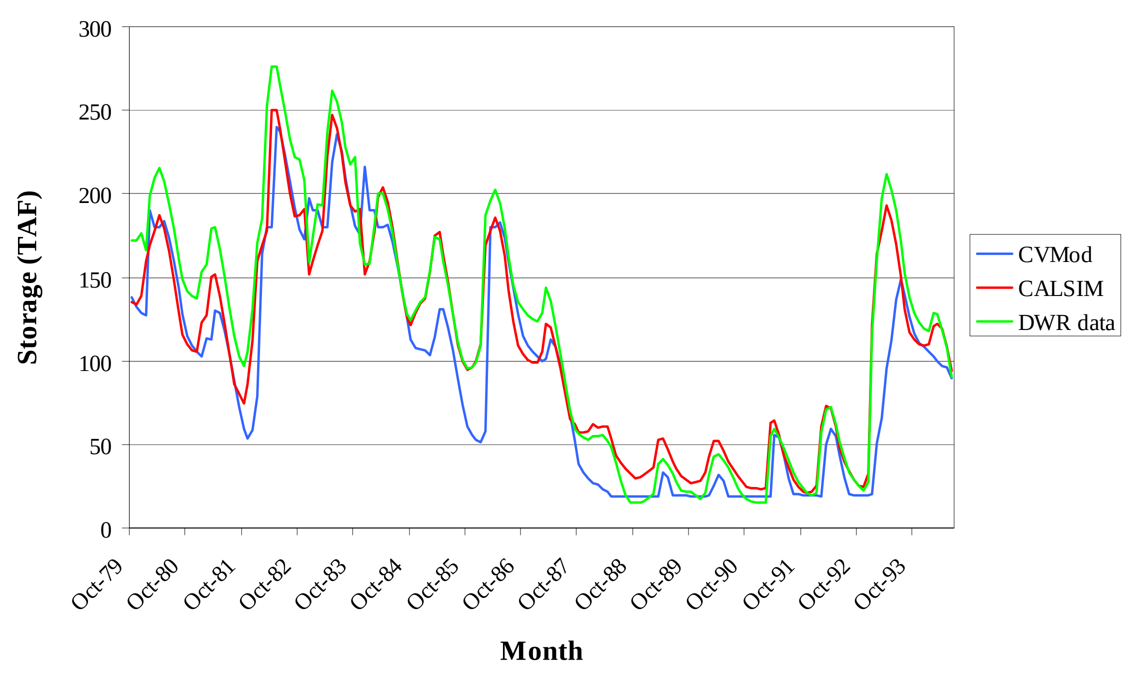
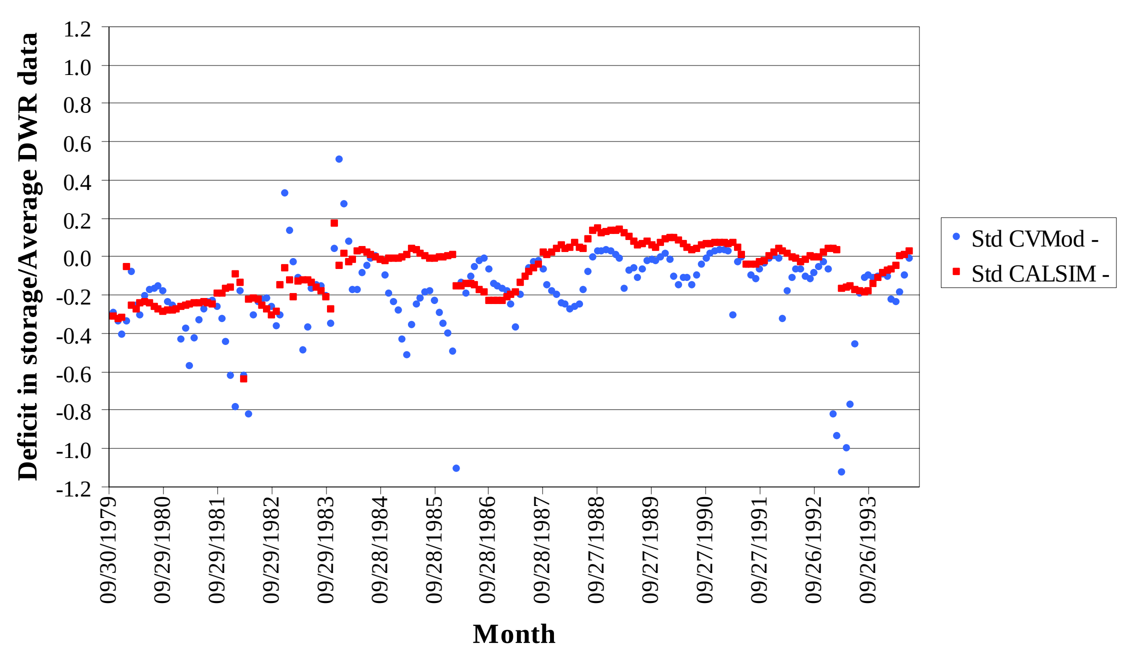


Figure C-17. Comparison of end of month New Hogan storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-18. CALSIM-II and CVMod standardized deficit/surplus in New Hogan storage level compared to historical data

