Sensitivity of Upper Tuolumne River Flow

to Climate Change Scenarios

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JANUARY 2012

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Glossary of Terms and Acronyms

Albedo
The fraction of short wave solar radiation reflected by a surface or object, often expressed as a percentage. Snow covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation covered surfaces and oceans have a low albedo.

Algorithm (modeling)
Software or a sequence of instructions for functions that model a physical process.

Anthropogenic
Resulting from or produced by human beings.

Aspect (Geography)
The direction that a mountain slope faces. Snow will melt out on south facing slopes while snow remains on north facing slopes.

Calibration (Hydrologic Models)
The adjustment of parameters in hydrologic process algorithms in a hydrologic model so that simulated streamflow and snowpack information more closely matches recorded streamflow and snow course measurements.

CDEC
The California Data Exchange Center collects data with the cooperation of 140 other agencies and provides real-time forecast and historical hydrologic data.

Climate
Climate is the "average weather", or more rigorously, is the statistical description of weather in terms of the mean and variability of relevant quantities (temperature, precipitation, wind) over a period of time ranging from months to tens or hundreds of years.

Climate Model (Global Climate Model or General Circulation Model, GCM)
A numerical representation of the climate system based on the physical, chemical and biological properties of its components and feedback processes. The climate system can be represented by models of varying complexity, with the complexity increasing with the number of spatial dimensions and the physical, chemical or biological processes that are explicitly represented, or the level at which empirical parameterizations are involved. Coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCMs) provide the most comprehensive representation of the climate system.

Climate System
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere.

Diurnal Temperature Range (DTR)
The difference between the maximum and minimum temperature during a day.

El Niño-Southern Oscillation (ENSO)
El Niño is a warm water current which periodically flows toward the coast of Ecuador and Peru. This is associated with a fluctuation of the inter-tropical surface pressure pattern and circulation in the Indian and Pacific oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation, or ENSO.

Evapotranspiration
The combined process of evaporation from the Earth's surface and transpiration from vegetation. *Potential* evapotranspiration is the total evapotranspiration that could occur if moisture were continuously available. *Actual* evapotranspiration is the evapotranspiration that occurs given the available moisture supply.

Exceedance Probability
The likelihood that an event or condition will be exceeded expressed as the ratio of the number of actual occurrences of exceedance to the number of possible occurrences of exceedance. Exceedance probability is often used in environmental risk modeling.

GNL, HRS, SLI, PDS, TUN, CHV, HTH, BKM, MCN, MSR, MID
Acronyms used by the California Data Exchange Center (CDEC) for hydrometeorological stations in the Tuolumne watershed.

Greenhouse Gas (GHG)
Greenhouse gases trap heat within the surface-troposphere system. They are natural and anthropogenic gases that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the atmosphere.

HFAM
Hydrologic Forecast and Analysis Modeling developed by Hydrocomp, Inc. HFAM version 2.3, completed in 2011, was used for the climate change analysis. HFAM is a continuous simulation model that operates on hourly time steps. The model interface is the computer screens used to operate the model and view results.

Historic Meteorological Database
Historic data refers to observed and extended historic data. Meteorological data were processed to provide hourly timeseries when observed hourly data were not available. Processing included:

- Temperature – estimating hourly values from max-min daily records, correlations with other sites.
- Precipitation – daily to hourly distributions from other sites or from prior events at the same site. Correlations with other sites.
- Solar radiation – top of atmosphere data reduced by atmospheric absorption and cloud cover.

- Potential Evapotranspiration – diurnal patterns and seasonal median values.
- Wind – diurnal patterns and seasonal median values.

(See also Static Meteorological Database)

Hydrologic Model
A numerical representation of processes in the hydrologic cycle (snow accumulation and melt, soil moisture, infiltration, evapotranspiration, runoff and streamflow) based on continuous meteorological timeseries (precipitation, potential evapotranspiration, solar radiation, wind, air temperature). HFAM is a hydrologic model that has been calibrated to represent hydrologic processes in the Tuolumne River.

IPCC
The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization and the United Nations Environmental Program.

Land Segment
A portion of the land surface for which hydrologic processes are modeled. Land segments in HFAM have unique characteristics (elevation, slope, aspect, vegetal cover, soils, etc.). Runoff from land segments enters stream reaches that carry flows through the channel network.

Lapse Rate
The decrease in temperature in the atmosphere per unit of elevation. A typical lapse rate for moist air is 3 ˚F per 1000 ft. of elevation but lapse rates are highly variable.

Median
A value in an ordered set of values that separates the higher half of the values from the lower half.

MID
Modesto Irrigation District

NCDC
National Climate Data Center, NOAA, Ashville, NC

Parameterization
In climate and hydrologic models, this is the technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes).

PDO
The Pacific (inter) Decadal Oscillation, or PDO, is a long-lived El Niño-like oscillatory pattern of climate variability centered over the Pacific Ocean and North America. The PDO has considerable influence on climate sensitive natural resources in the Pacific and over North America, including the water supplies and snowpack in some selected regions in North America (Mantua N.J. 2002)

Response Time (or Time to Equilibrium)
The response time or adjustment time is the time needed for the climate system or its components to re-equilibrate to a new state, following a forcing resulting from external and internal processes or feedbacks. Atmospheric response times are relatively short (days to weeks). Ocean response times, due to their large heat capacity, are much longer (decades to centuries).

SFPUC
San Francisco Public Utilities Commission

Simulation
The imitation of a real process or processes that entails representing certain key characteristics or behaviors of a selected physical system to gain insight into their functioning. Simulation can be used to show the eventual real effects of alternative conditions and courses of action. Hydrologic models and climate models are examples of simulation models. Output from these models may be called 'simulated data'.

SNOWCF
The snow correction factor is a HFAM model parameter which increases precipitation when precipitation falls as snow to compensate for reduced catch at gages.

Soil Moisture
Water stored in or at the land surface and available for evaporation or transpiration.

Solar Radiation
Radiation emitted by the Sun. It is also referred to as short-wave radiation.

Static Meteorological Data Base
Historic data that have been adjusted by removing historic trends. Only air temperature records at Hetch Hetchy Reservoir and Cherry Valley Dam were adjusted. The static meteorological database is used to create weather inputs for 2010 current conditions and future conditions under climate change scenarios. (See also Historic Meteorological Database)

SRES
Special Report on Emissions Scenarios developed by the IPCC.

Surficial Hydrologic Processes
Hydrologic processes (snow accumulation and melt, infiltration, soil moisture storage, evapotranspiration, etc.) that occur at the land surface, or (typically) within a few meters of the land surface.

TID
Turlock Irrigation District

Trend Analysis
Analyzing information or data with the goal of identifying a pattern, or trend, in the data. In climate change studies, trends in meteorological timeseries are evaluated by fitting a straight line

to the data over twenty or more years (least squares fit) to separate climate change effects from the chaotic variability of weather.

XML (Extensible Markup Language)
XML is a general purpose specification for creating custom markup languages. Its purpose is to aid information systems in sharing structured data. It is used by HFAM so that input and output can be shared easily with WORD, EXCEL and other XML conversant software.

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Executive Summary

Climate change is a concern to water managers with facilities within the Tuolumne watershed. The purpose of this study was to determine streamflow sensitivities to possible increases in temperature and change in precipitation due to climate change. For this study, the likelihood of any particular climate future was not assessed, and the report did not seek to comprehensively frame all the changes climate scientists expect from global warming. Nor did the report seek to address potential water supply impacts of climate change. The goal of the study was simply to assess the sensitivity of reservoir inflows to a range of changes in two variables, temperature and precipitation. For that reason, a physically-based conceptual hydrology simulation model was calibrated against past conditions and used to assess potential changes in the timing and volume of runoff that may occur for the years 2040, 2070 and 2100 as compared to the conditions in 2010. A review of the literature and consultation with climate science experts allowed selection of climate scenarios that encompassed a range of temperature and precipitation changes that may be experienced through 2100 so that potential changes in watershed runoff could be simulated and analyzed.

Climate Change Scenarios

Climate change scenarios for this study were selected to represent a range of possible future climate conditions based on the range of predictions by global climate models.

Table ES-1 lists the potential future climate condition in terms of a change in temperature and precipitation from the 2010 conditions for the years 2040, 2070 and 2100 for each climate change scenario. A 34-year stationary meteorological database was developed and the increments shown in Table ES-1 were used to create adjusted temperature and precipitation timeseries that represent potential future conditions for each climate change scenario. This technique allowed the analysis of a 34-year period with consistent climate conditions at three future dates, each of which had six combinations of temperature and precipitation changes.

Hydrologic Simulation Model

The HFAM hydrologic model of the Tuolumne, developed by Hydrocomp over a twelve year period for the Turlock Irrigation District (TID), was used in this study to simulate the watershed's hydrologic response to precipitation, temperature, evaporation, solar radiation and wind. The model calculates the hydrologic response of more than 900 land segments in the watershed above Don Pedro and routes runoff downstream to reservoirs through 75 channel reaches. Each land segment represents the elevation, soil and rock outcrop, vegetation and aspect associated with a portion of the watershed. The model performs detailed mass and energy budget calculations to simulate the hydrologic cycle on each land segment. By combining and routing the flow from each segment, the model provides detailed information on the effects of basin-wide temperature and precipitation changes on runoff, snow, evapotranspiration and soil moistures.

Table ES-1. Constructed climate change scenarios with temperature increases and precipitation changes

Scenario	Description	Mean Annual Temperature (˚F (˚C))[1]			Mean Annual Precipitation (in)[1]		
Current Conditions	2010 conditions	55.1 (12.8)			36.9		
Future Climate Change Scenarios		**Change from Base (˚F (˚C))[2]**			**Change from Base (%)[3]**		
		2040	**2070**	**2100**	**2040**	**2070**	**2100**
1A	Low temperature increase no precipitation change	+1.1 (0.6)	+2.3 (1.3)	+3.6 (2)	0	0	0
2A	Moderate temperature increase no precipitation change	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	0	0	0
2B	Moderate temperature increase precipitation decrease	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	-5	-10	-15
2C	Moderate temperature increase Precipitation increase	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	+2	+4	+6
3A	High temperature increase no precipitation change	+3.0 (1.65)	+6.3 (3.5)	+9.7 (5.4)	0	0	0
3B	High temperature increase Precipitation decrease	+3.0 (1.65)	+6.3 (3.5)	+9.7 (5.4)	-5	-10	-15

[1] Mean annual temperature and precipitation at HTH station.
[2]Temperature increases are given in degrees F (degrees C) added to the 2010 current conditions static meteorological database.
[3]Precipitation changes are given in percent change to the 2010 current conditions static meteorological database.

Simulated Reservoir Inflows

Climate change in the Tuolumne River affects snow accumulation and melt, soil moisture and forests, reservoir inflows, and the water supplies available for all purposes. Table ES.2 summarizes the modeling results in terms of the change in simulated median annual runoff at O'Shaughnessy and Don Pedro dams for the different future climate conditions (climate change scenario at future climate date).

Simulated changes in median annual runoff do not fully describe how water supplies would be affected. When firm yield from reservoirs is evaluated, low runoff years are critical. Climate change effects are exacerbated in low runoff years. Table ES.3 summarizes the modeling results in terms of the change in simulated 5 (extremely wet), 50, and 95 (critically dry) percent exceedance annual runoff for two climate change scenarios, 2A moderate temperature increases with no precipitation change, and 3B high temperature increases with precipitation decreases.

Table ES.2. Change in median runoff volume for future climate conditions

Climate Change Scenario		O'Shaughnessy Runoff (% change from 2010)			Don Pedro Runoff (%change from 2010)		
		2040	**2070**	**2100**	**2040**	**2070**	**2100**
1A	low temperature increase no precipitation change	-0.7%	-1.5%	-2.6%	-1.1%	-2.4%	-3.6%
2A	moderate temperature increase no precipitation change	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2B	moderate temperature increase precipitation decrease	-7.6%	-15.8%	-24.7%	-9.5%	-19.1%	-28.7%
2C	moderate temperature increase precipitation increase	1.4%	2.2%	2.4%	1.1%	2.0%	2.8%
3A	high temperature increase no precipitation change	-2.1%	-5.6%	-10.2%	-3.0%	-6.5%	-10.1%
3B	high temperature increase precipitation decrease	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%

Table ES.3. Change in runoff volume for future climate conditions for extremely wet, median, and critically dry years (based on results from 1975-2008)

Climate Change Scenario		Example years	O'Shaughnessy Runoff (% change from 2010)			Don Pedro Runoff (% change from 2010)		
			2040	**2070**	**2100**	**2040**	**2070**	**2100**
2A	moderate temperature increase no precipitation change	Extremely wet	-0.6%	-1.4%	-2.4%	-1.1%	-2.6%	-3.7%
2A	moderate temperature increase no precipitation change	Median	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2A	moderate temperature increase no precipitation change	Critically dry	-3.4%	-8.8%	-15.1%	-4.2%	-9.8%	-16.1%
3B	high temperature increase precipitation decrease	Extremely wet	-7.1%	-14.3%	-21.8%	-8.7%	-16.7%	-24.3%
3B	high temperature increase precipitation decrease	Median	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%
3B	high temperature increase precipitation decrease	Critically dry	-14.7%	-30.9%	-46.5%	-16.6%	-33.3%	-48.1%

Runoff timing within the water year changes under the future climate conditions. Figure ES-1 shows the average monthly median runoff volume at O'Shaughnessy for the current climate and for the 2040, 2070 and 2100 future climate condition for two climate change scenarios (2A moderate temperature increases with no precipitation change and 2B moderate temperature increases with precipitation decreases). Reservoir operations may need to be revised to manage increased runoff in November through April, and decreased runoff in May for most scenarios, and in June and July for all scenarios.

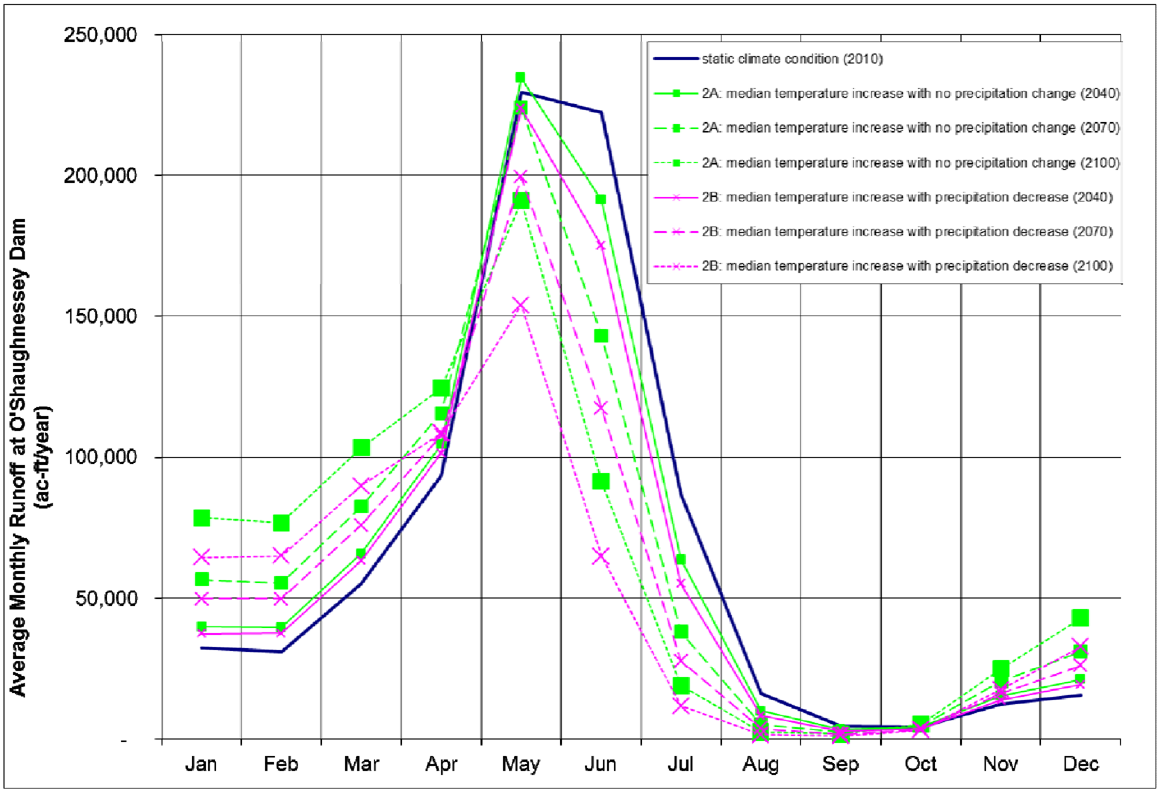

Figure ES-1. Average monthly runoff at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios at future climate dates

Conclusions

The simulated change in 2040, 2070 and 2100 hydrologic conditions based on the climate change scenarios results in a progressively altered snow and runoff regime in the watershed. Snow accumulation is reduced and snow melts earlier in the spring. Fall and early winter runoff increases while late spring and summer runoff decreases, and these changes become more significant at the later time periods. Total runoff is projected to decrease under the climate change scenarios evaluated, in some cases marginally and others significantly.

The reliability of projected changes in reservoir inflows for the climate change scenarios is good because the model is physically-based and has been calibrated over a 34-year period to accurately represent hydrologic conditions in the Tuolumne watershed during a range of temperature and precipitation conditions. The temperature and precipitation timeseries used for the climate change scenarios increases are within the range of temperatures experienced in the Tuolumne during the calibration period. For example, a climate change scenario may have higher temperatures than experienced in the same period historically but similar temperatures would have been observed at other times in the calibration period.

This study created daily reservoir inflow data during the 34-year analysis period (water years 1974 to 2008) for all climate change scenarios which can be used for subsequent water resources planning studies by TID and SFPUC.

Reduced snow accumulation and a resulting shift of runoff from the spring to the winter runoff in the Tuolumne were expected due to the temperature increases of the climate change scenarios. In addition, the climate change scenario results showed that:

- Climate change effects are most exacerbated in low runoff years because of increased evapotranspiration results, particularly when expressed as a percent of runoff.

- Soil moisture reductions in summer would be significant by 2070 and 2100. The predicted reduction in summer soil moistures would be expected to change vegetation distribution within the watershed. The potential changes in vegetation would cause a secondary change in the hydrologic response of some land segments but this effect was not modeled in this study.

- The future climate condition in year 2040 of climate change scenario 3B (high temperature increases with precipitation decrease) results in reductions in median runoff of -8.6% at O’Shaughnessy Dam and -10.7% at Don Pedro Dam. Relatively large reductions in runoff may take place in 30 years if both temperature rise and precipitation decrease occurs.

- The future climate condition in year 2040 of climate change scenario 1A (low temperature increase and no precipitation change) results in minimal runoff reductions of 0.7% at O’Shaughnessy Dam and 1.1% at Don Pedro Dam. The 1A results in terms of runoff and timing changes are small compared to the year-to-year variation that is currently experienced.

1. Introduction

The Tuolumne River, located on the western slopes of the Sierra Nevada in California, provides 85 percent of the San Francisco Public Utilities Commission (SFPUC)'s water supply for 2.5 million Bay Area residents and water to 8,000 agricultural customers and over 200,000 electrical customers of the Turlock and Modesto Irrigation Districts (TID/MID).

1.1 Purpose and Objectives

Water managers with facilities within the Tuolumne watershed are concerned about the potential impact that climate change may have on their future water availability. Water resources in the Tuolumne watershed, like any mountainous watershed in the Western United States, depend on snowpack, which accumulates precipitation during winter months and releases melt water to the river during spring and early summer months. Changes to precipitation would affect reservoir inflow through changes in snowpack accumulation. Similarly, changes to temperature would also affect reservoir inflow through watershed evapotranspiration, snow accumulation and snowmelt. The SFPUC and TID are working together to better understand the possible impacts of climate change on Tuolumne River streamflow.

The key objective of this study is to assess changes in streamflow and watershed hydrologic response to potential temperature and precipitation changes for the years 2040, 2070 and 2100 as compared to the conditions in 2010. Scenarios of temperature and precipitation changes through 2100 were constructed based on literature review and interviews with climate experts. The scenarios encompass a range of temperature and precipitation changes that may occur in the 21^{st} century as a result of climate change. These climate scenarios, however, are not ranked or characterized in terms of their likelihood, and do not represent a "projection" of climate change in the watershed. To characterize possible future changes to climate more precisely, the use of climate model ensemble output, careful characterization of uncertainties contained in that output, lessons learned from paleoclimate reconstructions, and other climate science assessment techniques are required.

A physically-based conceptual model, Hydrologic Forecast and Analysis Model (HFAM) (Hydrocomp, Inc., 2011, HFAM II Reference and User's Manual), was calibrated and used to simulate hydrologic processes (snow accumulation and melt, infiltration, runoff, channel flow). Simulation results were used to assess changes in the timing and volume of runoff. The analysis compared simulated unimpaired inflows (full natural flow) to Hetch Hetchy, Eleanor, Cherry and Don Pedro reservoirs under the 2010 current climate condition with the constructed potential future climate conditions. Results of the analysis will help water resource planners understand the sensitivity of water supply, irrigation and power generation to potential changes in streamflow resulting from climate change.

This report describes the study area, which consists of the 1,532- square miles drainage area above La Grange Dam; the evidence of climate change; the study approach with assumptions, methods and limitations, and the construction of climate change scenarios. The report also describes model set-up and calibration of the HFAM hydrologic model of the Upper Tuolumne watershed and simulations made with the model to determine the potential effects of temperature and precipitation changes on streamflows.

1.2 Scope

The scope of this study was limited to:

1. Reviewing climate change studies applicable to the Central Sierra Nevada and the Tuolumne watershed and seeking expert advice.
2. Constructing six scenarios of temperature and precipitation changes that represent a range of 18 potential future climate conditions in 2040, 2070 and 2100.
3. Examining the 79-year (1930 to 2008) historical weather observations to identify trends in historical climate and create a 34-year (1975 to 2008) static weather sequence to represent current climate condition (2010).
4. Creating 34-year weather sequences based on 1975 to 2008 but adjusted to represent the future climate condition in 2040, 2070, and 2100 for each of the six climate change scenarios.
5. Improving calibration of the existing HFAM model, particularly at Hetch Hetchy, Cherry and Eleanor reservoirs.
6. Simulating unimpaired inflows (full natural flow) to Hetch Hetchy, Eleanor, Cherry and Don Pedro reservoirs using the Tuolumne HFAM model for the current climate condition and for each of the eighteen future climate conditions.
7. Analyzing changes in runoff and hydrologic processes from the current condition for all climate change scenarios at the 2040, 2070 and 2100 time horizons.

1.3 Acknowledgements

This report was jointly prepared by Hydrocomp, SFPUC and TID. Hydrocomp was responsible for watershed model setup, model calibration, simulations of climate change scenarios and interpretation of the model results. Hydrocomp produced sections 4, 5, 6 and 7.

1.4 Study Area

The Tuolumne River, which drains a 1,960-square-mile watershed on the western slope of the Sierra Nevada range (Figure 1-1), is the largest of three major tributaries to the San Joaquin River. The mainstem of the river originates in Yosemite National Park and flows southwest to its confluence with the San Joaquin River, approximately 10 miles west of Modesto. The study area consists of the drainage area above La Grange Dam which encompasses 1,532 square miles. This watershed extends from the crest of the Sierra Nevada near 13,200 feet to the base of the foothills in the Central Valley of California near 800 feet. The sub-study areas are the watersheds of Cherry Lake, Lake Eleanor and Hetch Hetchy (Figure 1-1).

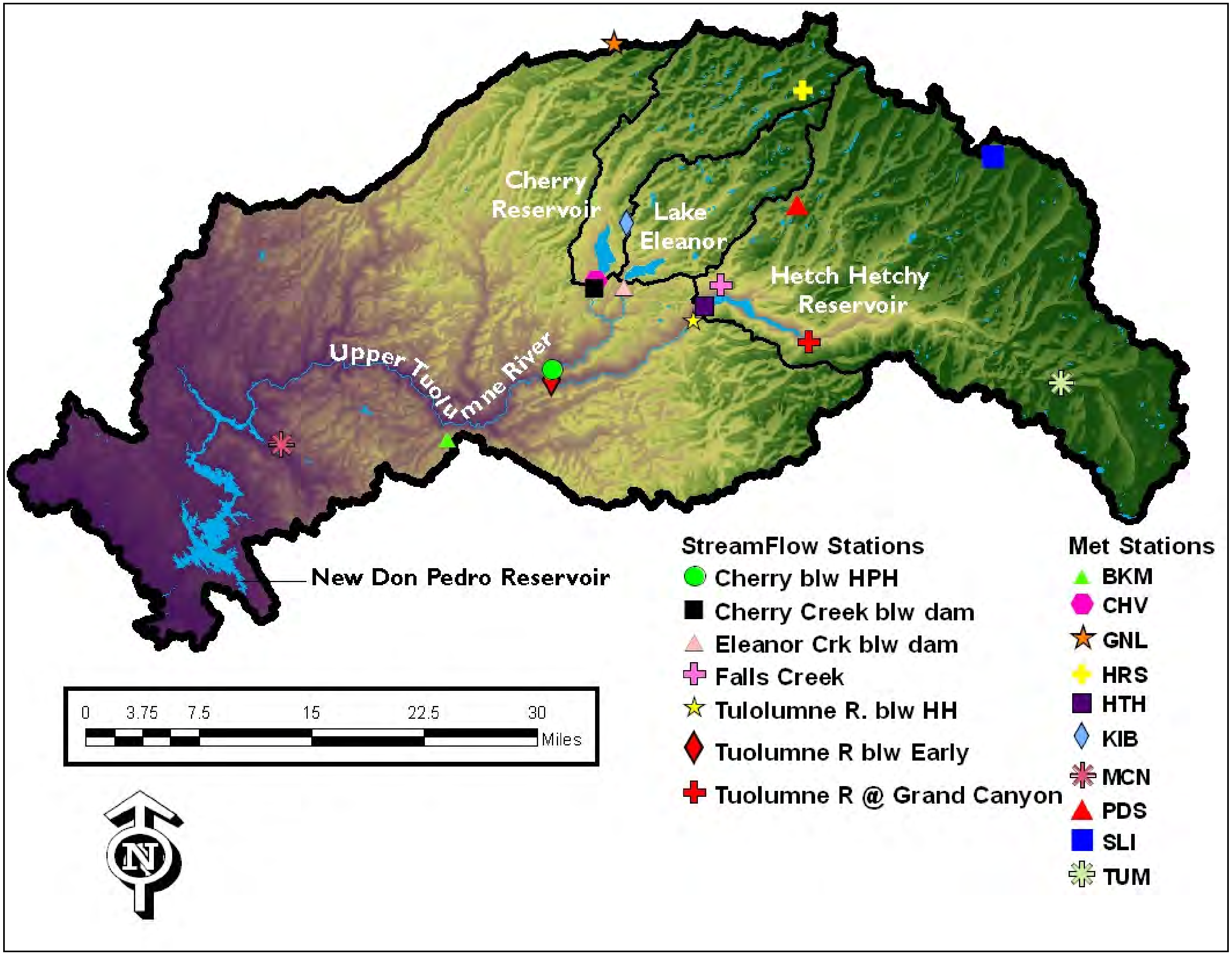

Figure 1-1 Tuolumne River Watershed, stream and meteorological station locations and key reservoirs

The distribution of watershed area for the Tuolumne basin above Don Pedro exhibits a nearly linear trend (Fig 1-2). Nearly 10% of the watershed is contained in each 1,000 ft elevation band up to about 10,000 ft. Only a small fraction of the watershed exists at higher elevations. The SFPUC-managed watersheds show a similar pattern with much of the watershed area lying between 5,000 and 9,000 ft.

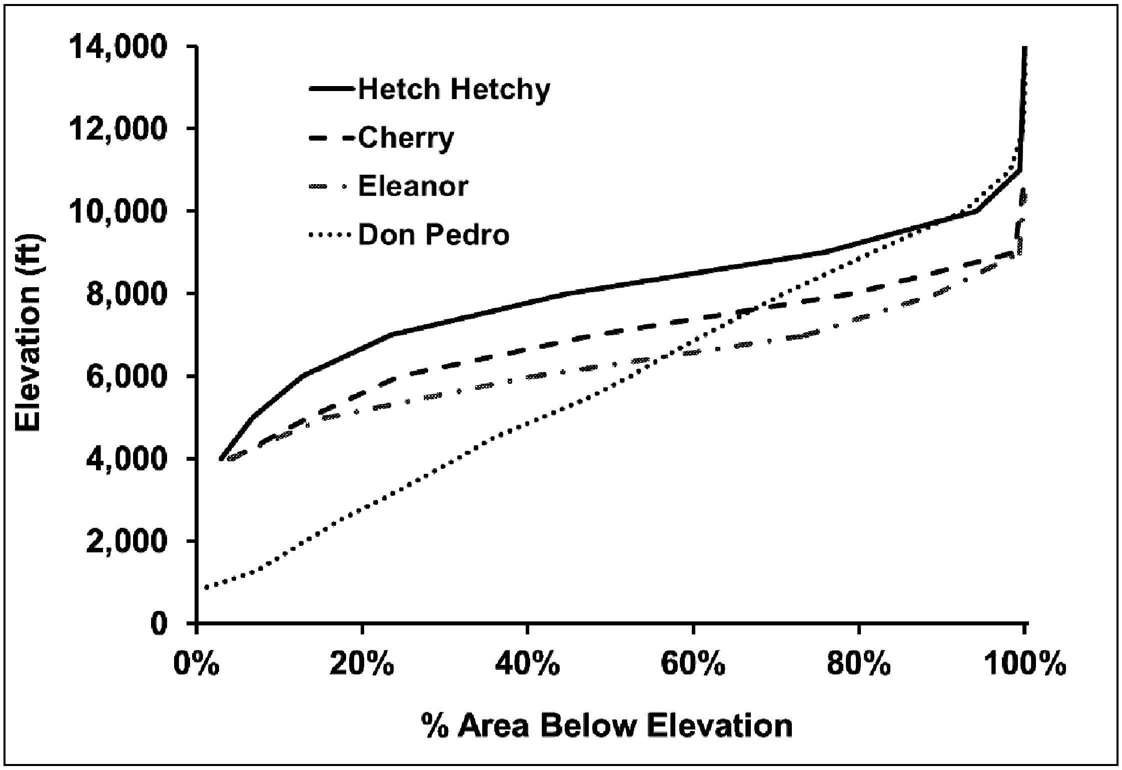

Figure 1-2. Hypsometry for the major Tuolumne River basin reservoirs

Given the great range in elevation, the Tuolumne watershed has vast variation in vegetation, soil structure and morphology. At higher elevations (6,000 -13,200 ft), the watershed is exposed granitic bedrock that was scoured by glaciers during the Tioga and earlier glacial periods, with steep mountains and deep canyons. The mountainous middle elevations (3,500-6,000 ft) are dominated by coniferous forest which begin to transition to oak dominated forests. Lower elevations (800-3,500) are composed of oak forests and oak savannah with a mix of rural land use and townships and grassy hillslopes. These variations in natural vegetation coverage are controlled by the large variation in available moisture due to a strong orographically-driven precipitation pattern.

Mean annual precipitation ranges from 8 inches to above 60 inches in the mountains. The watershed is dominated by a Mediterranean climate with hot, dry summers and cool, wet winter periods (Figure 1-3). The winter storm season may begin as early as October and extend into May. Typically winter snowline is near 5,500 feet but varies from year to year. The snow transition zone is between 4,000 and 5,500 feet, with snow events occurring often in the winter, but the snow accumulation may ablate. Snow events at elevations as low as 2,000 feet are not uncommon and occur nearly every year.

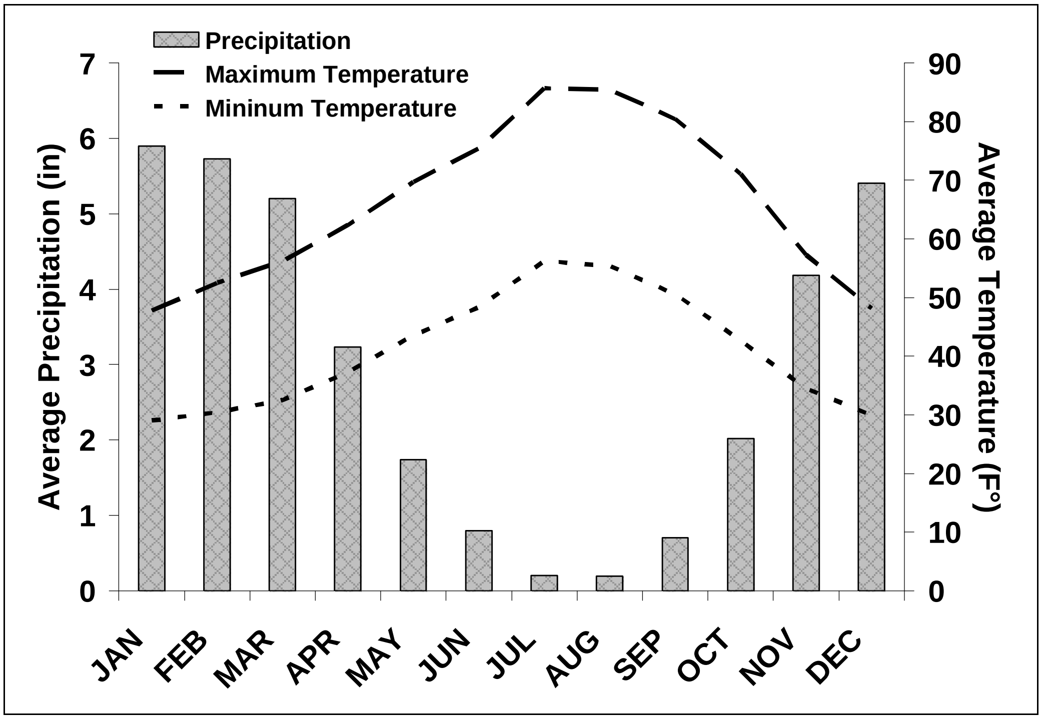

Figure 1-3. Climograph for the Hetch Hetchy meteorological station.

Annual variation in precipitation and hydrologic conditions results in a large disparity of annual inflow – ranging from 20 to 250% of average inflow. This variation is controlled by the snow accumulation during the winter season as typically 75% of the annual runoff occurs during the April thru July snowmelt runoff period. Due to this pattern reservoir management typically focuses on this period.

Table 1-1. Watershed Characteristics at Primary Reservoirs in the Study Area

Reservoir	Drainage Area (sq. mi.)	Elevation range (ft)	Average annual inflow (thousand acre-feet)
Hetch Hetchy	459	3,800-13,200	747
Eleanor	79	4,650-10,400	171
Cherry	117	4,700-10,800	281
New Don Pedro	1,532	800-13,200	1,844

Two main water projects exist on the Tuolumne River. The SFPUC owns and operates the Hetch Hetchy Water and Power Project (Hetch Hetchy Project). This system, located in the upper Tuolumne River watershed, includes dams and flow diversions on the Tuolumne River, Cherry Creek (a tributary to the Tuolumne River), Eleanor Creek (a tributary to Cherry Creek), and Moccasin Creek (tributary to Don Pedro Reservoir). Water from this project is utilized for the Hetch Hetchy Regional Water System which delivers water to the San Francisco Bay area. The second major project is New Don Pedro Reservoir which is owned and operated by Turlock Irrigation District and Modesto Irrigation District. The two irrigation districts utilize watershed runoff and reservoir storage to meet irrigation demands, domestic water supply and power generation needs. Water that is released from Don Pedro Dam can be diverted into two diversion canals (Turlock Canal and Modesto Canal) which serve as the main distribution for each district's operations.

1.5 Evidence of changing climatic conditions

The world's climate has been changing and the vast majority of scientists attribute this change to an increase in the emission of carbon dioxide (CO2) and other greenhouse gases (Intergovernmental Panel on Climate Change, 2007). The global average surface temperature has risen between 1.08˚F and 1.26˚F (0.6˚C and 0.7˚C) since the start of the 20th century (World Meteorological Organization, 2005). Figure 1-4 presents the trend in annual global average temperature.

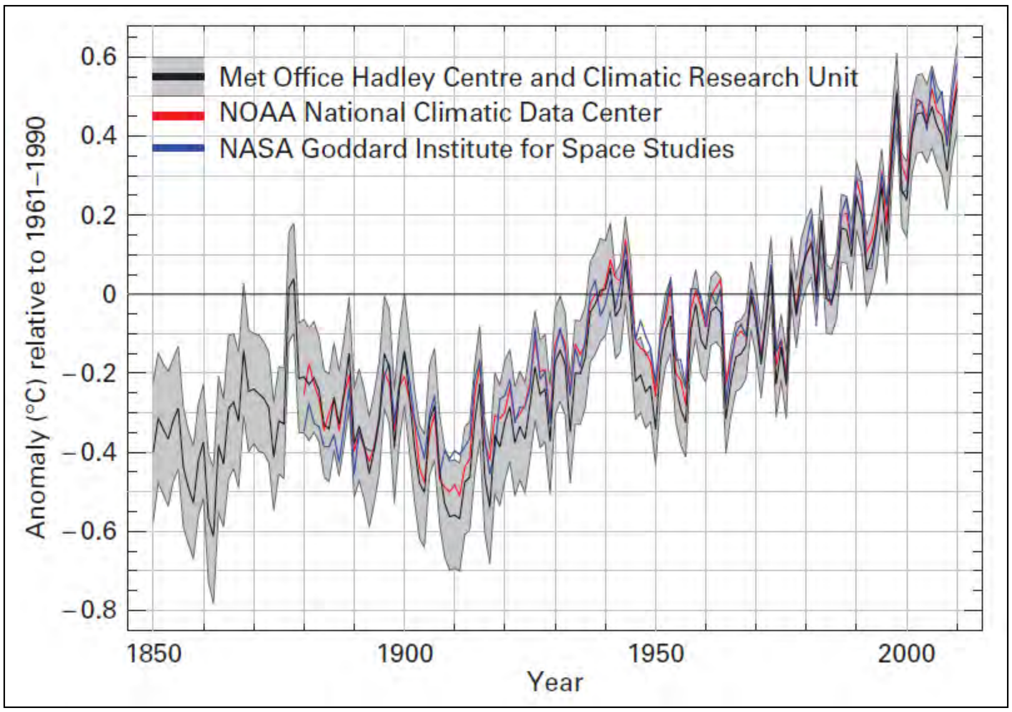

Figure 1-4. Annual global average temperature anomalies (relative to 1961–1990) from 1850 to 2010 from the Hadley Centre/CRU (HadCRUT3) (black line and grey area, representing mean and 95 per cent uncertainty range), the NOAA National Climatic Data Center (red); and the NASA Goddard Institute for Space Studies (blue) (Source: WMO, 2011)

2. Study Approach

This study analyzes the hydrologic response of the Upper Tuolumne watershed to changes in temperature and precipitation. To assess this response, a physically-based conceptual model, HFAM was used. The Hydrocomp Forecast and Analysis Model or HFAM was completed in 2007 and is the most recent edition in the Stanford (Crawford and Linsley 1966), Hydrologic Simulation Program (Hydrocomp, Inc., 1976), Hydrologic Simulation Program-Fortran (HSPF, Bicknell et al. 1997) and Seattle Forecasting Model (SEAFM), (Hydrocomp, Inc., 1993) family of continuous simulation models. An application of HFAM to the Tuolumne (Tuolumne HFAM model) has been developed over the last twelve years by Hydrocomp for TID (Hydrocomp 2000, 2007). It has been used in operations at Don Pedro Reservoir since 1999. The Tuolumne HFAM model simulates hydrologic processes (snow accumulation and melt, infiltration, runoff, channel flow and reservoir operations) using hourly input meteorological data (precipitation, temperature, evaporation, solar radiation and wind speed). The model set-up and calibration are discussed in Section 3.

A historical meteorological database was developed by Hydrocomp for the Tuolumne HFAM model for the period of 1930 to 2008. Historic meteorological records at real-time stations that report to CDEC were extended prior to the period of record by correlations to the long-term stations. This study focuses on the “Historic” 34-year period from 1975 to 2008 to rely more on observed weather data rather than extended data and to use better reservoir inflow records for calibration and validation. In addition, this period covers a reasonable cross-section of wet, dry and average years to represent long-term variability. Using the water year type classification at Hetch Hetchy Reservoir, the study period includes 10 extremely wet years, 3 wet years, 9 normal years, 4 dry years and 8 critically dry years[1].