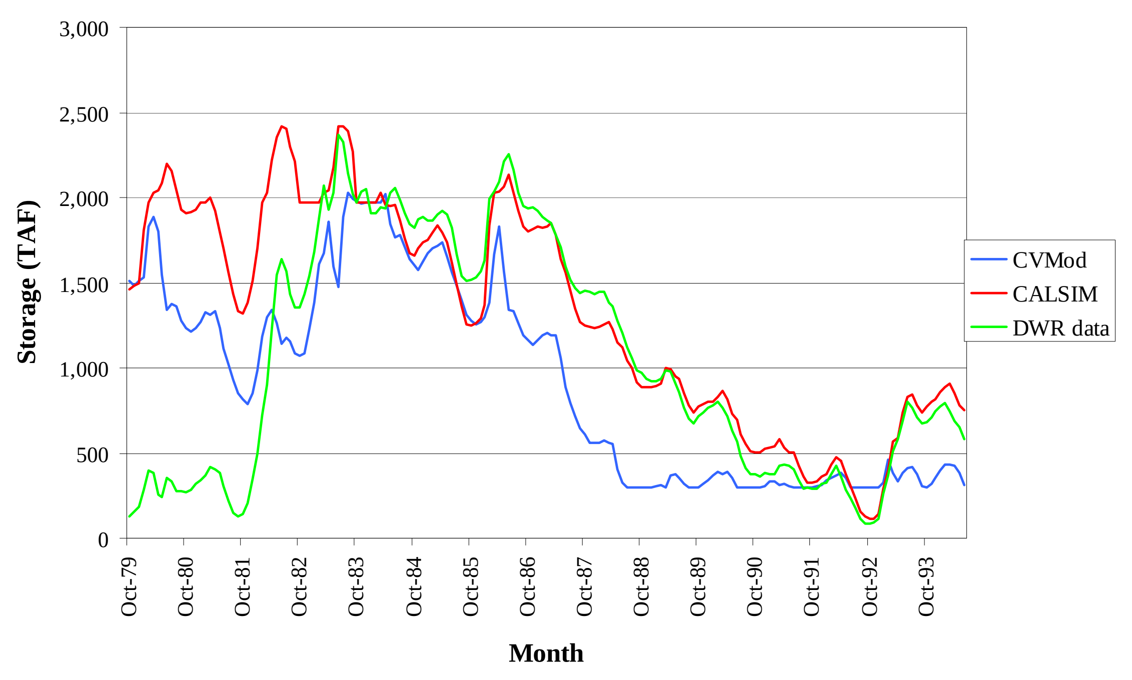
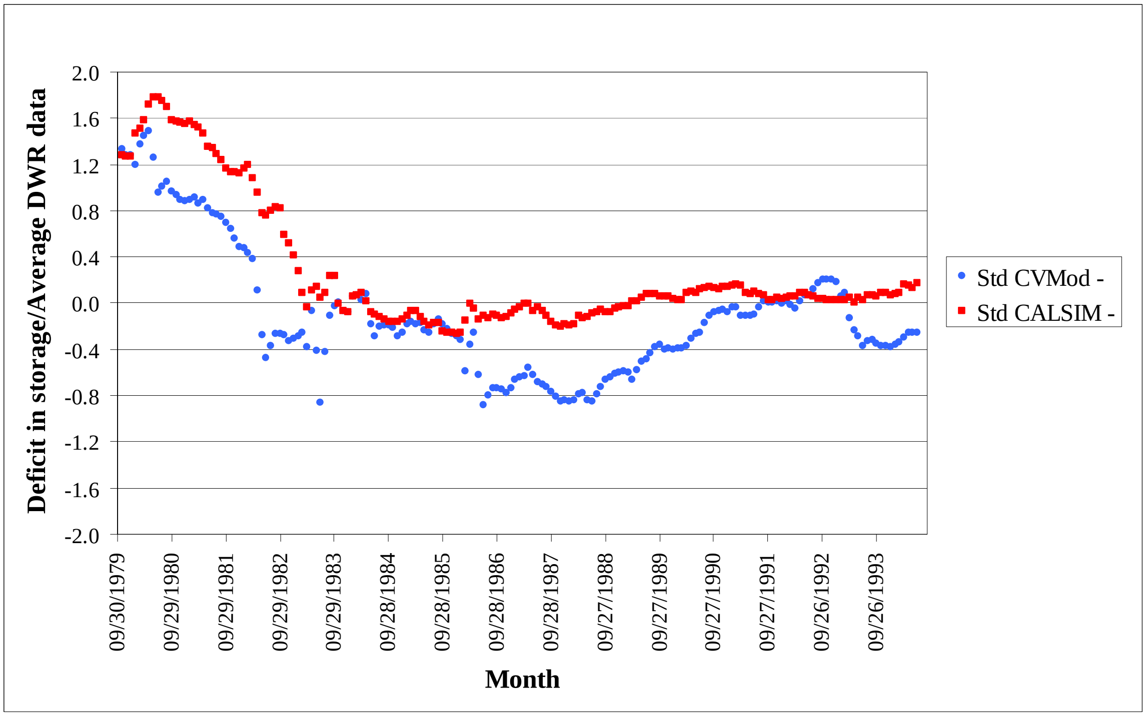


Figure C-19. Comparison of end of month New Melones storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-20. CALSIM-II and CVMod standardized deficit/surplus in New Melones storage level compared to historical data

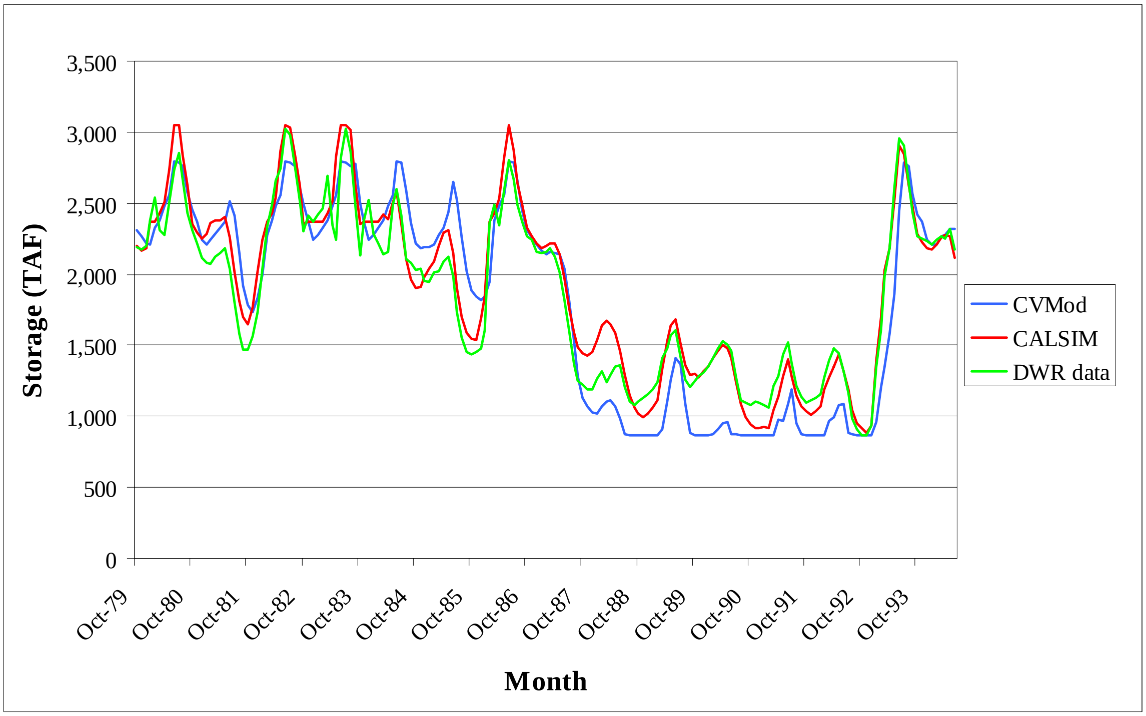
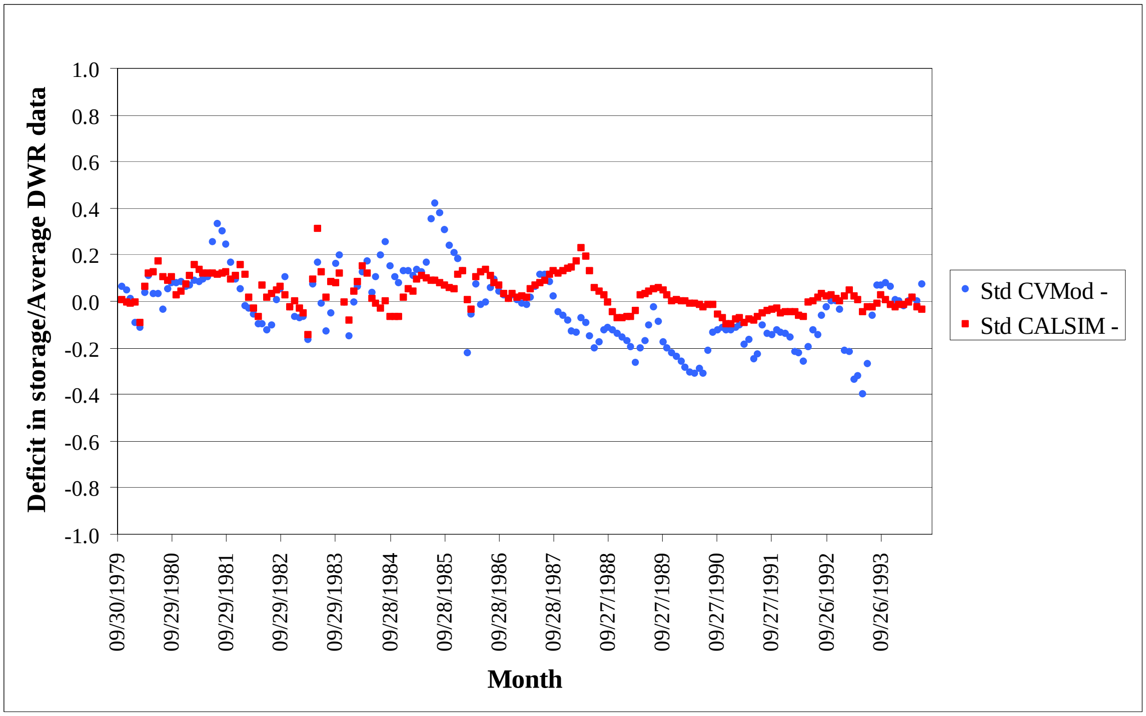


Figure C-21. Comparison of end of month New Don Pedro + Lake McClure storage levels