A warming pattern has been detected in the Sierra Nevada (Barnett et al. 2008, Bonfils et al. 2008), and upward trends in temperature were observed at stations within the study area as well (Section 5.1). Trends over several decades are an integral part of climate and have been observed in the past. However, recent warming trends are significant because they “differ in length and strength from trends expected as a result of natural variability” (Barnett et al. 2008). The anthropogenic influence on the climate system is changing the means and variability of hydrologic variables (IPCC, 2007, Milly et al. 2008). These upward trends in temperature indicate a non-stationary process and so undermine the assumption of stationarity used in water resources engineering.

Stationarity is the property of natural systems to fluctuate within an unchanging envelope of variability. This is a fundamental concept in the practice of water resources engineering. Most hydrologic analyses used in water resources planning assume that hydrologic data are stationary, which means that probabilistic behavior of any variable is time invariant. Weather and streamflow data that includes progressive climate effects may be outside of this unchanging

[1] The classification is based on a runoff indictor representing the cumulative inflow to Hetch Hetchy Reservoir since October 1 of the current water year. Extremely wet, wet, normal, dry and critically dry represent 15%, 20%, 30%, 20%, 15% of the years on record, respectively.

envelope and this creates difficulties for reservoir system yield or reliability analysis. To determine reservoir system yield and reliability, one needs the average yield of the river basin and the variability of the flows over time. The purpose of storage is to even out the variability of flows to give a sustained firm yield over time. Yield/reliability analysis with climate change effects, e.g. without a stationary record to rely upon, is uncharted territory. Traditional analysis is not applicable, and research will be needed to develop analysis methods. For that reason, it was decided that records needed to be adjusted to a hypothetical quasi-steady condition at each of the time horizons of interest. For each of those quasi-steady state conditions, a firm yield can be computed and storage needs assessed.

Because streamflow simulated with the Tuolumne HFAM model may later be used in water resources planning analysis, a "Current Condition" 34-year weather sequence was developed by increasing earlier temperature records to remove upward trends in the "Historic" weather sequence and hence creating a stationary (quasi-steady or static) weather sequence (Figure 2-1 and Section 5.2) that represents the climate in 2010.

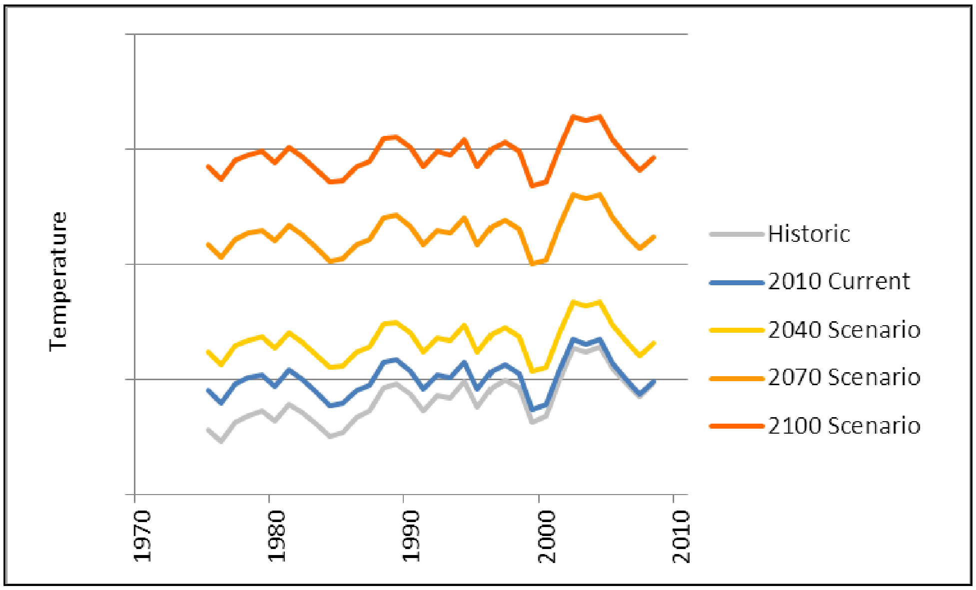

Figure 2-1. Conceptual representation of "Historic" weather sequence, "2010 Current Condition", and potential conditions in 2040, 2070 and 2100 time horizons using delta method

The well-known approach of scenario planning was selected to incorporate potential changes in future climate rather than using climate model outputs. Constructed climate change scenarios were developed through review of climate science, climate modeling, current climate projections and discussion with climate experts. The result of this process is six climate change scenarios of changing temperature and precipitation that represent a plausible range of climate uncertainties (Section 3).

The climate change scenarios consist of changes in mean annual temperature and precipitation over the study area. The "Current Condition" 34-year weather sequence is adjusted using the delta method to include the effects of changing mean annual temperature or mean annual precipitation (Figure 2-1). The delta method is described by Bader et al. (2008) as: "Climate model output is used to determine future change in climate with respect to the model's present-day climate, typically a difference for temperature and a percentage change for precipitation. Then, these changes are applied to observed historical climate data for input to an impacts model". The application of the delta method is discussed in Section 5.2.

This study approach has some limitations. First, climate projections indicate not only changes in annual precipitation and temperature but also indicates greater climate variability during the 21st century. They indicate both a greater frequency in extreme temperature events and diurnal range, as well as greater frequency of extreme precipitation events – both wet and dry (IPCC, 2007). The change in frequency of events and seasonal shift are not captured by this study approach.

Secondly, the Tuolumne HFAM model parameters are calibrated for current watershed vegetation conditions but studies show that vegetation may change as climate changes. With changes in temperature and precipitation, ecosystem structure (e.g. vegetation patterns, drainage network, soil properties) will change. Panek et al. (2009) modeled vegetation shifts in Yosemite National Park for the next century based on IPCC climate scenarios. Under all scenarios, alpine vegetation disappeared, the spatial extent of subalpine conifer forests decreased and shifted upwards, while montane chaparral and hardwoods expanded and desert vegetation appeared. Evapotranspiration and runoff will change as new vegetation is established. The water balance will also be affected by an increase in forest fires and the death of current vegetation, which will temporarily decrease transpiration and increase storm runoff. The Tuolumne HFAM model setup assumes that the types and spatial extent of vegetation will remain the same as today. Addressing this variable would require adjustments to the calibrated land segment parameters based on expert judgment, a potential task for future model development.

3. Defining Climate Change Scenarios

Considering the wide range of climate change projections from different emission scenarios and different climate models, as well as the complexity of using climate model outputs in the Tuolumne HFAM model, it was decided that for a first assessment of streamflow sensitivity to temperature and precipitation changes, a selection of constructed scenarios that represents a plausible range of future climate conditions would be sufficient.

The construction of scenarios was guided by consultations with two experts in the state of climate change science and the current literature for California, Joel B. Smith[2] and Dan Cayan[3]. In addition to their expertise, both have extensive experience working with utilities in understanding vulnerability to climate change. The experts' guidance was based on review of climate science, climate modeling, and climate projections as of 2008-2009.

The six constructed scenarios are described by changes in mean annual temperature and precipitation from 2010 conditions for time horizons 2040, 2070 and 2100 (Table 3-1).

The climate change scenarios have temperature increases from the present-day conditions (2010) to 2100 ranging from 3.6 ˚F (low increase) to 9.72 ˚F (high increase). Mean annual precipitation changes in three of the six scenarios. The dry scenarios have a 15% reduction from the present-day in 2100 whereas the wet scenario has a 6% increase by the end of the 21st century.

Following the work done by Cayan et al. (2009) for the 2008 California Climate Change Scenarios Assessment, the changes in temperature and precipitation were based on projections from six GCMs that contributed to the IPCC Fourth Assessment (IPCC 2007) using two Special Report on Emissions Scenarios (SRES) emissions scenarios – a moderately low emissions scenario (B1) and a medium-high emissions scenarios (A2). Models were chosen on the basis of having a climatology which gives reasonable representation of precipitation in California, having a semblance of ENSO, having reasonable spatial resolution, and providing daily output.

[2] Joel B. Smith, Principal at Stratus Consulting (http://www.stratusconsulting.com) and lead author for the Synthesis Report on climate change impact for the Third Assessment Report of the IPCC in 2001.
[3] Dr. Daniel R. Cayan. Researcher meteorologist at the Scripps Institution of Oceanography, University of California San Diego and U. S. Geological Survey. He heads the California Nevada Applications Program and the California Climate Change Center.

Table 3-1. Constructed climate change scenarios

Scenario	Description	Mean Annual Temperature (˚F (˚C))[1]			Mean Annual Precipitation (in)[1]		
Current Conditions	2010 conditions	55.1 (12.8)			36.9		
Future Climate Change Scenarios		**Change from Base (˚F (˚C))[2]**			**Change from Base (%)[3]**		
		2040	**2070**	**2100**	**2040**	**2070**	**2100**
1A	Low temperature increase no precipitation change	+1.1 (0.6)	+2.3 (1.3)	+3.6 (2)	0	0	0
2A	Moderate temperature increase no precipitation change	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	0	0	0
2B	Moderate temperature increase precipitation decrease	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	-5	-10	-15
2C	Moderate temperature increase Precipitation increase	+1.8 (1)	+4.0 (2.2)	+6.1 (3.4)	+2	+4	+6
3A	High temperature increase no precipitation change	+3.0 (1.65)	+6.3 (3.5)	+9.7 (5.4)	0	0	0
3B	High temperature increase Precipitation decrease	+3.0 (1.65)	+6.3 (3.5)	+9.7 (5.4)	-5	-10	-15

[1] Mean annual temperature and precipitation at HTH station.
[2]Temperature increases are given in degrees F (degrees C) added to the 2010 current conditions static meteorological database.
[3]Precipitation changes are given in percent change to the 2010 current conditions static meteorological database.

Figure 3-1 presents evolution of annual temperature and precipitation for the Sacramento Region based on projections from six GCMs for two emissions scenarios (Cayan et al. 2009).

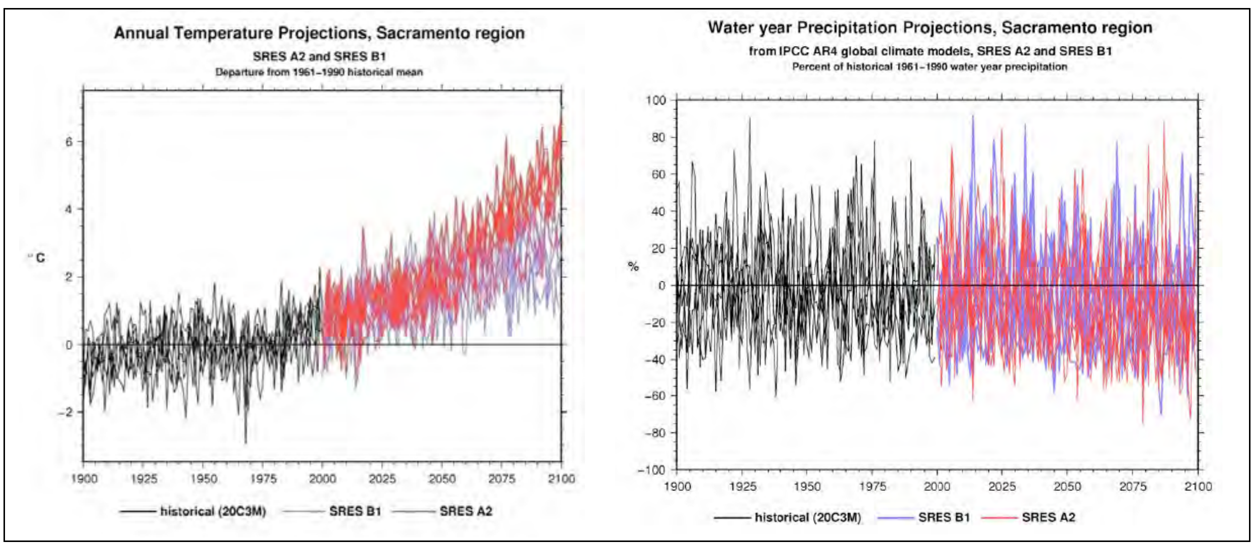

Figure 3-1. Annual temperatures and precipitation near Sacramento, for six for the six GCMs (CNRM CM3.0, GFDL CM2.1 MIROC3.2, MPI ECHAMS, NCAR CCSM3, NCAR PCM1) for the 1901-1999 historical period (black) and for the projected 2000–2100 periods under the A2 (red) and B1 (blue) GHG emissions scenarios. In this case, the values plotted are taken directly from the GCMs from the grid point nearest to Sacramento (Source: Cayan et al. 2009).

Temperatures in California are projected to rise significantly over the 21st century. According to Smith (2008), "there is virtually no doubt that temperatures will continue to rise in California (and over the entire United States), so assuming a rise in temperature is reasonable." It is important to note that the two main sources of uncertainty in the temperature projections are the imperfect physics in modeling the many complex atmospheric processes and the emissions scenarios themselves. Cayan states (pers. comm. June 2008): "The choice of emissions scenario does not make a big difference on the temperature change until after 2050. At 2100, the choice of scenario makes a big difference." Overall, these GCMs project warming in the mid-century from about 1.8˚F to 5.4˚F (1˚C to 3˚C), and rising by the end of the 21st century from about 3.6˚F to 9˚F (2˚C to 5.4˚C).

It is fair to say that there is no conclusive evidence the region will become drier, but there is a reasonable possibility that annual precipitation will decrease. At Sacramento, change in precipitation lacks consensus for the early period, but by mid and late 21st century the models tend toward drier, especially for the SRES A2 scenario (Figure 3-2). Median of results range from just a couple of percent drier to about 8 percent drier for A2 at end-of-Century but some individual models project up to 15 percent drier. Because winter precipitation in Sacramento is well correlated to that in the Sierra Nevada, these precipitation projections are considered at this time to be representative of precipitation variability in the central Sierra Nevada (Cayan et al. 2009).

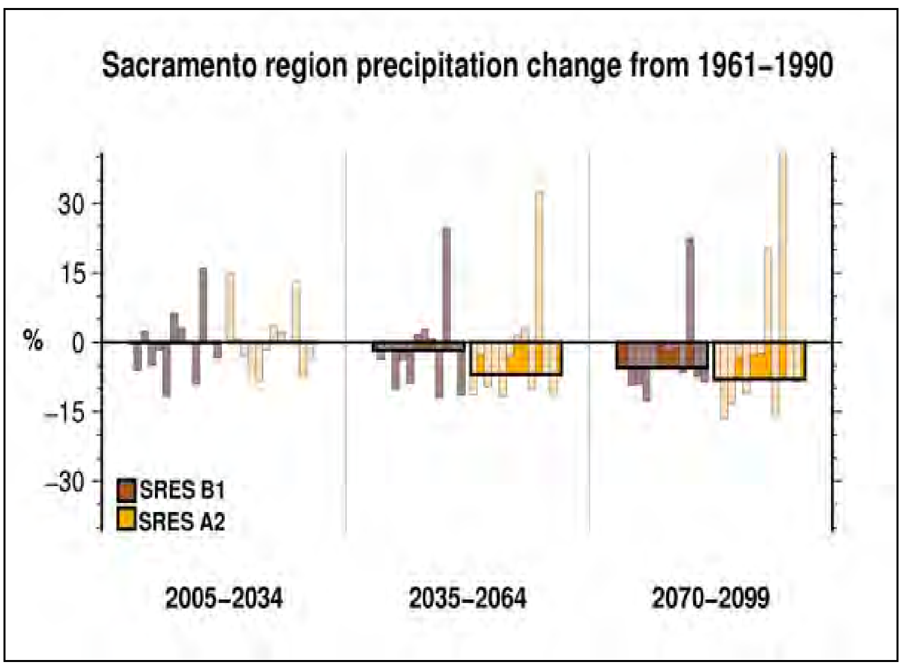

Figure 3-2. Differences in 30-year mean annual precipitation for early, middle and late 21st century relative to 1961-1990 climatology for 12 GCMs for SRES B1 and A2. Light bars are individual model averages and heavy lines are the median of the 12 GCMs. Precipitation is taken directly from the GCMs from the grid point nearest to Sacramento (Cayan, pers. comm., Jan 2009).

4. Tuolumne HFAM Model

4.1 Model Setup

The current Tuolumne HFAM model system includes:

- HFAM program, version 2.3
- watershed input files that describe the physical characteristics of the watershed (topography, soils, vegetation, channel reaches) and the operations of reservoir spillways and outlets, diversions, tunnels and power houses
- a historical meteorological database of precipitation, temperature, evaporation, wind movement and solar radiation
- data management software and spreadsheets

The Tuolumne HFAM model includes the following components:

- land segments: simulate surficial hydrologic processes (snow accumulation and melt, infiltration, evapotranspiration and soil moisture storage, and runoff)
- river reaches: simulate channel processes (flow velocity, stage in channel reaches)
- reservoirs: simulate the storage and release of flow from natural lakes and reservoirs

The current Tuolumne HFAM model set up is described in detail in previous reports (Hydrocomp, Inc., 2000, 2007)

Figure 4-1 shows a schematic of river reaches and reservoirs in the Tuolumne HFAM model. For the analysis of climate and hydrologic changes, reservoirs are simulated as reaches with no storage. This allows calculation of the total unregulated inflow to each reservoir.

The drainage area of each river reach was subdivided into land segments, areas with quasi-homogeneous hydrologic characteristics, such as mean annual precipitation, soils and vegetation cover. Selected physical processes in land segments, e.g. infiltration and interflow outflow, are modeled as frequency distributions. Figure 4-2 shows the land segments within the drainage area of the Dana Fork of the Tuolumne River (reach 3010). The Dana drainage area is 27 square miles and was divided into 14 land segments based on elevation and aspect. Land segments need not be contiguous and some land segments are composed of non-contiguous areas.

The Tuolumne HFAM model calculates the hydrologic response of more than 900 land segments in the watershed above Don Pedro and routes runoff downstream to reservoirs through 75 channel reaches. Each land segment represents the elevation, soil and rock outcrop, vegetation and aspect associated with a portion of the watershed. The model performs detailed mass and energy budget calculations to simulate the hydrologic cycle on each land segment. By combining and routing the flow from each segment, the model provides detailed information on the effects of basin-wide temperature and precipitation changes on runoff, snow, evapotranspiration and soil moistures.

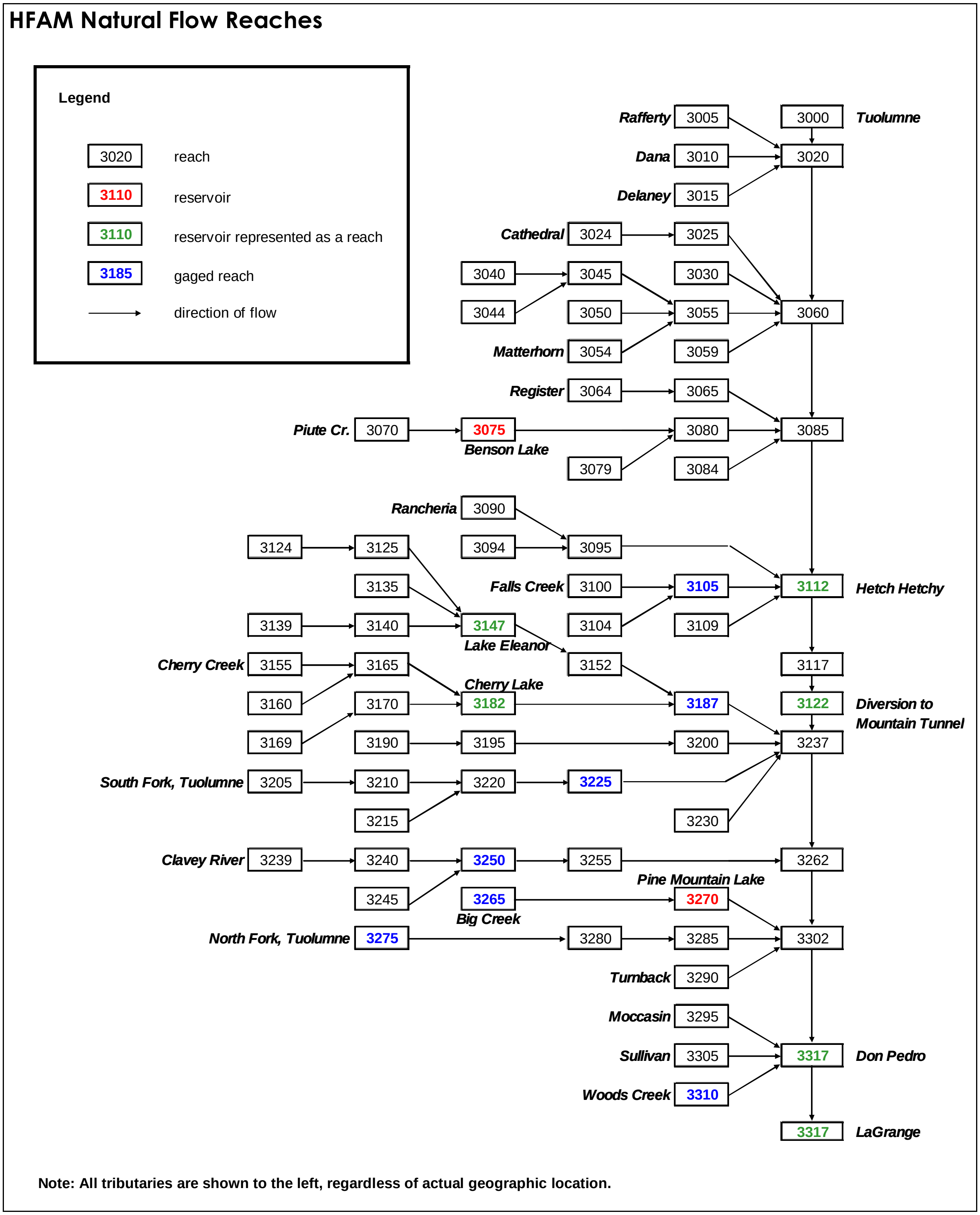

Figure 4-1. Tuolumne HFAM model reaches and reservoirs

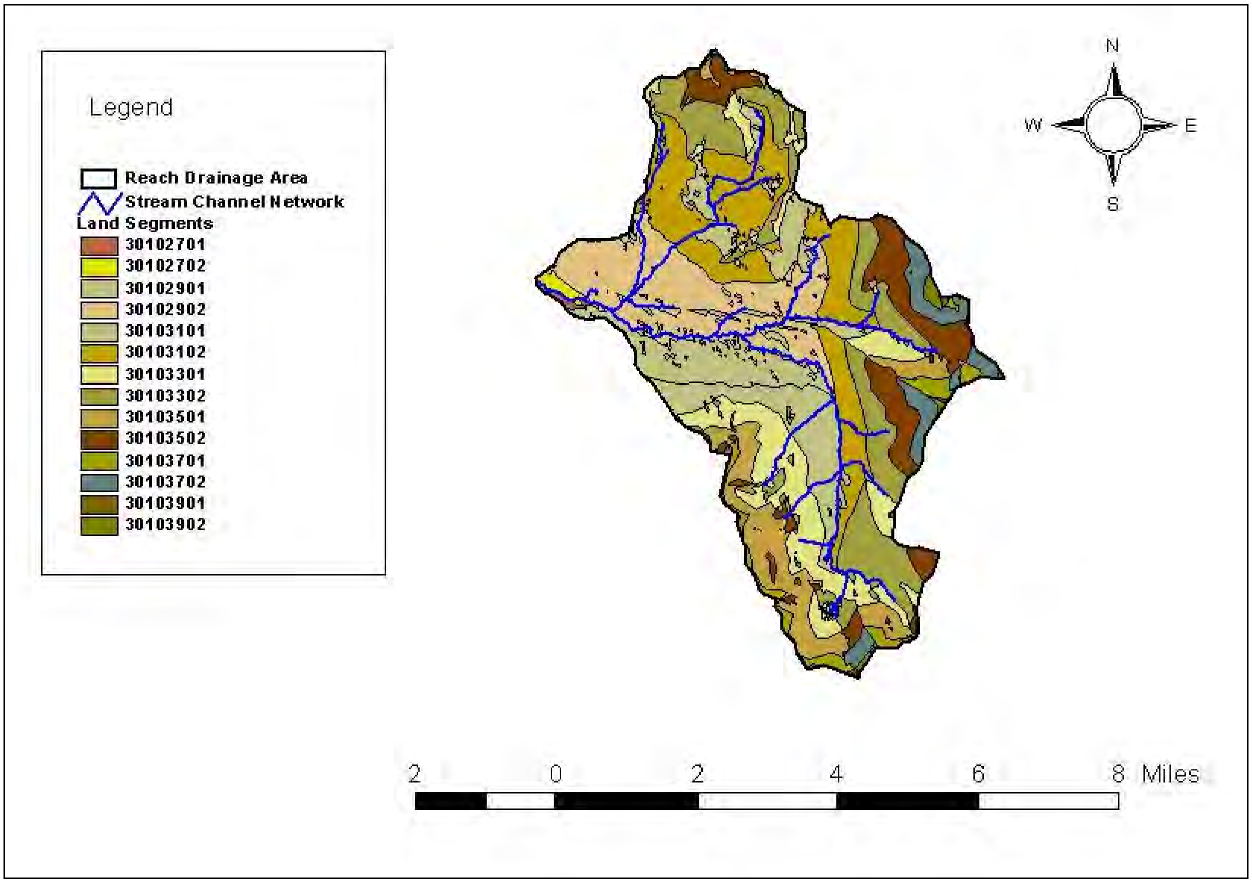

Figure 4-2. Dana Fork Tuolumne River land segments

The model requires continuous hourly meteorological input timeseries and produces comprehensive hourly output timeseries for many variables including soil moisture, snowpack, evapotranspiration, runoff from the land surface, and reservoir inflows. HFAM results can be viewed in the HFAM interface or exported as hourly or daily data files for use in other programs. HFAM creates XML output files readable by Microsoft Word and Excel.

4.2 Meteorological Database

The Tuolumne watershed model includes a historical meteorological database of hourly precipitation, temperature, evaporation, solar radiation and wind speed for period of 10/1/1930 to 9/30/2008. Precipitation and evaporation are used to calculate rainfall and runoff on the land surfaces and in the channel reaches and reservoirs. Temperature, solar radiation and wind speed data are needed for simulation of snowpack heat exchange and melt on the land segments.

Figure 1-1 shows the California Data Exchange Center (CDEC) station identifier and location of each meteorological station used by the Tuolumne HFAM model. Table 4-1 lists the meteorological stations used by the Tuolumne HFAM model and indicates which of the meteorological data types are available at each station (precipitation, temperature, wind, solar radiation, and evaporation).

Table 4-1. Tuolumne meteorological stations

Station ID	Name	Precip	Temp	Evap	Solar	Wind
MID	Modesto Roof	✓				
MOR	Modesto Reservoir	✓				
HTH	Hetch Hetchy Reservoir	✓	✓	✓		
BKM	Buck Meadows	✓	✓		✓	✓
TMM	Tuolumne Meadows	✓	✓			
TUM	Tuolumne Meadows	✓	✓			
PDS	Paradise Meadows		✓			
HRS	Horse Meadow		✓			
SLI	Slide Canyon		✓			
CHV	Cherry Valley Dam	✓	✓			
MCN	Moccasin	✓	✓			
GNL	Gianelli Meadow		✓			

Table 4-2 lists station elevations and the long-term average daily temperature range (daily maximum temperature minus daily minimum temperature) of each of the temperature stations. The daily temperature range at stations in mountainous terrain is affected by upslope movement of warm air during the day and by cold air drainage into valleys at night. The topography at each station determines these air movements. The daily temperature range in the Tuolumne watershed decreases with elevation at all locations except TUM/TMM. TUM/TMM has a large temperature range and is unique due to cool air pooling (Lundquist 2008).

Table 4-2. Tuolumne temperature stations

Station	Elevation (ft.)	Start of Records	Daily Temperature Range (deg F)
BKM	3200	1989	27.5
PDS	7650	1989	25.1
HRS	8400	1987	23.5
GNL	8400	1998	21.1
TUM/TMM[1]	8600	1992	32.3[2]
SLI	9200	1985	24.6
MCN	938	1950	31.4
CHV	4764	1950	26.1
HTH	3858	1930	26.0

Notes:

1. Temperature records at TUM (8600 ft) begin in 1998. These TUM records were extended for the period 1992 to 1998 using records taken at TMM (9200 ft).
2. The TUM station records from 1998 to 2008 have an average daily range of 32.8 deg. F. The TUM station records from 1992 to 1998 have an average daily range of 31.4 deg F.

Data records are not available for the entire historical data period (1930 to 2008) for all the meteorological stations, as shown in Table 4-2. The real-time stations (BKM, TUM/TMM, PDS, HRS, GNL and SLI) that record and transmit data in real-time did not begin recording data until 1985 or later. Hydrocomp extended the records back in time by estimating meteorological conditions prior to the period of real-time records based on the data recorded at nearby stations with long periods of record (historical stations), adjusted according to the difference in long-term average temperature between the real-time station and the historical station. Data sources and extension is discussed in detail in Appendix E.

A maximum/minimum temperature adjustment method was developed to extend real-time temperatures by adjusting data from the historical stations using the difference between long-term minimum daily temperature and long-term maximum daily temperature at the real-time and historical stations (this adjustment method is described further in Appendix E). This adjustment method does not bias the daily temperature range and was used to estimate the revised extended data period at all the real-time stations.

4.3 Modeling System Calibration

Modeling system calibration in the Upper Tuolumne, a large and geographically complex watershed, requires:

- Analysis of watershed topography, soils, vegetation and forest cover to define watershed elements (land segments, reaches).
- Analysis of historic meteorological data including locations of stations, estimating missing and invalid measurement from correlations among stations, and analysis of atmospheric lapse rates.
- Analysis of stream gage and reservoir release records
- Model parameters adjustments at multiple sites to reduce for modeled and recorded streamflow differences, and for improved representation of snow course snowpack water content.
- Analysis of model algorithms.

Although differences between model results and watershed measurements are deemed 'model error' and more descriptive term is 'modeling system error' where the modeling system includes the data series employed and the level of detail for watershed elements defined in the model.

The Tuolumne HFAM model was first developed by Hydrocomp in 1998 and has been used to support hydrologic forecasting for TID. Model calibration is an on-going activity, as more data are collected and new data stations are added. The model was re-calibrated in 2007, when the model was upgraded from HFAM 1.1 to HFAM II (Hydrocomp, 2007).

For the modeling of the Tuolumne climate change scenarios, the HFAM model parameter SNOWCF was changed from the value used for TID operational model (1.05 - 1.08) to 1.0 for all land segments so that temperature increases in the climate change scenarios would not change total precipitation depths.[4] The precipitation factor (ratio between precipitation at the gage and at the land surface) for each land segment was increased to compensate for the SNOWCF parameter change to maintain the same total precipitation on each land segment.

In addition, the Tuolumne HFAM model calibration was refined using the previously unavailable Hetch Hetchy estimated inflow records and the USGS gage on the Grand Canyon of the

[4] Precipitation falling as snow is not captured by gages as effectively as rainfall. The SNOWCF (snow correction factor) increases the precipitation depth for recorded snowfall events.

Tuolumne.[5] Biases between observed and HFAM-simulated streamflow were present prior to the recalibration, particularly for SFPUC reservoirs. The model was recalibrated based on available estimated reservoir inflows and gaged streamflow data for water years 1975 through 2008.

Steps taken to improve modeling system calibration for the Upper Tuolumne are described for watershed elements, the hydrometeorological data base, and for model structure, algorithms and parameters.

4.3.1 Watershed Elements

Upper Tuolumne watershed structural elements are land segments and stream reaches. Hydrologic processes in land segments, e. g. infiltration, evapotranspiration, snow accumulation and melt, provide runoff to streams. Stream reaches collect runoff and route flows downstream.

In the Upper Tuolumne HFAM application areas within land segments have similar elevation, soils or exposed rock, topography, aspect and vegetal cover. Land segments are non-contiguous. Approximately 32,000 GIS defined areas were combined into more than 900 land segments.

Increasing the number of land segments in the Upper Tuolumne application is possible, for example by reducing the elevation interval or by increasing the number of aspect categories used but this would not significantly improve the model calibration for inflows to O'Shaughnessey, Cherry Valley or Don Pedro. The level of watershed element detail that is needed or helpful for improved calibration is linked to basin scale; in a 2 sq. mi. watershed 100 land segments might be helpful, but in a 2000 sq. mi. watershed 100,000 land segments would be cumbersome, delaying calibration model runs without improving model accuracy. Increasing the number of stream reaches can be equally ineffective for improving model calibration.

Assignments of meteorological data to land segments in the Upper Tuolumne were changed during calibration based on model results. In mountainous watersheds, the distance from a gage to a land segment and elevation/exposure differences affects these assignments.

4.3.2 Meteorological Data Base

Each land segment requires hourly precipitation, temperature, potential evapotranspiration, wind and solar radiation. These data are rarely observed within a land segment and must be estimated or scaled to account for gage location to land segment differences, particularly for elevation and aspect differences (Appendix E).

Missing and incomplete records at gaged locations in the Tuolumne are filled using both program routines and human judgment. Outliers or erroneous data are located and replaced by human judgment. Data transmitted from real-time sensors at snow course sites are often erroneous and extended periods of missing data are common at these sites. Missing or erroneous data at CHV, HTH and MCN are uncommon.

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[5] USGS Site 11274790, Tuolumne in the Grand Canyon of the Tuolumne above Hetch Hetchy, installed in October 2006.

Hydrometeorological data records at the real-time snow course sites were extended back in time from 1974 to 1985 or later (Appendix E). Data from gaged sites were scaled as necessary to represent conditions at the land segments. Precipitation is scaled using isohyetal mapping. Wind is scaled as a function of elevation. Potential evapotranspiration are assumed constant with elevation.

Air temperatures in land segments are calculated using lapse rates, and affect the temperature dependent snowfall vs. rainfall assignments. Temperatures are important for snowpack heat exchange and snowmelt timing. Analyses attempted to estimate lapse rates continuously throughout the Upper Tuolumne from concurrently available hourly temperature, wind, and precipitation data series. These analyses were inconclusive due to limited concurrent historic data and station to station lapse rates based on long-term daily maximum and minimum temperature records were used (Table E-4, Appendix E).

Temperature is strongly dependent on elevation and often declines with increasing elevation at a ‘lapse rate’ of -2 to -6 degrees F. per thousand feet. Lapse rates are dynamic, cold air draining from mountain slopes into valleys may create temperature inversions. In the Tuolumne historic hourly temperatures are not available at CHV or HTH. Typical diurnal temperature cycles, with daily minimum temperatures at 4 to 6 a.m. and daily maximum temperatures at 2 to 4 p.m., are used to estimate hourly temperatures from daily maximum and minimum temperatures. These typical diurnal cycles are often not present during storms. Wind and heat releases by condensing water vapor during storms affect lapse rates.

Direct calculation of lapse rates from concurrent records at the real-time stations (PDS, HRS, SLI and TUM/TMM) was erratic and unrealistic due to distances between station locations and relatively small elevation differences between stations.

Much of the improvement in the calibration was due to corrections to the meteorological data. In addition, model calibration for the Tuolumne tributaries improved when extended temperature records were revised using the maximum/minimum temperature adjustment method as discussed in Section 4.2.

4.3.3 Model Algorithms and Parameters

The algorithms that calculate snow accumulation and melt and surficial hydrologic processes in the HFAM model were first developed at Stanford and have evolved over many years based on thousands of applications but algorithm updates are made when observed data warrants. One algorithm update was made during this project to attenuate liquid water outflow from snowpacks. Streamflow data showing the diurnal variability of flows during snowmelt were collected in the Upper Tuolumne for Raffery, Parker Pass and Gaylor basins (Lundquist and Dettinger, 2005). These are small basins, 6 to 10 sq. mi. in area, tributary to Tuolumne Reach 3000 (Figure 4-1). The Lundquist and Dettinger data for the time difference between maximum snowmelt rates, usually about 2 p.m., and the peak basin outflow measured during snowmelt indicated that liquid water releases from snowpacks were attenuated more than previously modeled in HFAM. The algorithm update delayed peak liquid water outflow timing by several hours.

Data collected at the recently installed streamgage at Tuolumne Grand Canyon (USGS 11274790, 301 sq. mi.) supported this algorithm change, although as drainage areas increase snowpack water outflow timing may not be separated from other flow attenuation processes; e. g. flow routing in reaches and flow through ponds and lakes.

The timing of peak flows measured during snowmelt is also dependent on where snow is melting in a watershed. Figure 4-3 shows snow water equivalent in the Tuolumne above the Tuolumne Grand Canyon gage on May 1, 2008. Modeled peak flow timing May 1st was 7:30 p.m. in Reach 3000 and 8 p.m. in Reach 3085 (Tuolumne Grand Canyon). Snowmelt runoff observed at Reach 3085 on May 1st was primarily coming from the northern watershed areas tributary to Puite, Matterhorn and Register Creeks rather than from land tributary to Reach 3000. Peak snowmelt timing would have minimal secondary effects on model results for climate change but the algorithm update does more closely follow snowpack processes.

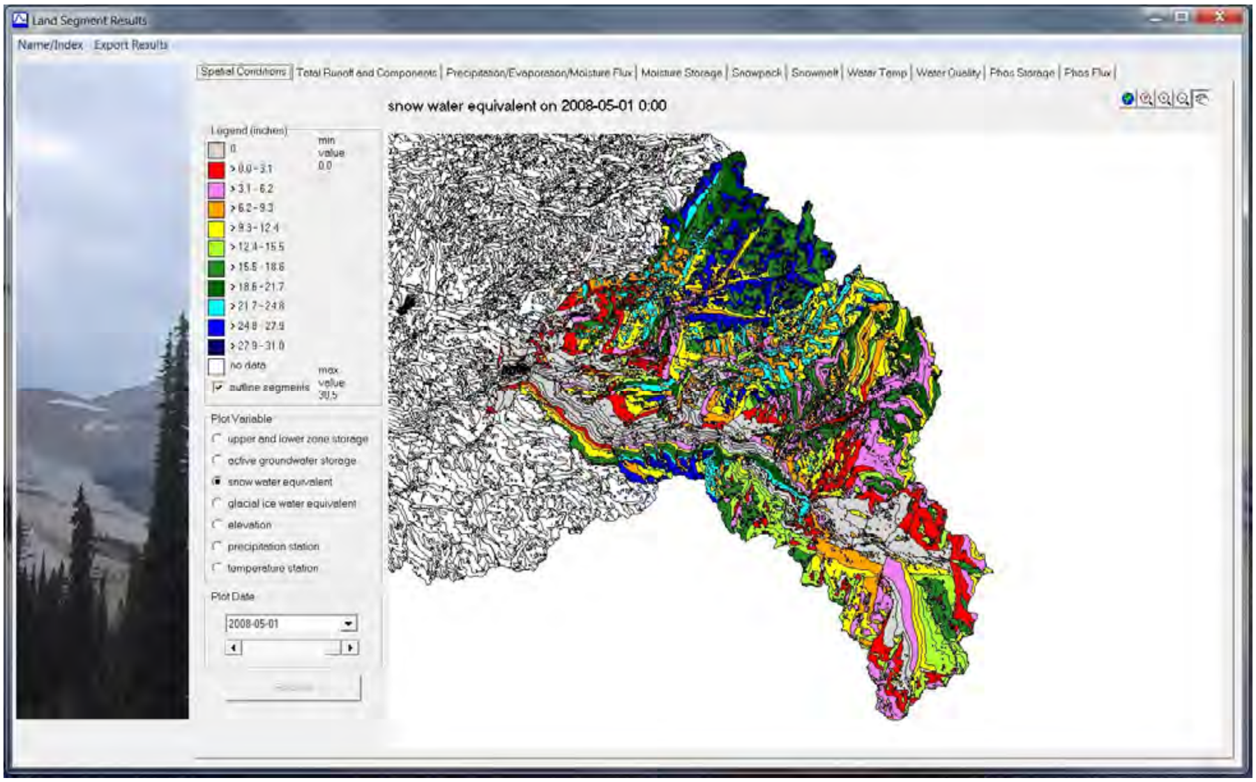


Figure 4-3. Modeled Snowpack Water Equivalent above Tuolumne Grand Canyon, May 1st, 2008

Model parameters represent the diverse characteristics of the Upper Tuolumne. Watershed land at elevations below 6500 ft. is covered by forests, shrubs and grass. Soils are granite derived silt and sand with relatively high infiltration rates and soil moisture holding capacities. Watershed lands above 6500 ft. are exposed granite with near zero infiltration rates and moisture holding capacities or valley meadows with substantial infiltration rates and soil moisture holding capacities. Lakes and ponds are found in high elevation valleys. Lakes, ponds and perched aquifers in meadows in high elevation valleys provide base or groundwater flows for streams even where exposed granite predominates.