Standardized Deficit = (Model Result – DWR historical data) / Average of DWR historical data

Figure C-22. CALSIM-II and CVMod standardized deficit/surplus in New Don Pedro + Lake McClure storage level compared to historical data

Appendix D: Assessing California water system reliability using CALSIM-II model. Sources of data and explanation of methodology

This Appendix explains the sources of data and the procedures followed to estimate the reliability measures for different users in the California Central Valley. Our analysis is based on the results of the most recent available simulations runs for CALSIM-II, known as the Benchmark Studies (DWR/USBR, 2002). Using the available data on demands and deliveries (only surface water deliveries) we calculated monthly and annual quantity-based reliability measures (eq 1), defined as the percentage of water delivered compared to a target delivery level (water demand).[22] With both the monthly and annual reliability measures we constructed frequency curves of these values and calculated an overall reliability measure (eq 2).

Monthly/Annually quantity-based reliability measure are calculated by:

$$R_{ij} = 1 - \frac{(Demand_{ij} - Delivery_{ij})}{Demand_{ij}} \text{ if } Demand_{ij} \geq Delivery_{ij}\text{; if not } R_{ij} = 1 \quad (1)$$

The overall reliability measure is calculated by:

$$R_i = 1 - \frac{\sum_j \left(Demand_{ij} - Delivery_{ij} \right)^+}{\sum_j Demand_{ij}} \quad (2)$$

where *i* represents a certain user (or group of users) and *j* represents the corresponding timestep (month or year). The + sign denotes that only positive values are considered.

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22 This definition is based on Hashimoto et al. (1982) and Bogardi J.J. and Verhoef A. (1995). A time-base definition of reliability would be the fraction of time a system is under a no failure mode defined by a certain target. Other measures of a system performance not included in this analysis are the vulnerability and resilience (see Hashimoto et al (1982).

The analysis was performed for different types of users according to geographic location, source of water, and water rights status. These different users were also aggregated into different levels. The first level considered the whole Central Valley system.[23] The second level compared reliability measures for broad geographic categories of users: North of the Delta (NOD) Project and non-project users; State Water Project (SWP) South of the Delta (SOD) users; Central Valley Project (CVP) SOD users and East San Joaquin users. Figure D-1 shows a map of these broad categories of users. The third and final level assesses the reliability of supply to more specific user groups.[24] An example of the analysis done at this step was the comparison of supply reliability among different CVP users (e.g., Between Exchange, Agriculture, M&I and Refugee Contractors). Figure D-2 shows a schematic of how the different users in the Central Valley are classified into this different types and levels of aggregation.