Model parameter changes in calibration affected surface runoff, interflow and groundwater flowpath assignments (HFAM parameters INFILT, INTFW, and AGWRC), and snow accumulation, net heat exchange and melt (HFAM parameters TSNOW, NEGHTE, HSHADE and FSHADE). HFAM parameters are defined in the HFAM II Reference and User's Manual (Hydrocomp, 2011).

Model parameter calibration for snow accumulation and melt and for surficial hydrologic processes, especially for inflows to O'Shaughnessey, Eleanor and Cherry Valley reservoirs, was significantly refined because reservoir inflow estimates for these sites were provided for 1974 through 2008 by SFPUC. Appendix B shows simulated reservoir inflows and newly calculated reservoir inflow estimates for O'Shaughnessey and Don Pedro for water years 1974 through 2008.

4.3.4 Calibration Results

Figure 4-4 shows a summary of the calibration results for the Clavey River, the South Fork Tuolumne River and for La Grange, as seen in the HFAM interface. The calibration results summary includes a plot of simulated and observed monthly flows, a bar chart of simulated and observed long-term average monthly flows, the total simulated and observed flow volumes and the percent difference in these volumes over the period of record within water years 1975 to 2008.

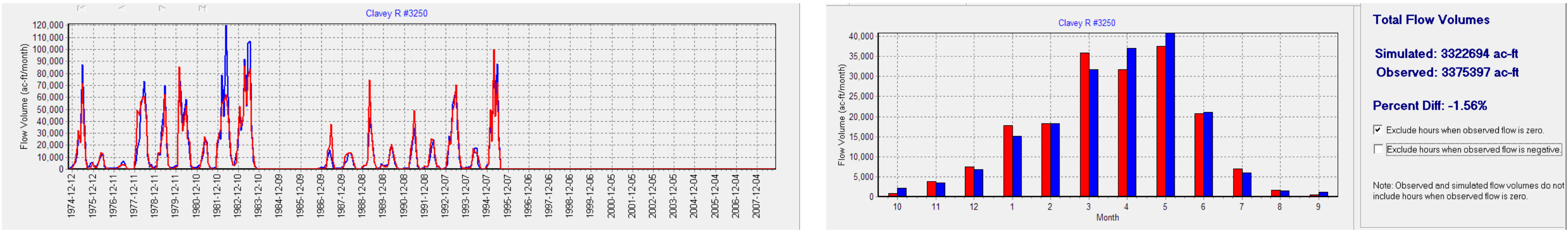
Figure 4-5 shows simulated inflows to O'Shaughnessey dam in water year 2002 (a sample normal year[6]) compared to calculated natural inflows, as seen in the HFAM interface.

Figure 4-6 shows an example of the calibration results in water year 2002, an average snow year, as seen in the HFAM interface. Observed snow water equivalent at the Horse Meadows (HRS) real-time data observation site at 8400 feet elevation is compared to simulated snow water equivalent on a land segment that represents the Horse Meadows location. The zero observed data point on May 21st is incorrect and is a bad data point.

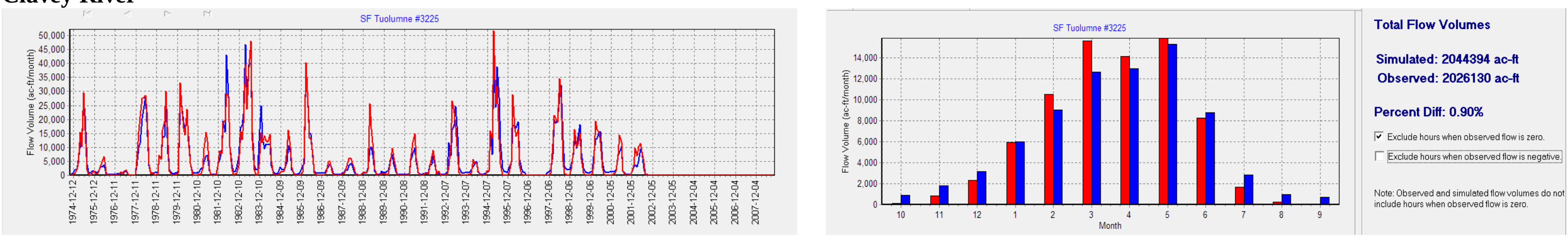
Annual hydrographs from October 1974 through September 2008 are given in Appendix B.

The USGS installed a new streamflow gage on the Tuolumne in the Grand Canyon of the Tuolumne above Hetch Hetchy (11274790) at 3,830 feet with a drainage area of 301 square miles. Data records began 10/21/2006 and will be useful for on-going calibration of the model.

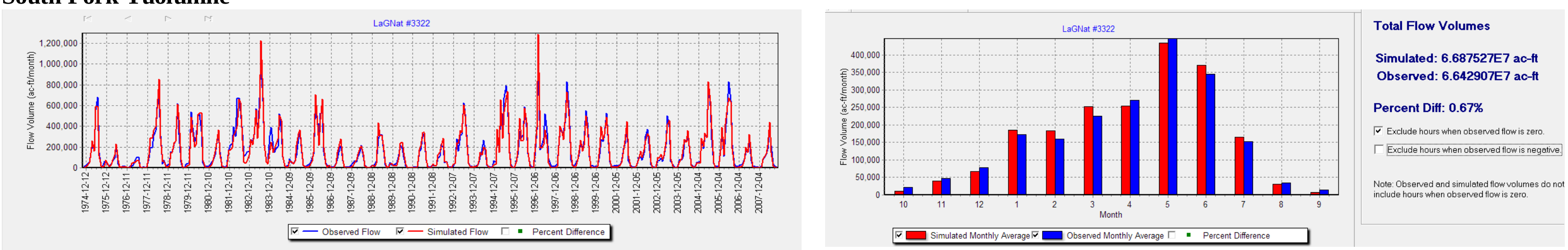
[6] See footnote 2 for description of water year classification system.



Clavey River



South Fork Tuolumne



La Grange

Figure 4-4. Calibration results for the Clavey River, the South Fork of the Tuolumne River and the Tuolumne River at New Don Pedro Reservoir

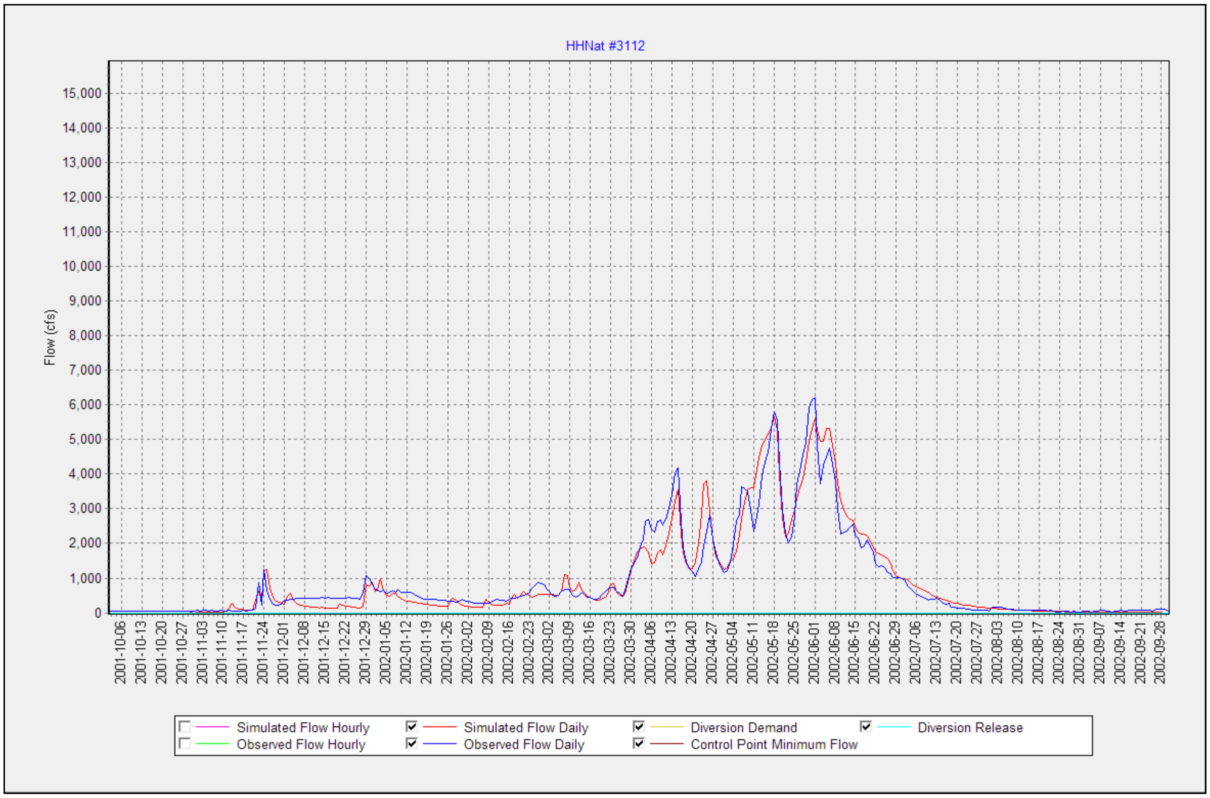


Figure 4-5. O'Shaughnessey simulated and observed natural inflow, 2002 (normal year)

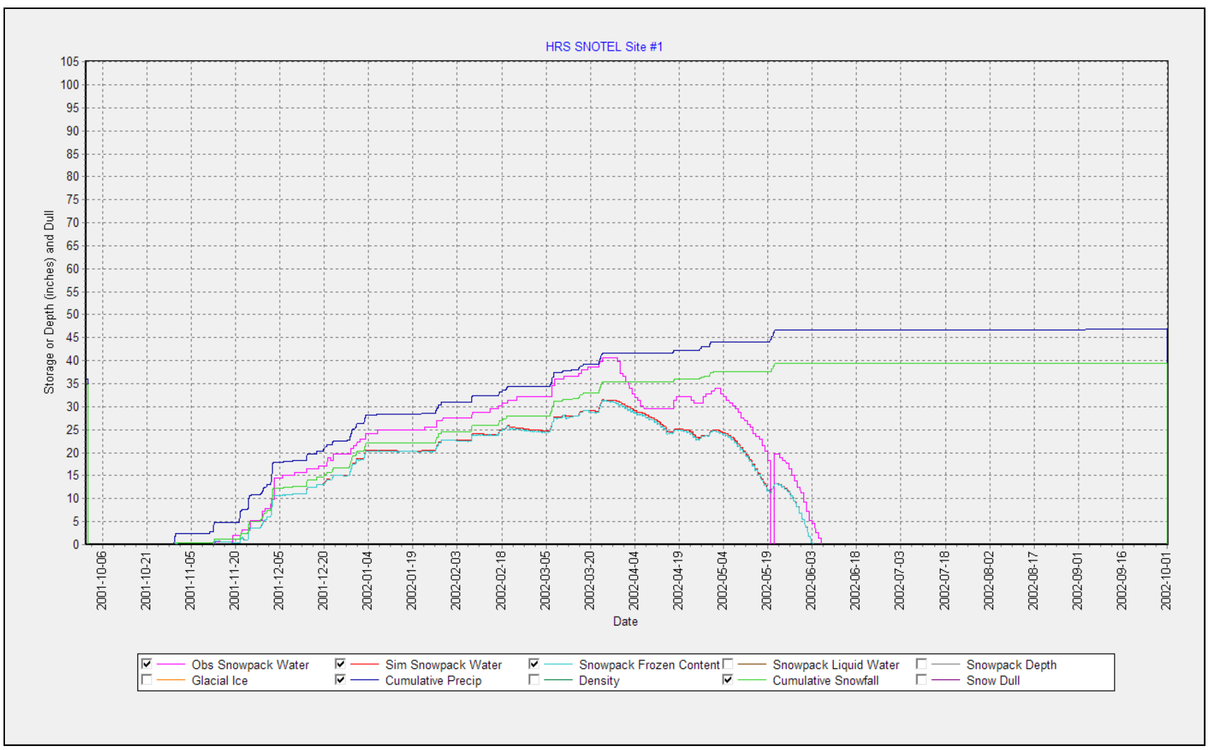


Figure 4-6. Simulated and observed snow water equivalent at 8400 ft., HRS, 2002

5. Constructing Current Conditions and Climate Change Scenarios Weather Inputs

5.1 Historical Trends and Current Climate

Climate is represented in the Tuolumne HFAM model as input timeseries of precipitation, temperature, wind, solar radiation, and evaporation. Climate change scenarios were developed to represent the range of plausible future conditions in the Upper Tuolumne River watershed. The input timeseries for the climate change scenarios were built based on trends and statistics seen in historical meteorological data.

This section summarizes the analysis of historical data. Specific details on the historical data and the analysis are available in Appendix E. Temperature was the only data series found to have consistent historic trends, as in detail in Appendix E and summarized below.

Hourly precipitation, temperature, wind, solar radiation, and evaporation data were compiled for the period of 1930 to 2008 into a 79-year Tuolumne historical meteorological database. These data include records collected at the stations for the period of record and extended records estimated from data recorded at historical stations using the maximum/minimum temperature adjustment method, as discussed in Appendix E.

The historical meteorological database for the Tuolumne watershed was found to have long-term temperature trends, but no trends were detected in precipitation, wind, solar radiation or evaporation. A meteorological database was needed for the climate change study that represents the current climate condition without the long-term trends, so that eventually reservoir yield could be computed and storage needs assessed using traditional analysis (see Section 2). A static meteorological database was created from the historical database, with adjustments to the historical temperature from 1960 to 2008 to remove the long-term temperature trends.

Methods used to adjust the historic temperatures to static conditions are in Appendix E. This static meteorological database was used as the current climate condition of 2010 in this analysis.

5.1.1 Precipitation Trends

Figure 5-1 shows the total annual precipitation at Hetch Hetchy (HTH) for the historical data period and the long-term historical annual precipitation trend. The historical annual precipitation trend line is relatively flat and does not indicate any long-term trend in precipitation.

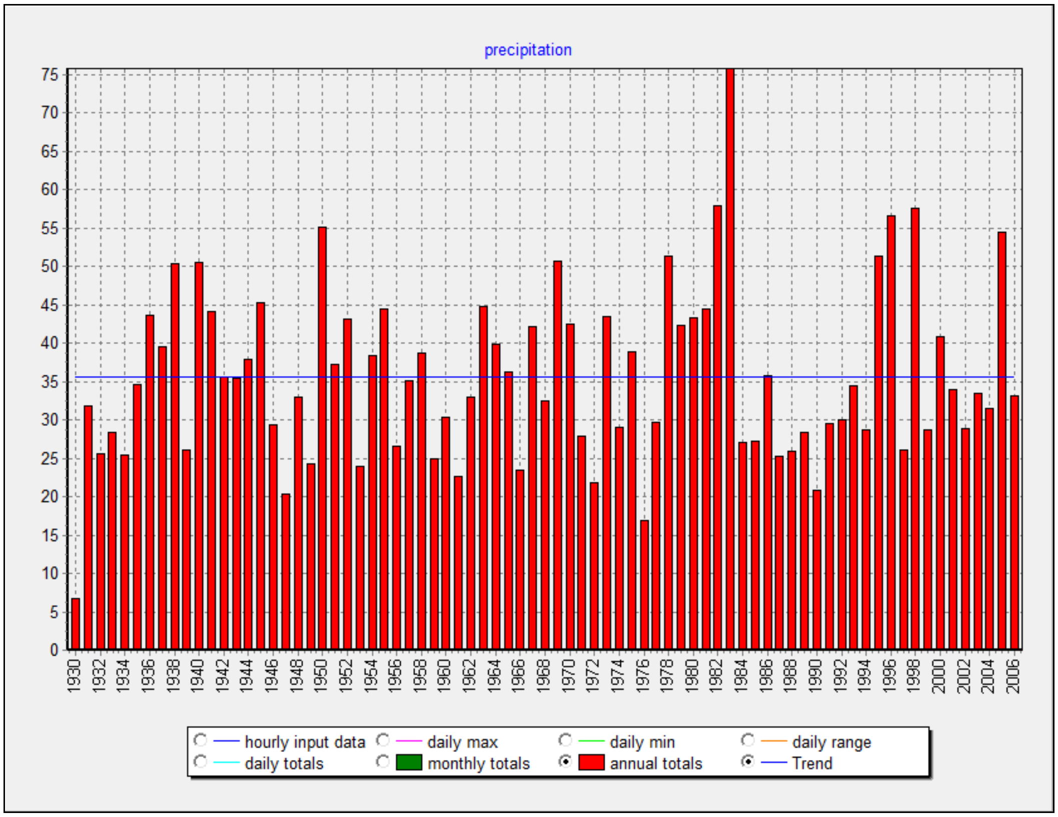


Figure 5-1. HTH historical annual precipitation and trend (plot generated by HFAM)

5.1.2 Temperature Trends

Analysis of historical data from the Tuolumne stations shows overall trends toward increasing temperatures. The details of these trends are complex, but in summary the trends are:

1) Average daily temperatures have increased over the full 79-year period 1930 to 2008, but increases are not consistent over the 79-year period.
2) There are no apparent trends in average daily temperatures from about 1930 to 1960.
3) From about 1960 to the present average daily temperatures at Hetch-Hetchy (HTH) and Cherry Valley (CHV) increase, but the increase is due to an increase in daily minimum temperatures. Daily maximum temperatures show no significant trend.
4) Temperature records at Moccasin at 938 ft. elevation do not show preferential increases in daily minimum temperatures relative to daily average or daily maximum temperatures.

These results correspond to the findings of other climatic studies in the region. Daily minimum temperatures in the Sierras have generally increased since 1900, with most of the increase occurring before 1930 and since 1960 (Behnke, R. 2011). Daily minimum winter temperatures in the Sierras increased over 1.5^{o}C (2.7^{o}F) between 1950 and 1999, while winter average daily maximum temperatures increased over 0.8^{o}C (1.4^{o}F) (Bonfils et al. 2008). Increasing minimum daily temperatures have also been noted at other stations in the Sierra Nevada (John Shaake, pers. comm. December 2009). While temperature has increased in the region overall, there is spatial variability in observed temperatures changes related to elevation and hillslope aspect at individual monitoring stations (Behnke R. 2011, Lundquist and Cayan 2007).

There is a correlation between climate in the Upper Tuolumne River basin and the Pacific Decadal Oscillation that is presented in Appendix E. However, accounting for this correlation has no significant impact on the observed temperature trends and therefore can be ignored in creating the static meteorological database for 2010 current conditions.

The increasing daily minimum temperature trends from 1960 to the present happened when the gage locations and instrumentation at Hetch Hetchy and Cherry Valley were stable (as discussed further in Appendix C.2). Tables of historic temperature trends at Tuolumne river stations are provided in Appendix E.

5.1.3 Solar Radiation Trends

Solar radiation data for the analysis period 1974 to 2008 were calculated from theoretical clear sky solar radiation and percent sunshine estimated from sky cover descriptions at Cherry Valley and Moccasin. The calculated data were compared to short record solar radiation observations at Buck Meadows (BKM) and at high elevation stations in the Tuolumne (TUM, DAN, and TES), (Appendix E). The calculated solar radiation data series show no significant trends.

5.1.4 Wind Speed Trends

Wind speeds for the analysis period 1974 to 2008 were from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis data set (Kalnay et al. 1996) and from limited observations at Buck Meadows (BKM). These data show no significant trends (Appendix E).

5.1.5 Evaporation Trends

Evaporation data were only recorded at Hetch Hetchy (HTH) for part of the historical data period. Evaporation data before and after the period of data collection are set to the monthly long-term averages with a diurnal pattern. These data have no significant trend.

5.2 Weather Inputs for Climate Change Scenarios

A simple and commonly-used method of developing meteorological timeseries to represent climate change scenarios is the “delta method”. The method was developed in the early days of climate change assessments but is still widely used today. In the delta method, a future timeseries is generated from an historical timeseries representing present-day climate by adding or multiplying it by an adjustment factor equally across all seasons and diurnally to represent future climate. One consequence of this assumption is that the future frequency and magnitude of extreme weather events are the same as they are in present-day climate. Another is that this approach assumes change will occur equally at all times of the year. The method assumes that changes in climates are only relevant at coarse scales, and that relationships between variables are maintained towards the future. While these assumptions might hold true in a number of cases, they could be wrong, particularly in highly heterogeneous landscapes where topographic conditions cause considerable variations over relatively small distances. Nevertheless, the relative simplicity of the delta method approach makes it appropriate for this first sensitivity analysis.

A delta-adjusted future meteorological database was generated from the 2010 current condition static meteorological database to represent each of the future climate conditions listed in Table 3-1. The precipitation for each future climate condition was applied as a multiplication factor to each precipitation record in the static meteorological database. The temperature increase for each future climate condition is stated as average temperature increases instead of increases to minimum and maximum temperatures. Since the historical temperature records in the Tuolumne at Hetch Hetchy and Cherry Valley show that minimum daily temperatures have increased much more than maximum daily temperatures, this tendency is assumed to continue, becoming gradually more moderate. The method of modeling the relative changes in the minimum and maximum temperatures is discussed in Appendix E.

6. Analysis of Hydrologic Response

This section presents the simulated hydrologic response for the period 1975 to 2008 for the climate change scenarios.

Section 6.1 provides results for the 2010 static current condition which uses the de-trended meteorological inputs discussed in Section 5.1. Sections 6.2 to 6.5 compare the 2010 static current condition simulated hydrology to the simulated hydrology for each constructed climate change scenario.

6.1 Effects of Historical Trends

The historical meteorological database was found to have long-term historical trend for minimum and average daily temperature. The observed minimum daily temperature increases over the 1960 to 2008 period at both the Hetch Hetchy (HTH) and Cherry Valley (CHV) gages. A "static meteorological database" was created (as described in Section 5.1) by adjusting the historical temperature data to remove trends using the methods discussed in Appendix E.

Table 6-1 lists the mean daily temperatures at Hetch Hetchy and Cherry Valley calculated from the historical and static meteorological database for the 34-year period, water years 1975 to 2008.

Table 6-1. Mean daily temperature in historical and static meteorological database

Station	Historical Meteorological Database (deg F)	Static Meteorological Database (deg F)	Difference (deg F)
Hetch Hetchy	54.19	55.07	+ 0.88
Cherry Valley	53.36	54.34	+ 0.98

The static meteorological database represents the current climate condition and was used to simulate the current hydrological conditions (year 2010). The higher temperatures in the static meteorological database resulted in increased simulated watershed evapotranspiration and decreased simulated total runoff in the 2010 current condition compared to the historical condition. Table 6-2 lists the percent change in simulated total runoff and total watershed actual evapotranspiration at O'Shaughnessy and Don Pedro dams.

Table 6-2. Change in current hydrological conditions from historical condition

Location	Hydrological Characteristic	Current Climate Condition[1] (% change from historical)
O'Shaughnessy	total runoff	**-** 0.5 %
O'Shaughnessy	actual evapotranspiration	+ 1.9 %
Don Pedro	total runoff	**-** 0.9 %
Don Pedro	actual evapotranspiration	+ 1.8 %

[1]The current climate condition (year 2010) was simulated using the static meteorological database.

The adjustments made to historical temperature to remove trends and create a static temperature record are constant from 1930 to 1960, and decrease linearly from 1960 to 2008 (Table E.7). The resulting change in simulated streamflow and actual evapotranspiration are also greater in the early record and become smaller after 1960, disappearing entirely by 2008.

6.2 Runoff Timing and Volume

The future hydrological conditions were simulated with HFAM using the future meteorological database which represents each of the future climate conditions (climate change scenario at a future climate date). The results of these simulations were compared with 2010 current climate simulated hydrologic conditions to analyze the potential hydrological effects of climate change at 2040, 2070 and 2100.

Appendix A provides comparisons of the change in simulated runoff, actual evapotranspiration and snow water equivalent for each future climate condition compared to the current condition.

The effect of temperature increase can be assessed by comparing the results of climate change scenarios 1A (low temperature increase with no precipitation change), 2A (moderate temperature increase with no precipitation change) and 3A (high temperature increase with no precipitation change). The effect of precipitation change can be assessed by comparing the results of climate change scenarios 2A (moderate temperature increase with no precipitation change), 2B (moderate temperature increase with precipitation decrease) and 2C (moderate temperature increase with precipitation increase) or by comparing 3A (high temperature increase with no precipitation change) with 3B (high temperature increase with precipitation decrease).

Table 6-3 summarizes the percentage change in median runoff volume at O'Shaughnessy and Don Pedro Dam for each future climate condition. The percentage changes in simulated runoff for each future climate condition are given in comparison with the current climate condition based on the 2010 current conditions meteorological database. Simulated runoff volumes based on the 2010 current conditions meteorological database are approximately one percent lower than the runoff simulated with the historical meteorological database (Table 6-2).

Climate change scenarios cause changes in monthly runoff timing that can be seen in the plots of simulated average monthly runoff for the current and future climate conditions, shown in Section A.1.3. Under climate change scenario 2A in 2100 at O'Shaughnessy, the May through August runoff would decrease by 45% from the current condition (31% of current condition annual runoff), the September through April runoff would increase by 81% (26% of annual runoff), and 5% of the annual runoff would be lost to additional evapotranspiration.

Table 6-3. Change in median runoff volume for future climate conditions

Climate Change Scenario		**O'Shaughnessy Runoff (% change from 2010)**			**Don Pedro Runoff (%change from 2010)**		
		2040	**2070**	**2100**	**2040**	**2070**	**2100**
1A	low temperature increase no precipitation change	-0.7%	-1.5%	-2.6%	-1.1%	-2.4%	-3.6%
2A	moderate temperature increase no precipitation change	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2B	moderate temperature increase precipitation decrease	-7.6%	-15.8%	-24.7%	-9.5%	-19.1%	-28.7%
2C	moderate temperature increase precipitation increase	1.4%	2.2%	2.4%	1.1%	2.0%	2.8%
3A	high temperature increase no precipitation change	-2.1%	-5.6%	-10.2%	-3.0%	-6.5%	-10.1%
3B	high temperature increase precipitation decrease	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%

These results illustrate that runoff is a residual. The long term water balance in the watershed is:

Precipitation – Actual Evapotranspiration = Total Runoff (E.6)

The effect of the climate change scenarios on actual ET was greater than initially anticipated. With warming, snow disappears earlier in the spring and so there is a longer snow free season. For that reason, there is an increase in actual ET in a warmer climate. At higher elevation, in 2010 conditions, soil moisture in valleys (e.g. Tuolumne Meadows) allows increased ET in a warmer climate; soil moisture is not completely depleted when snow returns. This explains the reduction in runoff above Hetch Hetchy in scenarios 1A, 2A and 3A.

The potential ET was kept constant in the model due to uncertainty in changes in land cover conditions in the future. A refinement of the model would be to make educated assumptions on land cover conditions and associated change potential ET in a warmer climate.

6.2.1 Actual Evapotranspiration

The watershed water balance equation (E.6) can be restated as:

Actual Evapotranspiration = Precipitation – Total Runoff (E.7)

As climate change increases temperatures, rainfall replaces snow in the fall and winter and reduced snowpacks melt earlier in the spring. Evapotranspiration increases in the fall and winter and begins earlier in the spring. Model algorithms follow a basic hierarchy; at low soil moisture water that reaches the land surface usually infiltrates into the soil profile and is later evaporated or transpired. Algorithms reduce infiltration and allow more runoff as soil moisture storage increases.

Evapotranspiration changes in the climate change scenarios are straightforward in principle but are complex in detail. In the Tuolumne, granite outcrops are common above 6500 ft. These outcrops have very low moisture storage capacity compared to soils at lower elevations. At lower elevations with higher forest density and more grasses, brush and shrubs, evapotranspiration will decrease as soil moistures are depleted in summer.

In climate change scenarios 1A, 2A and 3A, there is an increase in evapotranspiration and a decrease in simulated long-term runoff with no change in precipitation. In climate change scenario 2C, there is an increase in evapotranspiration and in simulated long-term runoff so the runoff increase is less than the increase in precipitation.

Section A.2 of Appendix A shows figures of simulated actual evapotranspiration for the future climate conditions compared to the current condition.

Figure 6-1 shows an example of simulated daily actual evapotranspiration on the watershed above O'Shaughnessy Dam in water year 1994, a sample dry year. The simulated daily actual evapotranspiration for the current climate condition is plotted in red; the simulated daily actual evapotranspiration for the future climate condition in year 2100 of climate scenario 2A (moderate temperature increases with no precipitation change) is plotted in blue. Figure 6-1 shows a consistent increase in evapotranspiration in 2100 from October through May compared to current evapotranspiration.

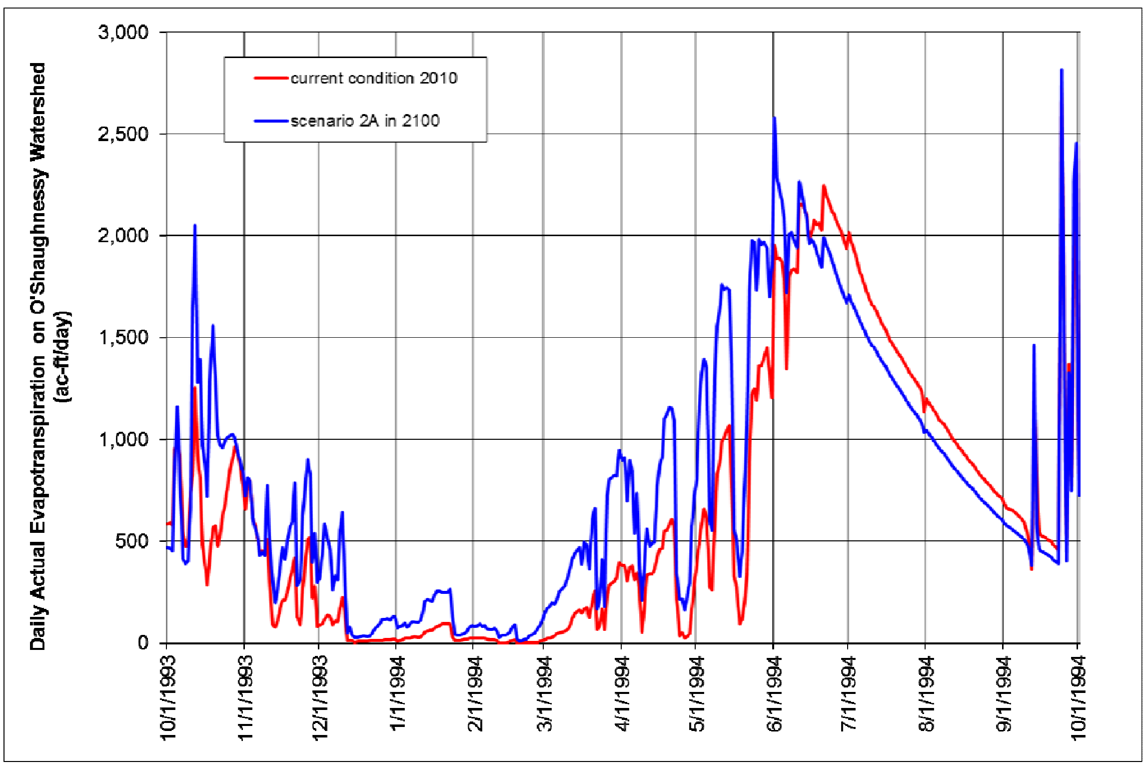


Figure 6-1. Simulated watershed actual evapotranspiration above O'Shaughnessy for current climate condition (red) and scenario 2A in 2100 (blue), water year 1994

Increasing temperatures due to climate change and reduced soil moisture will very likely, over time, alter forest extent and density. Forests may expand at higher elevations and decline at lower elevations. This could change evapotranspiration and require adjustments to the calibrated land segment parameters. Changes in total water yield from Tuolumne due to forest migration may be limited, however, if the total forest extent does not change.

6.2.2 Low and High Runoff Years

The results provided above in are valid for median runoff (exceeded in 50 percent of all water years). Simulated changes in median annual runoff do not fully describe how runoff would be affected during high runoff or drought years. When firm yield from reservoirs is evaluated, low runoff years are critical.

Table 6-4 summarizes the modeling results in terms of the change in simulated 5 (extremely wet), 50 (the median value as shown in Table 6-3) and 95 (extremely dry) percent exceedance annual runoff for two climate change scenarios (2A moderate temperature increases with no precipitation and 3B high temperature increases with precipitation decreases).

Table 6-4. Change in runoff volume for future climate conditions at 5%, 50%, and 95% exceedance level

Climate Change Scenario		Exceed Prob	O'Shaughnessy Runoff (% change from 2010)			Don Pedro Runoff (% change from 2010)		
			2040	**2070**	**2100**	**2040**	**2070**	**2100**
2A	moderate temperature increase no precipitation change	5%	-0.6%	-1.4%	-2.4%	-1.1%	-2.6%	-3.7%
2A	moderate temperature increase no precipitation change	50%	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2A	moderate temperature increase no precipitation change	95%	-3.4%	-8.8%	-15.1%	-4.2%	-9.8%	-16.1%
3B	high temperature increase precipitation decrease	5%	-7.1%	-14.3%	-21.8%	-8.7%	-16.7%	-24.3%
3B	high temperature increase precipitation decrease	50%	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%
3B	high temperature increase precipitation decrease	95%	-14.7%	-30.9%	-46.5%	-16.6%	-33.3%	-48.1%

Appendix A provides figures showing simulated runoff, actual evapotranspiration and maximum snow accumulation exceeded in 5, 50, and 95 percent of all water years for climate change scenario 2A. Simulated runoff exceeded in 5, 50, and 95 percent of all water years is also provided for climate change scenario 3B, the scenario which results in the greatest reduction in simulated runoff. These figures show the non-linear effects of climate change on runoff in low and high runoff years and illustrate that soil moisture and evapotranspiration have precedence over runoff in droughts.

Runoff in drought years is a relatively small percentage of precipitation and is very sensitive to changes in precipitation. This non-linear sensitivity is found in response to climate change scenarios too: Runoff reductions, as a percentage of current runoff, are greatest in drought years.

The non-linearity of the response to climate change is also reflected in the difference between the mean (average) change in runoff and the median (exceeded in 50 percent of all water years) change. The percent reduction in mean runoff is consistently less than the percent reductions in median runoff. Table 6-5 summarizes these changes for climate change scenarios 2A and 2B.

Table 6-5. Change in median and mean runoff for climate change scenarios 2A and 2B

Climate Change Scenario		**Hydrological Characteristic**	**O'Shaughnessy (% change from 2010)**			**Don Pedro (% change from 2010)**		
			2040	**2070**	**2100**	**2040**	**2070**	**2100**
2A	moderate temperature no precipitation change	precipitation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
		median runoff	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
		mean runoff	-1.2%	-2.9%	-5.1%	-1.8%	-3.9%	-5.9%
2B	moderate temperature precipitation decrease	precipitation	-5.0%	-10.0%	-15.0%	-5.0%	-10.0%	-15.0%
		median runoff	-7.6%	-15.8%	-24.7%	-9.5%	-19.1%	-28.7%
		mean runoff	-7.6%	-15.5%	-23.5%	-9.1%	-17.8%	-26.3%

6.3 Snow Accumulation, Areal Extent, and Snowmelt Timing

Simulated total watershed runoff and actual evapotranspiration are dependent on snow accumulation. Table 6-6 summarizes the percentage change in median annual maximum snow water equivalent on the watersheds above O'Shaughnessy and Don Pedro dams for all future climate conditions. Section A.3 of Appendix A shows figures of simulated annual maximum watershed snow water equivalent for each future climate condition compared to the current climate condition (year 2010). Appendix D provides additional details on the change in snow accumulation and snow melt due to the future climate conditions.

Figure 6-2 shows simulated watershed snowpack above O'Shaughnessy Dam in water year 1994. The simulated watershed snowpack for the current climate condition is plotted in red; the simulated watershed snowpack for the future climate condition in year 2100 of climate change scenario 2A (moderate temperature increase with no precipitation change) is plotted in blue. Figure 6-3 shows the simulated natural inflow to O'Shaughnessy Dam over the same period for the same climate conditions. It can be seen the inflows are accelerated. Precipitation events that fell mainly as snow under the 2010 current condition instead trigger rain events under the future climate scenarios which increase wintertime peak inflows. Meanwhile, snowmelt is accelerated due to warmer temperatures and less spatial snow coverage (shallower snowpack melts faster and need less energy to reach isothermal conditions to generate melt and the resulting runoff).

Table 6-6. Change in median annual maximum snow water equivalent for future climate conditions

Climate Change Scenario		**O'Shaughnessy Snow (% change from 2010)**			**Don Pedro Snow (%change from 2010)**		
		2040	**2070**	**2100**	**2040**	**2070**	**2100**
1A	low temperature increase no precipitation change	-1.6%	-11.4%	-21.7%	-11.9%	-26.6%	-38.8%
2A	moderate temperature increase no precipitation change	-4.3%	-24.5%	-43.8%	-20.8%	-41.6%	-59.8%
2B	moderate temperature increase precipitation decrease	-10.3%	-33.4%	-54.8%	-25.9%	-49.5%	-67.6%
2C	moderate temperature increase precipitation increase	-2.0%	-20.8%	-38.3%	-18.8%	-38.4%	-56.6%
3A	High temperature increase no precipitation change	-15.5%	-45.8%	-73.5%	-33.6%	-60.8%	-81.4%
3B	High temperature increase precipitation decrease	-20.6%	-53.6%	-79.5%	-38.2%	-66.2%	-85.6%

The simulated snow areal extent is also reduced for the future climate conditions. Figure 6-4 shows a spatial plot of the simulated snow water equivalent in the Tuolumne watershed on April 1, 1992 for the current climate condition displayed in the HFAM interface. April 1st is used as a reference point of peak annual snowpack accumulation. Figure 6-5 shows the same plot of simulated snow water equivalent for the future climate condition in year 2100 of climate change scenario 2A (moderate temperature increases with no precipitation change). Figure 6-6 shows the same plot of simulated snow water equivalent for the future climate condition in year 2100 of climate change scenario 2B (moderate temperature increases with precipitation decrease). Note that the color legend is different in each plot as it corresponds to an increasingly smaller range of snow water equivalent depth.

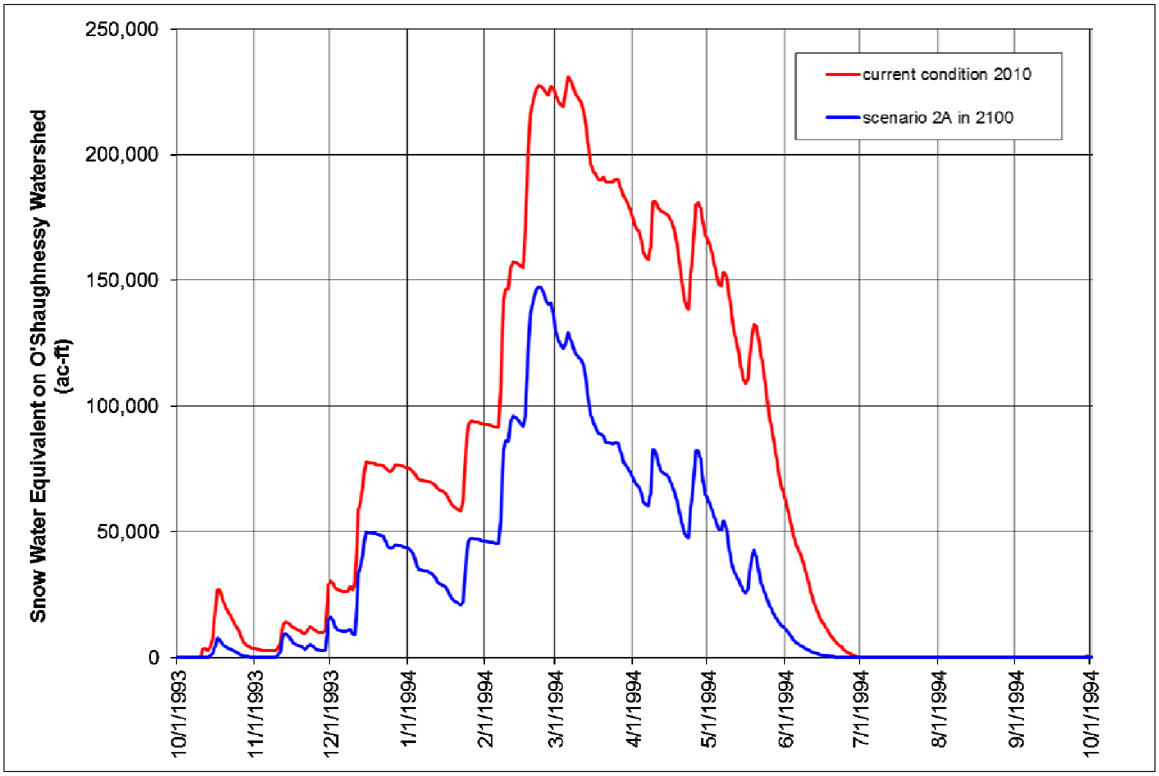


Figure 6-2. Simulated watershed snowpack above O'Shaughnessy Dam for current climate condition (red) and scenario 2A in 2100 (blue), water year 1994.