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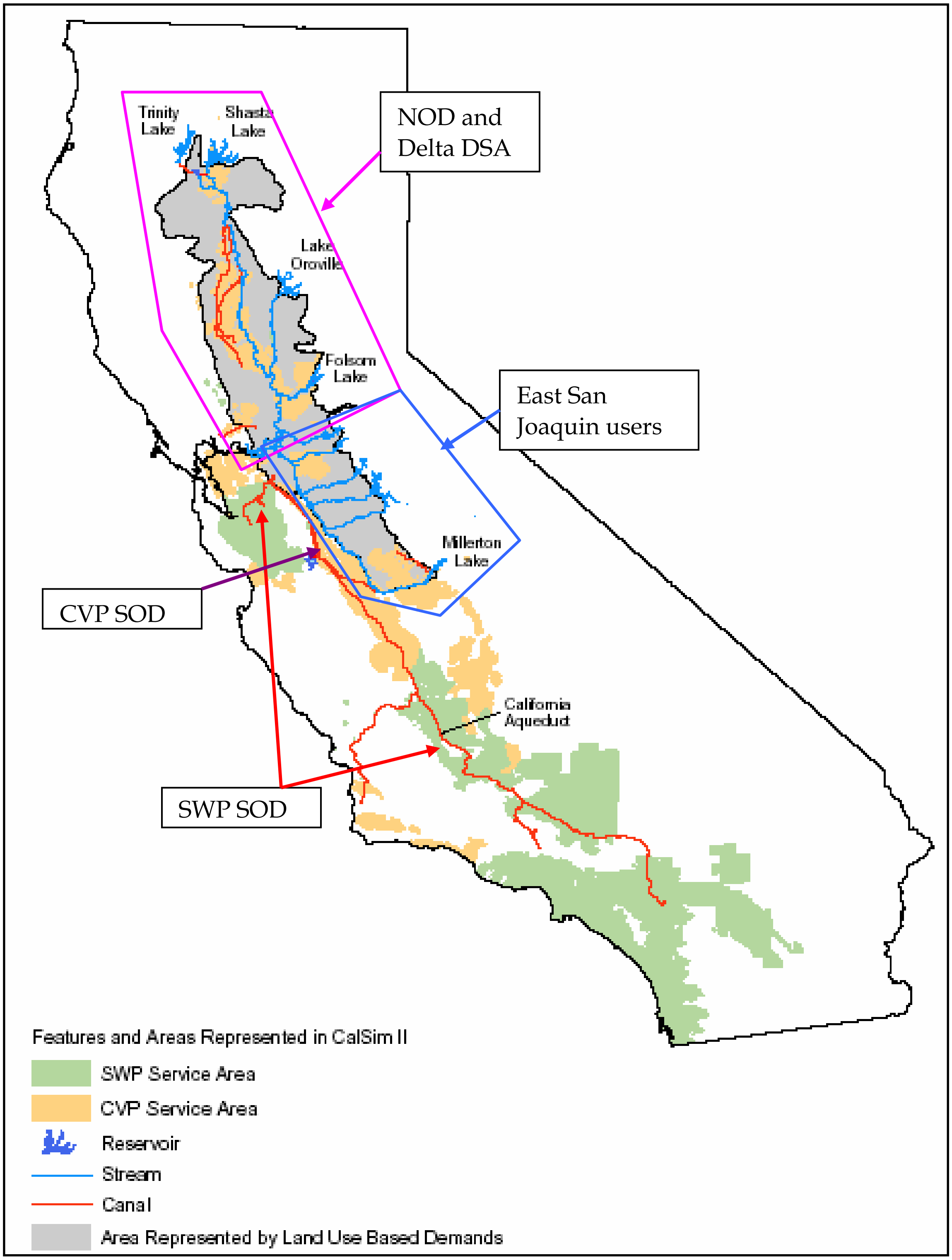
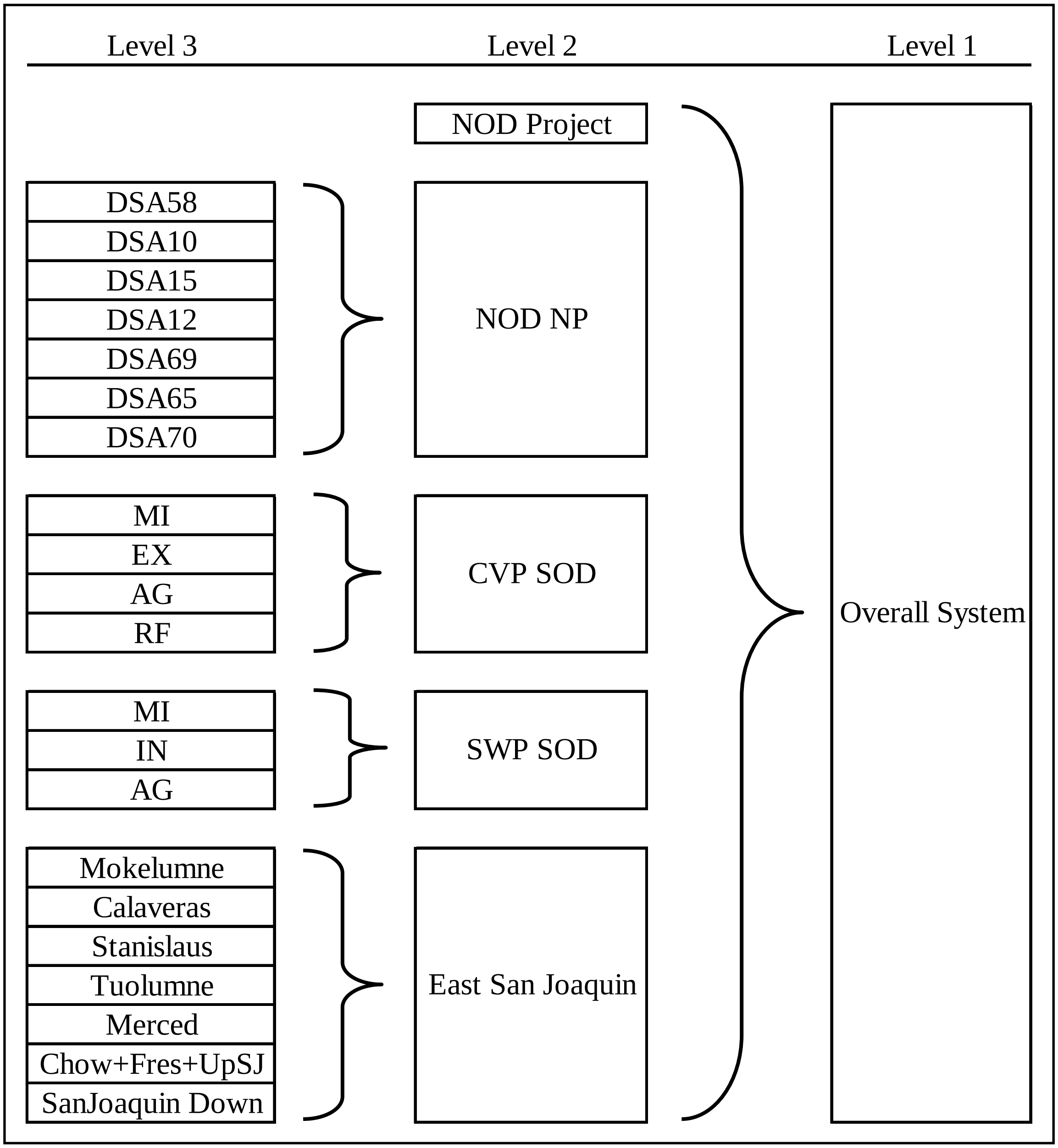
23 Delta users were not considered in the analysis because there are some concerns about the corresponding CALSIM-II results that need to be discussed with the DWR.

24 Using CALSIM-II it is possible to conduct a further step analysis of reliability at the level of Irrigation District, but there is not yet good representation of these users so we preferred not to do it at this time.



Notes: NOD = North of the Delta; DSA = Depletion Study Areas;
CVP = Central Valley Project; SWP = State Water Project

Figure D-1. Geographic location of users within CALSIM-II



Notes: NOD = North of the Delta; SOD = South of the Delta; DSA = Depletion Study Areas; CVP = Central Valley Project; SWP = State Water Project; AG = Agriculture Contractor; SC = Settlement Contractor; MI = M&I contractor; RF = Refugee Contractor; EX = Exchange Contractor

Figure D-2. Schematic showing group of users within CALSIM-II

The following Table details the source of data from CALSIM-II runs that were used to estimate reliability for all users in Level 3. The aggregation of this data (see Figure D-2) was used to determine the reliability measure for users in Level 2 and 1. We excluded arc couples that represented only depletions and associated accretions (there are many of these in the ESJ and Delta region). We also only include surface water deliveries.

Table D-1. CALSIM-II variables representing the demands and deliveries, for different water users in the Central Valley, used to estimate the reliability measures. (1)

Level 2 **Level 3**	**Demand Arc**	**Delivery Arc (2)**
NOD NP (3)		
DSA 58 NP	0.1 * /DR58/DEMAND/	/D104_NP/FLOW-DELIVERY/
DSA 10 NP	0.81 * /DR10/DEMAND/	/D117A_NP/FLOW-DELIVERY/
DSA 12 NP	0.25 * /DR12/DEMAND/	/C144B_SPILL_NP/FLOW-CHANNEL/
DSA 15 NP	0.34 * /DR15/DEMAND/	/D128_NP/FLOW-DELIVERY/
DSA 69 NP	0.30 * /DR69/DEMAND/	/D211_NP/FLOW-DELIVERY/ /D213A_NP/FLOW-DELIVERY/ /D207A/FLOW-DELIVERY/ /D217/FLOW-DELIVERY/
DSA 65 NP	0.88 * /DR65/DEMAND/	/C152A_NP/FLOW-CHANNEL/
DSA 70 NP	0.62 * /DR70/DEMAND/	/D308_NP/FLOW-DELIVERY/ /D168/FLOW-DELIVERY/
NOD PRJ (3)		
DSA 58 PRJ	0.9 * /DR58/DEMAND/	/D104_PRJ/FLOW-DELIVERY/
DSA 10 PRJ	0.19 * /DR10/DEMAND/	/D112B_PRJ/FLOW-DELIVERY/ /D117A_PRJ/FLOW-DELIVERY/
DSA 12 PRJ	0.75 * /DR12/DEMAND/	/D122_PRJ/FLOW-DELIVERY/ /C144B_SPILL_PRJ/FLOW-CHANNEL/ /C142C/FLOW-CHANNEL/ /D112A_PRJ/FLOW-DELIVERY/
DSA 15 PRJ	0.66 * /DR15/DEMAND/	/D128_PRJ/FLOW-DELIVERY/
DSA 69 PRJ	0.70 * /DR69/DEMAND/	/D206A_PRJ/FLOW-DELIVERY/ /D206B_PRJ/FLOW-DELIVERY/ /D201_PRJ/FLOW-DELIVERY/ /D202_PRJ/FLOW-DELIVERY/ /D204_PRJ/FLOW-DELIVERY/ /D7A_PRJ/FLOW-DELIVERY/ /D7B_PRJ/FLOW-DELIVERY/ /D6_PRJ/FLOW-DELIVERY/
DSA 65 PRJ	0.12 * /DR65/DEMAND/	/C152A_PRJ/FLOW-CHANNEL/