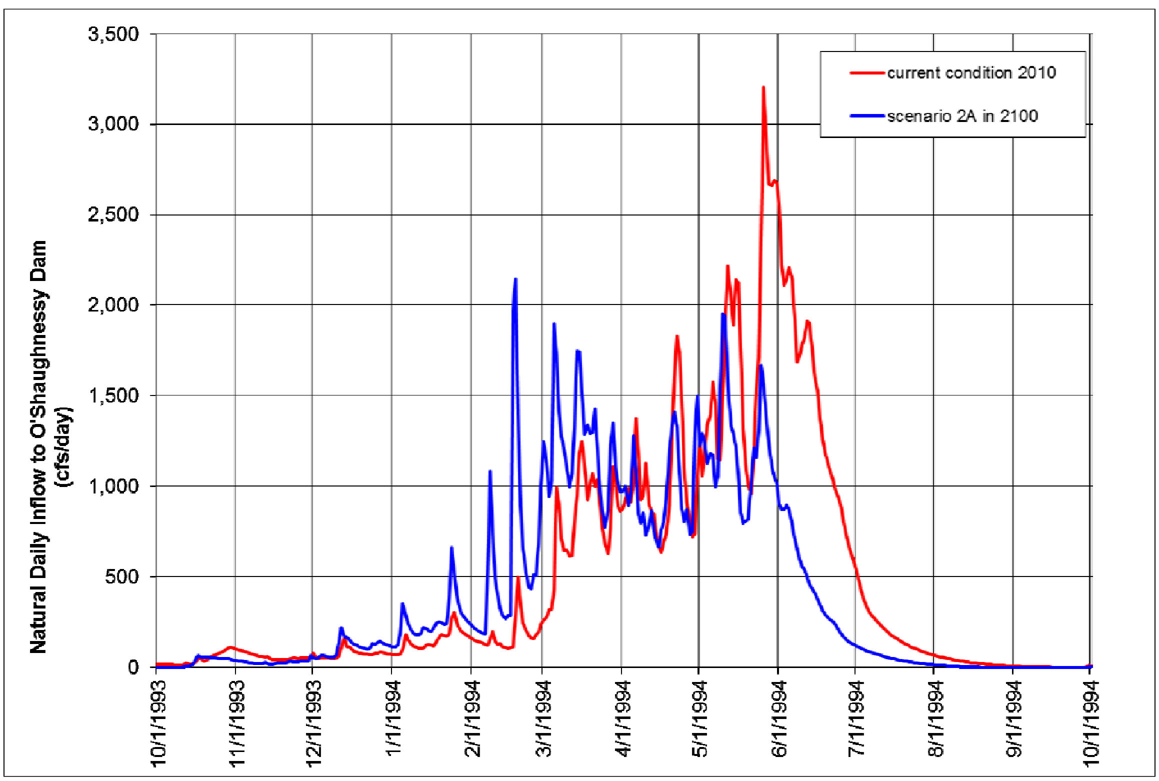


Figure 6-3. Simulated natural inflow to O'Shaughnessy Dam for current climate condition (red) and scenario 2A in 2100 (blue), water year 1994

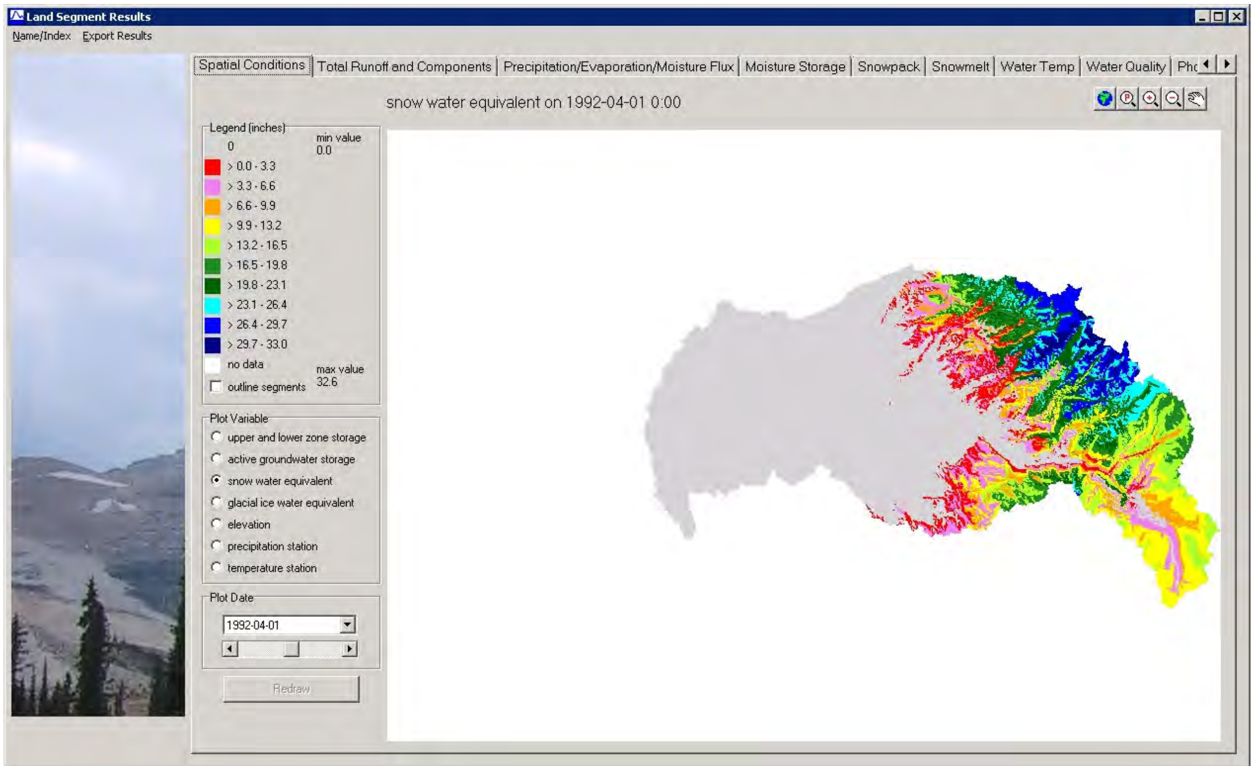


Figure 6-4. Simulated snow water equivalent on 4/1/1992 for current climate condition

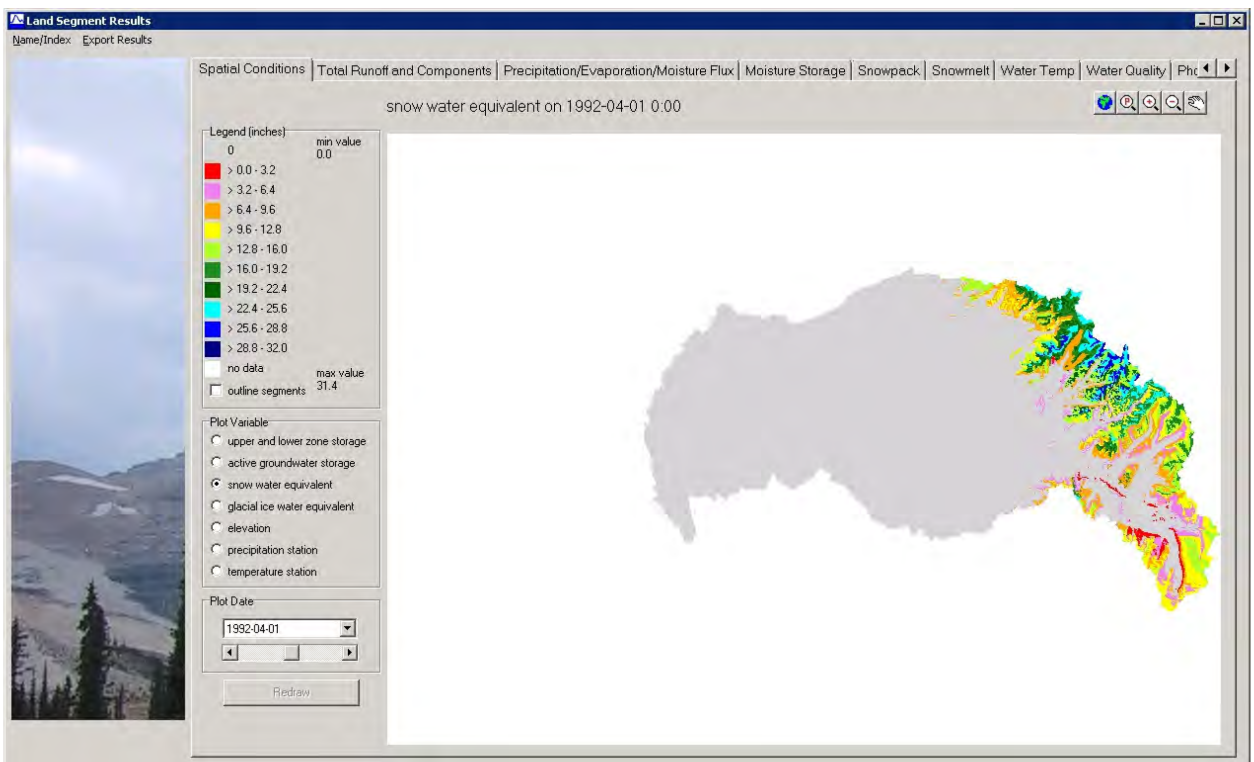


Figure 6-5. Simulated snow water equivalent on 4/1/1992 for scenario 2A in 2100

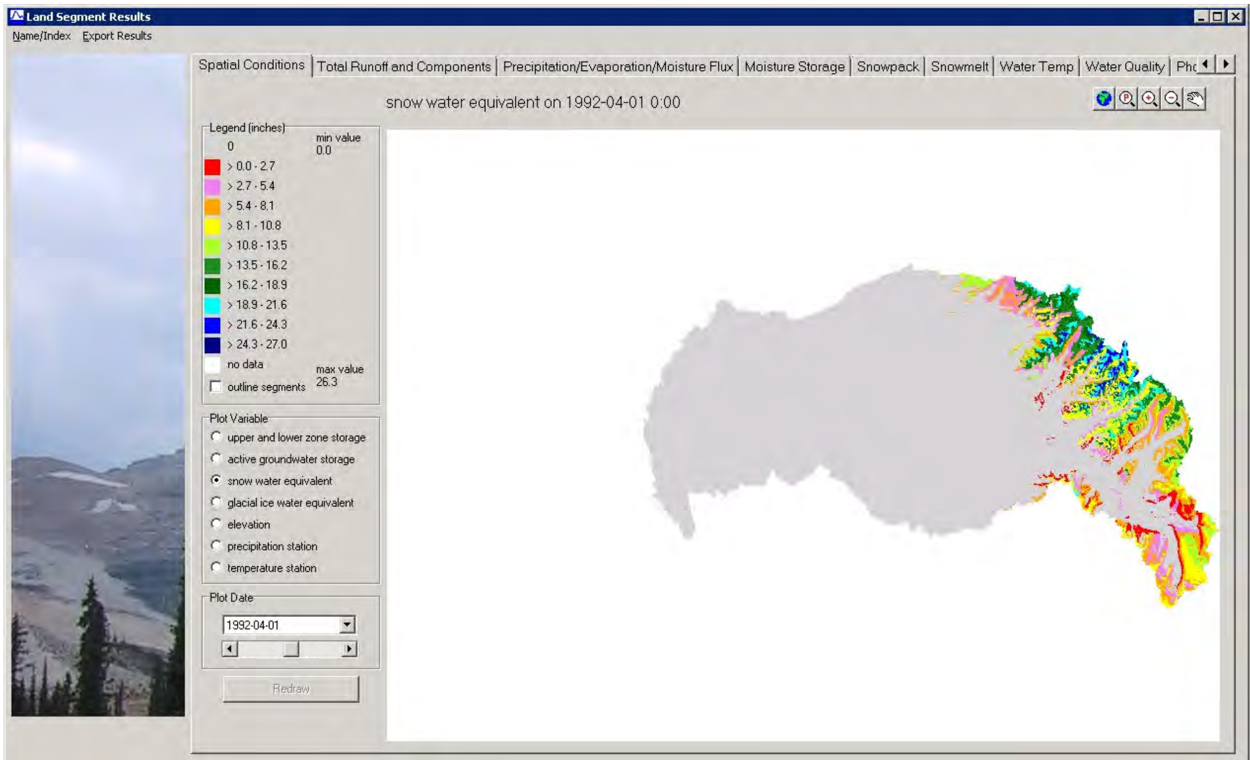


Figure 6-6. Simulated snow water equivalent on 4/1/1992 for scenario 2B in 2100

Figure 6-7 shows the simulated snow water equivalent in the watershed above O'Shaughnessy Dam for water years 1987 to 1995. The simulated snow water equivalent for the current climate condition is plotted in red; the simulated snow water equivalent for the future climate condition in year 2100 of climate change scenario 2A (moderate temperature increases with no precipitation change) is plotted in blue. The reduction in snowpack in the watershed above O'Shaughnessy Dam and the increased actual evapotranspiration that occurs with earlier spring melt result in a 5.6% reduction in simulated flow at O'Shaughnessy Dam over water years 1987 to 1995 compared to the current condition. Simulated flows at Don Pedro Dam are reduced by 6.5% over the same period.

Figure 6-8 shows the simulated snow water equivalent on two land segments with SW aspect at different elevations in the Tuolumne watershed for water year 1992. Snow water equivalent for the land segment at 10,000 feet shown as a solid line; snow water equivalent for the land segment at 7,000 feet is shown as a solid line. The simulated snow water equivalent for the current climate condition is plotted in red; the simulated snow water equivalent for the future climate condition in year 2100 of climate change scenario 2A (moderate temperature increases with no precipitation change) is plotted in blue.

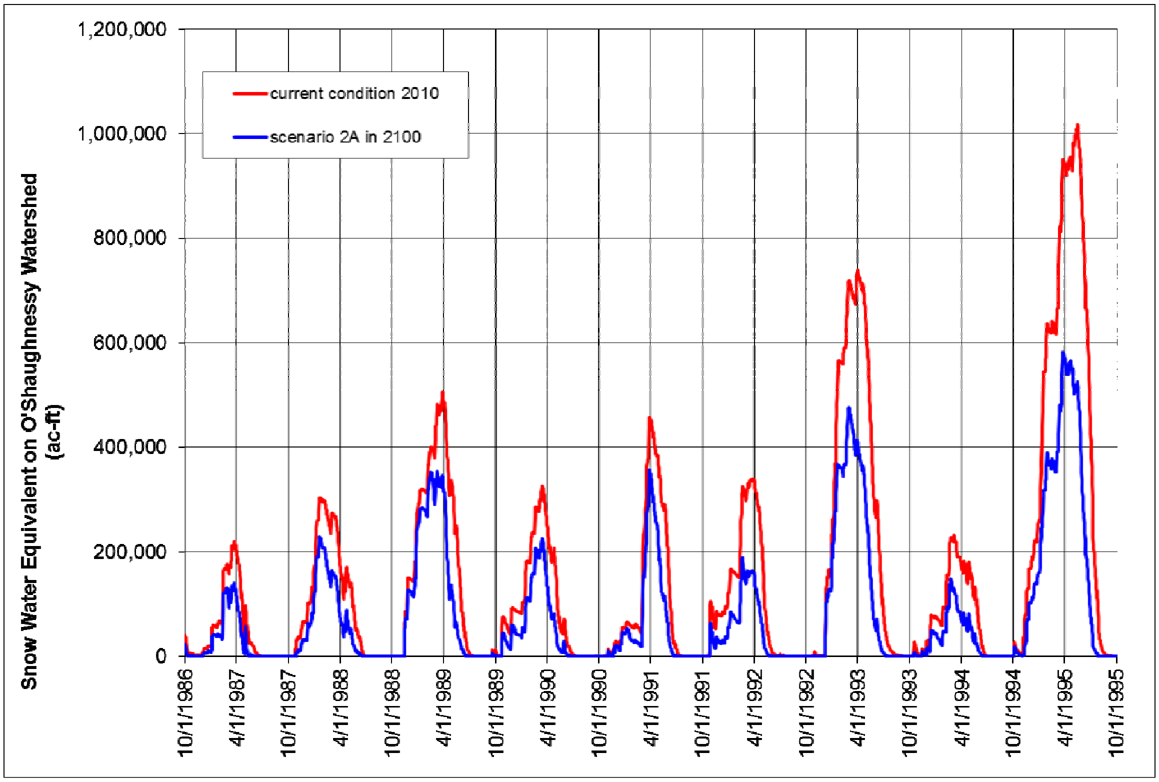


Figure 6-7. Simulated watershed snow water equivalent above O'Shaughnessy Dam for current climate condition (red) and scenario 2A in 2100 (blue), water years 1987 to 1995

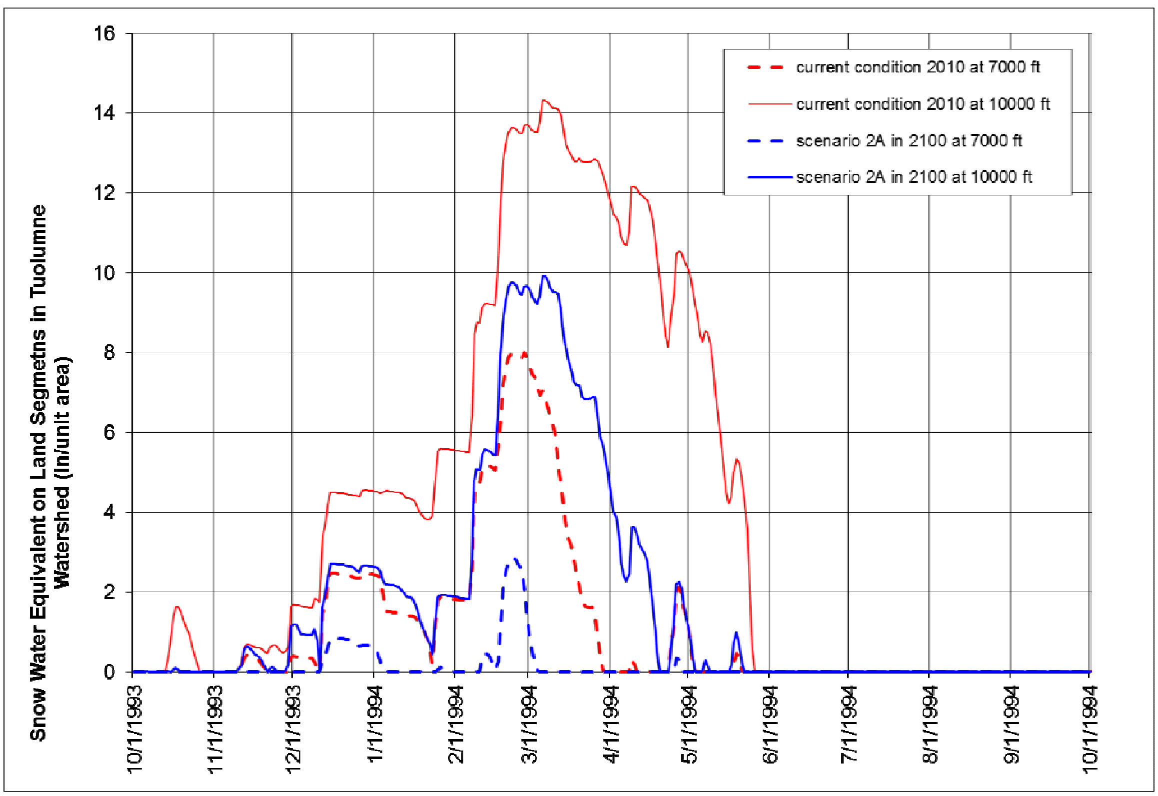


Figure 6-8. Simulated watershed snow water equivalent on land segments at 10000 ft (solid) and 7000 ft (dashed) ft for current climate condition (red) and scenario 2A in 2100 (blue), water year 1992

6.4 Physical Processes, Snowmelt Runoff and Actual Evapotranspiration

Under future climate conditions, winter snow decreases and melts earlier in the spring, resulting in an increase in actual evapotranspiration and a decrease in watershed runoff. Runoff reductions are greater in years with less than normal precipitation. Actual evapotranspiration in all water years is key for runoff reductions.