Level 2 **Level 3**	**Demand Arc**	**Delivery Arc** [(2)]
DSA 70 PRJ	0.38 * /DR70/DEMAND/	/D304_OMI/FLOW-DELIVERY/ /D308_OMI/FLOW-DELIVERY/ /D309A_OMI/FLOW-DELIVERY/ /D308_PSC/FLOW-DELIVERY/
CVP SOD		
RF	/DEM_D708_PRF/DEMAND-CVP-RF/ /DEM_D856_PRF/DEMAND-CVP-RF/ /DEM_D607C_PRF/DEMAND-CVP-RF/	/D708_PRF/FLOW-DELIVERY/ /D856_PRF/FLOW-DELIVERY/ /D607C_PRF/FLOW-DELIVERY/
MI	/DEM_D711_PMI/DEMAND-CVP-MI/ /DEM_D844_PMI/DEMAND-CVP-MI/	/D711_PMI/FLOW-DELIVERY/ /D844_PMI/FLOW-DELIVERY/
EX	/DEM_D707_PEX/DEMAND-CVP-EX/ /DEM_D607B_PEX/DEMAND-CVP-EX/	/D707_PEX/FLOW-DELIVERY/ /D607B_PEX/FLOW-DELIVERY/
AG	/DEM_D700_PAG/DEMAND-CVP-AG/ /DEM_D701_PAG/DEMAND-CVP-AG/ /DEM_D710_PAG/DEMAND-CVP-AG/ /DEM_D706_PAG/DEMAND-CVP-AG/ /DEM_D833_PAG/DEMAND-CVP-AG/ /DEM_D835_PAG/DEMAND-CVP-AG/ /DEM_D837_PAG/DEMAND-CVP-AG/ /DEM_D839_PAG/DEMAND-CVP-AG/ /DEM_D841_PAG/DEMAND-CVP-AG/ /DEM_D843_PAG/DEMAND-CVP-AG/ /DEM_D855_PAG/DEMAND-CVP-AG/ /DEM_D607A_PAG/DEMAND-CVP-AG/	/D700_PAG/FLOW-DELIVERY/ /D701_PAG/FLOW-DELIVERY/ /D710_PAG/FLOW-DELIVERY/ /D706_PAG/FLOW-DELIVERY/ /D833_PAG/FLOW-DELIVERY/ /D835_PAG/FLOW-DELIVERY/ /D837_PAG/FLOW-DELIVERY/ /D839_PAG/FLOW-DELIVERY/ /D841_PAG/FLOW-DELIVERY/ /D843_PAG/FLOW-DELIVERY/ /D855_PAG/FLOW-DELIVERY/ /D607A_PAG/FLOW-DELIVERY/
SWP SOD		
MI	/DEM_D810_PMI/DEMAND-SWP-MI/ /DEM_D813_PMI/DEMAND-SWP-MI/ /DEM_D814_PMI/DEMAND-SWP-MI/ /DEM_D815_PMI/DEMAND-SWP-MI/ /DEM_D869_PMI/DEMAND-SWP-MI/ /DEM_D851_PMI/DEMAND-SWP-MI/ /DEM_D877_PMI/DEMAND-SWP-MI/ /DEM_D878_PMI/DEMAND-SWP-MI/ /DEM_D879_PMI/DEMAND-SWP-MI/ /DEM_D881_PMI/DEMAND-SWP-MI/ /DEM_D25_PMI/DEMAND-SWP-MI/ /DEM_D883_PMI/DEMAND-SWP-MI/ /DEM_D884_PMI/DEMAND-SWP-MI/ /DEM_D27_PMI/DEMAND-SWP-MI/ /DEM_D885_PMI/DEMAND-SWP-MI/ /DEM_D899_PMI/DEMAND-SWP-MI/ /DEM_D895_PMI/DEMAND-SWP-MI/ /DEM_D886_PMI/DEMAND-SWP-MI/	/D810_PMI/FLOW-DELIVERY/ /D813_PMI/FLOW-DELIVERY/ /D814_PMI/FLOW-DELIVERY/ /D815_PMI/FLOW-DELIVERY/ /D869_PMI/FLOW-DELIVERY/ /D851_PMI/FLOW-DELIVERY/ /D877_PMI/FLOW-DELIVERY/ /D878_PMI/FLOW-DELIVERY/ /D879_PMI/FLOW-DELIVERY/ /D881_PMI/FLOW-DELIVERY/ /D25_PMI/FLOW-DELIVERY/ /D883_PMI/FLOW-DELIVERY/ /D884_PMI/FLOW-DELIVERY/ /D27_PMI/FLOW-DELIVERY/ /D885_PMI/FLOW-DELIVERY/ /D899_PMI/FLOW-DELIVERY/ /D895_PMI/FLOW-DELIVERY/ /D886_PMI/FLOW-DELIVERY/

Level 2 **Level 3**	**Demand Arc**	**Delivery Arc** [(2)]
	/DEM_D887_PMI/DEMAND-SWP-MI/	/D887_PMI/FLOW-DELIVERY/
	/DEM_D888_PMI/DEMAND-SWP-MI/	/D888_PMI/FLOW-DELIVERY/
	/DEM_D28_PMI/DEMAND-SWP-MI/	/D28_PMI/FLOW-DELIVERY/
	/DEM_D29_PMI/DEMAND-SWP-MI/	/D29_PMI/FLOW-DELIVERY/
	/DEM_D896_PMI/DEMAND-SWP-MI/	/D896_PMI/FLOW-DELIVERY/
IN	/DEM_D810_PIN/DEMAND-SWP-IN/	/D810_PIN/FLOW-DELIVERY/
	/DEM_D814_PIN/DEMAND-SWP-IN/	/D814_PIN/FLOW-DELIVERY/
	/DEM_D815_PIN/DEMAND-SWP-IN/	/D815_PIN/FLOW-DELIVERY/
	/DEM_D868_PIN/DEMAND-SWP-IN/	/D868_PIN/FLOW-DELIVERY/
	/DEM_D846_PIN/DEMAND-SWP-IN/	/D846_PIN/FLOW-DELIVERY/
	/DEM_D848_PIN/DEMAND-SWP-IN/	/D848_PIN/FLOW-DELIVERY/
	/DEM_D849_PIN/DEMAND-SWP-IN/	/D849_PIN/FLOW-DELIVERY/
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	/DEM_D883_PIN/DEMAND-SWP-IN/	/D883_PIN/FLOW-DELIVERY/
	/DEM_D884_PIN/DEMAND-SWP-IN/	/D884_PIN/FLOW-DELIVERY/
	/DEM_D27_PIN/DEMAND-SWP-IN/	/D27_PIN/FLOW-DELIVERY/
	/DEM_D885_PIN/DEMAND-SWP-IN/	/D885_PIN/FLOW-DELIVERY/
	/DEM_D899_PIN/DEMAND-SWP-IN/	/D899_PIN/FLOW-DELIVERY/
	/DEM_D895_PIN/DEMAND-SWP-IN/	/D895_PIN/FLOW-DELIVERY/
AG	/DEM_D867_PAG/DEMAND-SWP-AG/	/D867_PAG/FLOW-DELIVERY/
	/DEM_D868_PAG/DEMAND-SWP-AG/	/D868_PAG/FLOW-DELIVERY/
	/DEM_D802_PAG/DEMAND-SWP-AG/	/D802_PAG/FLOW-DELIVERY/
	/DEM_D846_PAG/DEMAND-SWP-AG/	/D846_PAG/FLOW-DELIVERY/
	/DEM_D847_PAG/DEMAND-SWP-AG/	/D847_PAG/FLOW-DELIVERY/
	/DEM_D848_PAG/DEMAND-SWP-AG/	/D848_PAG/FLOW-DELIVERY/
	/DEM_D849_PAG/DEMAND-SWP-AG/	/D849_PAG/FLOW-DELIVERY/
	/DEM_D851_PAG/DEMAND-SWP-AG/	/D851_PAG/FLOW-DELIVERY/
	/DEM_D853_PAG/DEMAND-SWP-AG/	/D853_PAG/FLOW-DELIVERY/
	/DEM_D859_PAG/DEMAND-SWP-AG/	/D859_PAG/FLOW-DELIVERY/
	/DEM_D863_PAG/DEMAND-SWP-AG/	/D863_PAG/FLOW-DELIVERY/
ESJ		
Mokelumne	/DEMAND_D90_PAG/DEMAND/	/D90_PAG/FLOW-DELIVERY/
	/DEMAND_D90_PMI/DEMAND/	/D90_PMI/FLOW-DELIVERY/
	/DEMAND_D502_PAG/DEMAND/	/D502_PAG/FLOW-DELIVERY/
	/DEMAND_D502_PMI/DEMAND/	/D502_PMI/FLOW-DELIVERY/
	/DEMAND_D503A_NP/DEMAND/	/D503A_NP/FLOW-DELIVERY/
	/DEMAND_D503A_PAG/DEMAND/	/D503A_PAG/FLOW-DELIVERY/
	/DEMAND_D503A_PMI/DEMAND/	/D503A_PMI/FLOW-DELIVERY/
Calaveras	/DEMAND_D506_PAG/DEMAND/	/D506_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D506_PMI/DEMAND/	/D506_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D507A_NP/DEMAND/	/D507A_NP_SW/FLOW-DELIVERY/
	/DEMAND_D507A_PAG/DEMAND/	/D507A_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D507A_PMI/DEMAND/	/D507A_PMI_SW/FLOW-DELIVERY/

Level 2 **Level 3**	**Demand Arc**	**Delivery Arc** (2)
Stanislaus	demand_D520_PAG (4)	/D520_CSJSEWD_PAG/FLOW-DELIVERY/
	demand_D520_PMI (4)	/D520_SEWD_PMI/FLOW-DELIVERY/
	demand_D16A_OID (4)	/D16A_OID/FLOW-DELIVERY/
	demand_D16A_SSJID (4)	/D16A_SSJID/FLOW-DELIVERY/
	/DEMAND_D525/DEMAND/	/D525_NP/FLOW-DELIVERY/
Tuolumne	/DEMAND_D540_PAG/DEMAND/	/D540_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D540_PMI/DEMAND/	/D540_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D541_PAG/DEMAND/	/D541_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D541_PMI/DEMAND/	/D541_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D544/DEMAND/	/D544_NP/FLOW-DELIVERY/
Merced	/DEMAND_D562_PAG/DEMAND/	/D562_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D562_PMI/DEMAND/	/D562_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D567/DEMAND/	/D567_NPSW/FLOW-DELIVERY/
Chowchilla +Fresno + Upper San J.	/DEMAND_D580_PAG/DEMAND/	/D580_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D580_PMI/DEMAND/	/D580_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D583_PAG/DEMAND/	/D583_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D583_PMI/DEMAND/	/D583_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D600A/DEMAND/	/D600A/FLOW-DELIVERY/
	/DEMAND_D602/DEMAND/	/D602_NP/FLOW-DELIVERY/
SanJoaquin Down	/DEMAND_D613/DEMAND/	/D613_NP/FLOW-DELIVERY/
	/DEMAND_D621B/DEMAND/	/D621B_NP/FLOW-DELIVERY/
	/DEMAND_D625/DEMAND/	/D625_NP/FLOW-DELIVERY/
	/DEMAND_D639/DEMAND/	/D639_NP/FLOW-DELIVERY/

Notes:

(1) All these variable names represent the "B" and "C" parts of DSS-type of time-series of data available from CALSIM-II Benchmark studies run (http://modeling.water.ca.gov/hydro/studies/Version2_Benchmark.html).

Demand DSS files are found in:
\BST_2001D10A_ANNBENCHMARK_1_2\common\DSS\2001D10ASV.DSS
Deliveries DSS files are found in:
\BST_2001D10A_ANNBENCHMARK_1_2\D1641\DSS\2001D10ADV.DSS

We do not consider users represented only by a depletion arc coupled with an accretion arc. These are common in the Delta and East San Joaquin regions.

(2) We only consider surface water deliveries, and not the groundwater pumping that fulfills part of the user's demands.

(3) Demand estimates for NOD users within CALSIM-II are timeseries based on land-use (e.g. dr10). These are further split into project and non-project demands based on predefined percentages.

(4) These demands are considered in CALSIM-II as intermediate variables and are not included in the final output. The names of these intermediate variables are considered here (see CALSIM file: *stan_dem.wresl*).