Actual evapotranspiration (AET) is dependent both on soil moisture, decreasing as soil moisture is depleted, and on snow cover. AET decreases as soil moisture is depleted. In years when there is a large snowpack and in years when cool spring temperatures delay snowmelt, actual evapotranspiration is reduced.

The relative influence of soil moisture and snowpack on actual evapotranspiration losses depends on soil moisture storage and on elevation. The watershed above O’Shaughnessy Dam has more exposed granite and higher elevations, so its actual evapotranspiration is more dependent on snowpack than soil moisture. Lower elevations have less snow and deeper soils so actual evapotranspiration is more dependent on soil moisture.

To illustrate the relationship between actual evapotranspiration, snowpack and soil moisture for the O’Shaughnessy watershed, simulation results are shown for water year 1995, a year with a large snowpack and late spring melt, and for water year 1994, a year with a low snowpack and early spring melt.

Figure 6-9 shows simulated cumulative actual evapotranspiration for the O’Shaughnessy watershed for each year of the 34-year meteorological database for the future climate condition in year 2100 of climate change scenario 2A. The red line shows the simulated actual evapotranspiration for water year 1995, a sample wet year. The blue line shows the results for water year 1994, a sample dry year.

The simulated 1995 runoff to O’Shaughnessy Dam for the future climate condition in year 2100 of climate change scenario 2A was 1,378,000 acre-feet. Simulated actual evapotranspiration was 258,000 acre-feet, approximately 19 percent of runoff. In comparison, the simulated 1994 runoff for the same future climate condition was 299,000 acre-feet and simulated actual evapotranspiration was 283,000 acre-feet, approximately 95 percent of runoff.

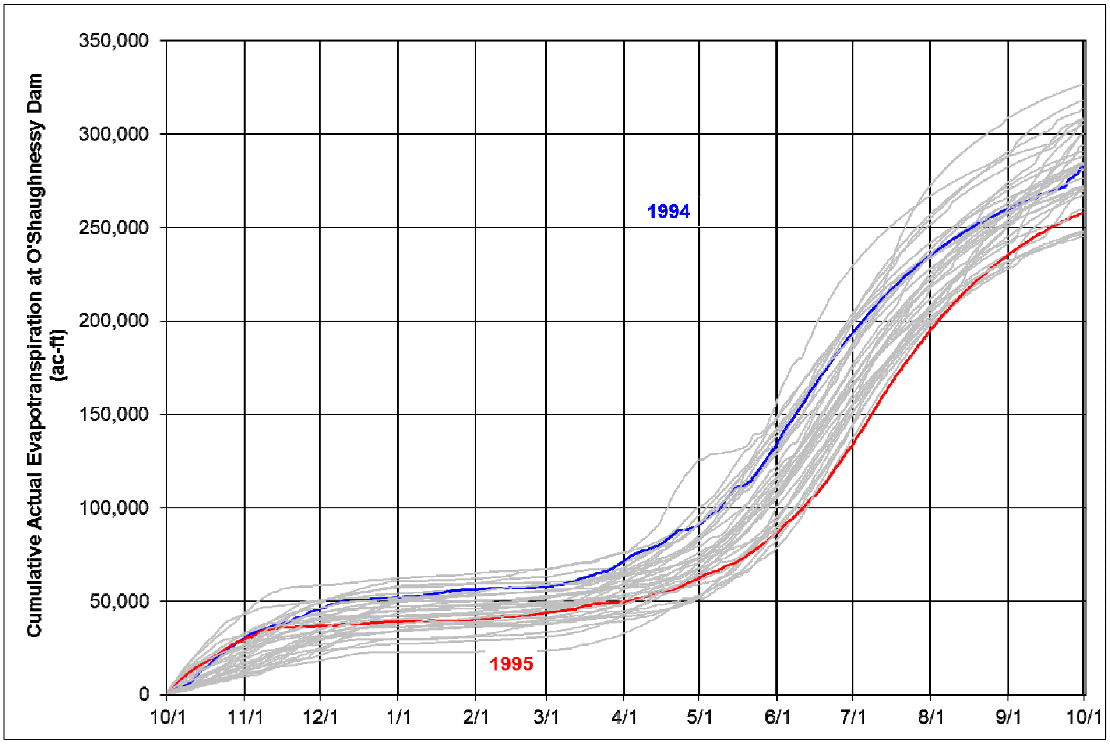


Figure 6-9. Simulated watershed cumulative actual evapotranspiration above O'Shaughnessy Dam for scenario 2A in 2100, water year 1995 in red and water year 1994 in blue.

Figure 6-10 shows the simulated watershed snow water equivalent above O'Shaughnessy Dam for each year of the 34-year meteorological database for the future climate condition in year 2100 of climate change scenario 2A. The red line shows the simulated snow water equivalent for water year 1995. The blue line shows the simulated snow water equivalent for water year 1994.

Figure 6-11 shows the same information for soil moisture. The much larger snowpack in 1995 increases soil moisture in April and May, 1995, compared to April and May, 1994. This increase in soil moisture is not proportional to the difference in snowpack between 1995 and 1994. Soil moisture storage is limited by soil moisture storage capacity.

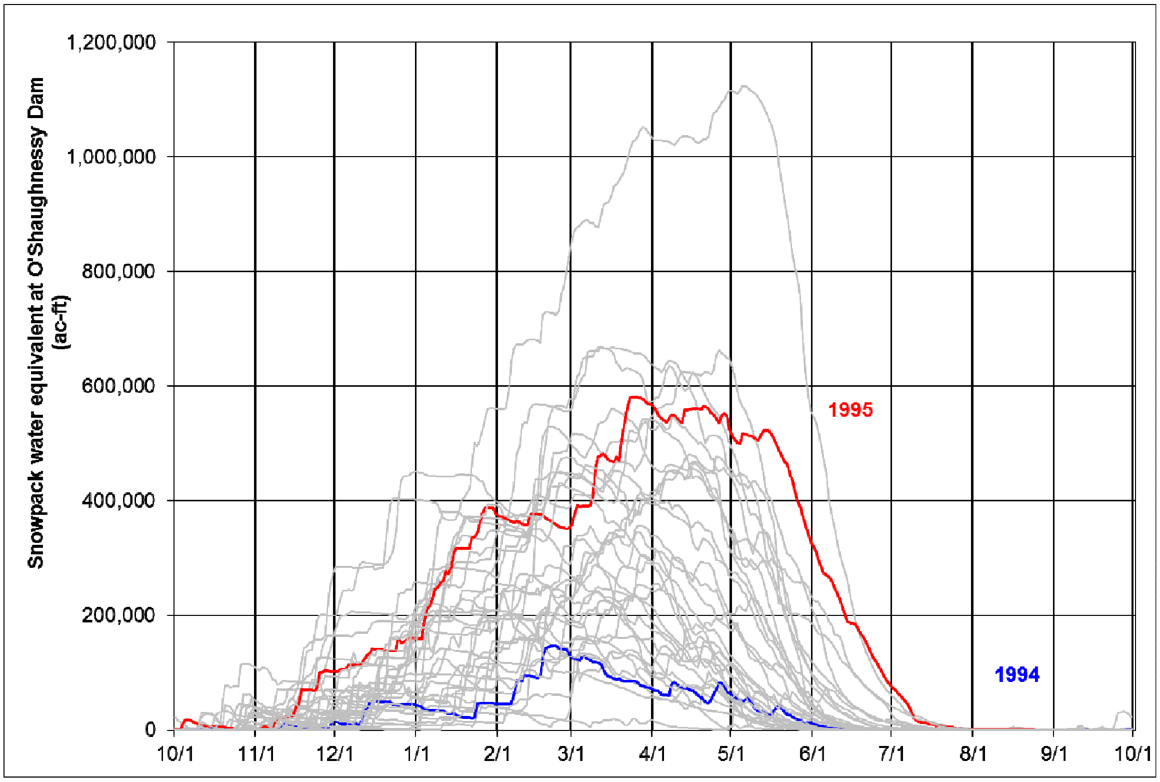


Figure 6-10. Simulated watershed snow water equivalent above O'Shaughnessy Dam for scenario 2A in 2100, water year 1995 in red and water year 1994 in blue.

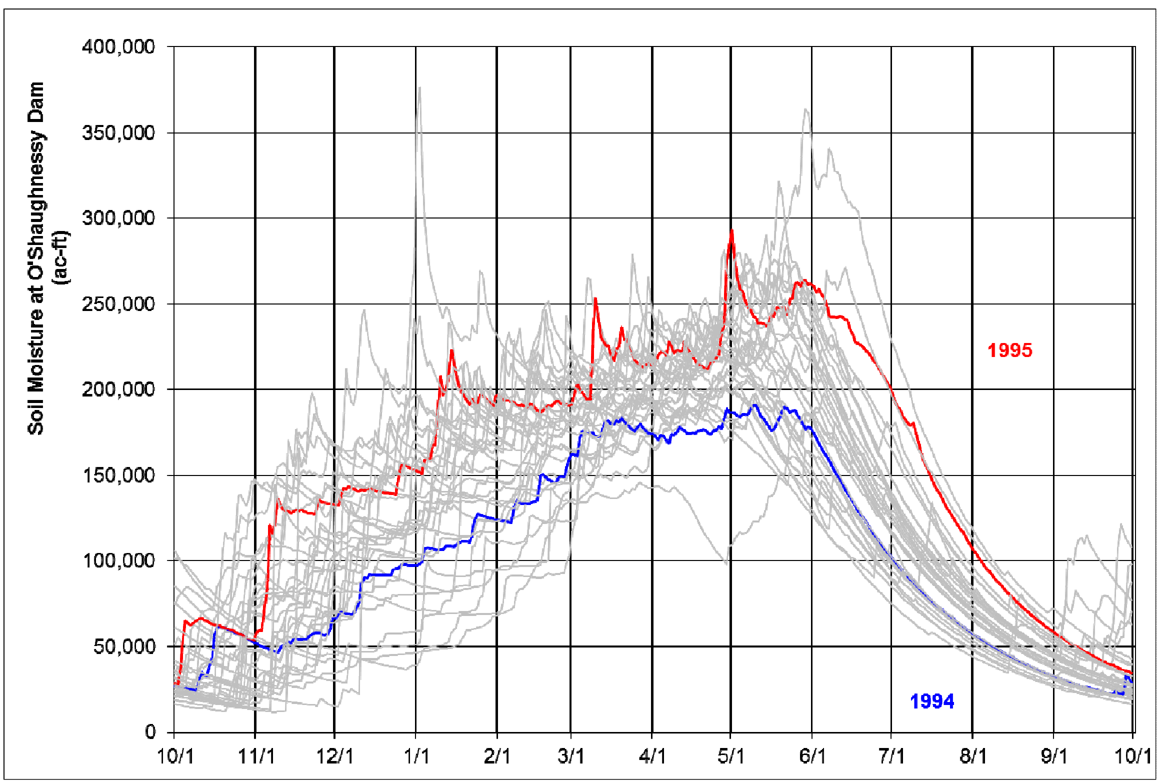


Figure 6-11. Simulated watershed soil moisture above O'Shaughnessy Dam for scenario 2A in 2100, water year 1995 in red and water year 1994 in blue.

6.5 Soil Moisture

HFAM II calculates the hydrologically active moisture storage, the storage that is depleted during the summer and refills in the late spring in most years. Simulated soil moisture storage volumes do not include water in deep alluvium that is not accessible to transpiration or evaporation.

Figure 6-12 shows the simulated watershed soil moisture above O'Shaughnessy Dam for the current climate condition (red) and the future climate condition in year 2100 of climate change scenario 2A (blue) for water year 1995, a year with a large snowpack and late spring melt.

In contrast, Figure 6-13 shows the same results for water year 1994, a year with a low snowpack and early spring melt.

Soil moisture changes under future climate conditions are more noticeable in years with above average precipitation, but reduced soil moistures in summer are found in all years. The amount of change in soil moisture under the future climate condition in year 2100 of climate change scenario 2A would affect all types of vegetation.

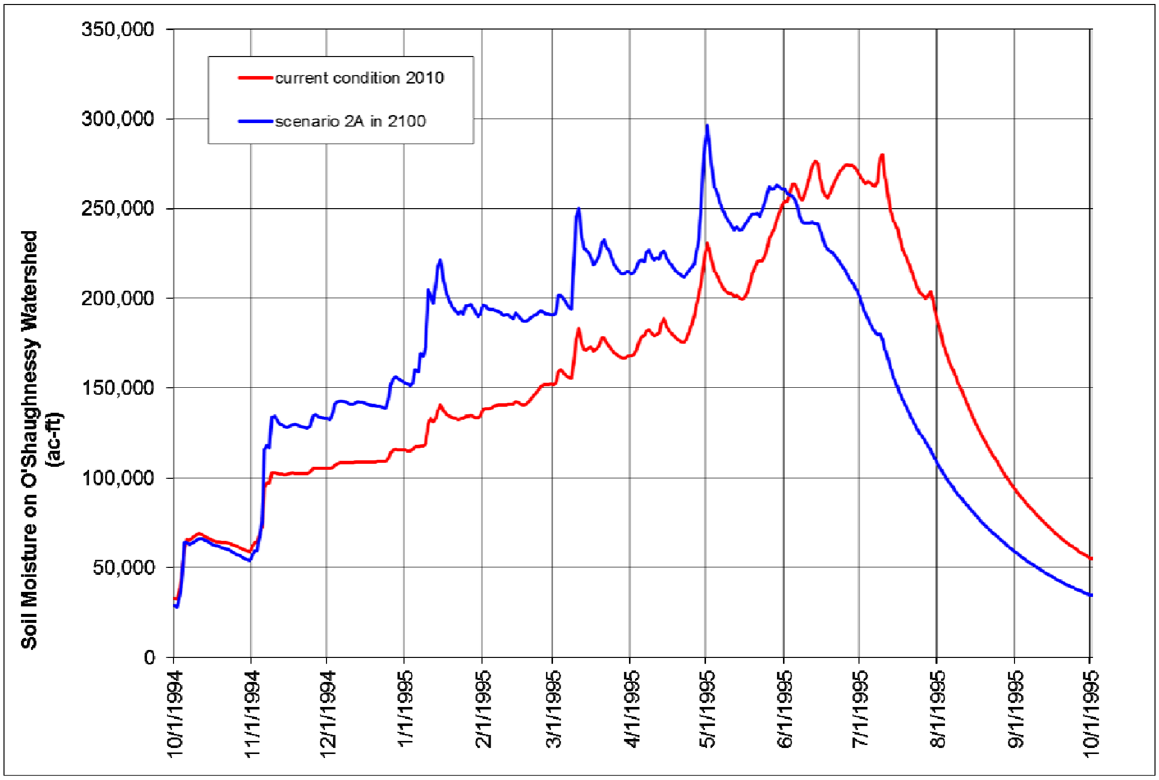


Figure 6-12. Simulated watershed soil moisture above O'Shaughnessy Dam for current climate condition (red) and scenario 2A in 2100 (blue), water year 1995

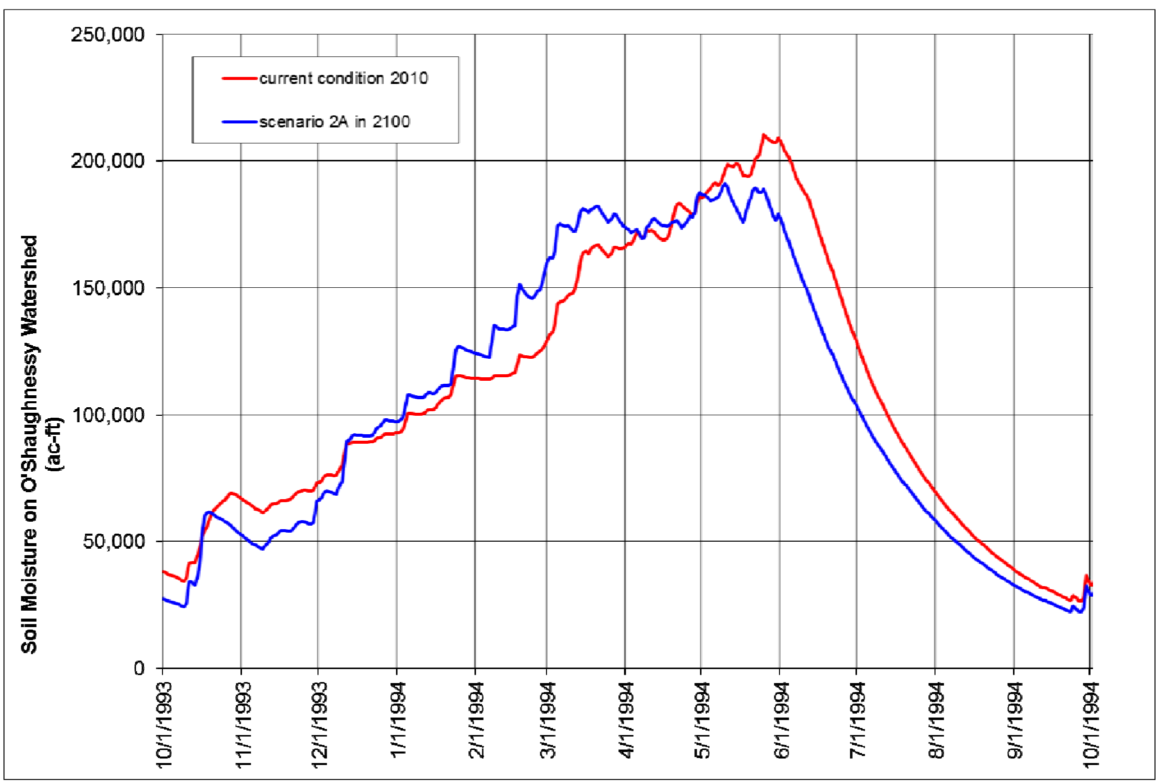


Figure 6-13. Simulated watershed soil moisture above O'Shaughnessy Dam for current climate condition (red) and scenario 2A in 2100 (blue), water year 1994

7. Conclusions

7.1 Tuolumne Climate Change Modeling Methods

Minimum daily temperature increases in the Sierra Nevada are known to be sensitive to climate change but the historical trends of increasing minimum daily temperatures and reduced daily temperature range found at Hetch Hetchy and Cherry Valley from 1960 to the present were unexpected. A method was developed to create the average temperature increases in the climate change scenarios consistent with historical trends in daily minimum temperatures while retaining a reasonable daily range in temperatures.

The modeling results of the climate change scenarios are internally consistent and are generally within the range of conditions found in the historical meteorological records. For example, model runs for the 2A climate change scenario in 2100 have a 46.5 degrees F average temperature at Hetch Hetchy, 6.2 degrees F higher than the average current January temperature (40.3 degrees F), but equal to the average current March temperature at Hetch Hetchy. The HFAM model uses detailed soils, vegetation, and topographic information and these data together with meteorological timeseries to create the model results.

Assumptions and limitations in this study include:

- Observed data are not sufficient to document the physical processes responsible for the increasing minimum daily temperatures at Hetch Hetchy and Cherry Valley; water vapor and cloud cover changes may have occurred. Changes in gage locations, instrumentation and shading at Hetch Hetchy as described in Appendix C-2 are likely to have had effects, but similar increasing daily minimum temperatures are present at Cherry Valley without known instrumentation changes, and minimum daily temperature increases begin in 1960 at Hetch Hetchy before instrumentation changes occurred. Increasing daily minimum temperatures have been observed elsewhere in the Sierra Nevada. (John Schaake, pers. Comm., Behnke, R. 2011, Bonfils et al. 2008)

- Existing vegetation distributions were assumed unchanged and calibrated land segment parameters for current conditions were used without adjustments to model the future climate conditions in 2040, 2070, and 2100. This assumption might be refined by further analysis.

- Historical meteorological temperature and precipitation were assumed to retain their current characteristics, e.g., temperatures retain observed seasonal patterns and storms are no more or less frequent in the future climate conditions. Historical solar radiation, potential evapotranspiration and wind speed were assumed unchanged in the future climate conditions.

- The climate change scenarios have broad ranges for projected future temperatures and precipitation.

- The effects of climate change on Tuolumne River flood frequency were not established by this analysis because the frequency and magnitude of large storms in the future climate change scenarios are uncertain.

As additional data are collected in the Tuolumne, and as more detailed GCM results become available, it will be possible to refine the future climate and watershed runoff projections.

7.2 Tuolumne Climate Change Modeling Results

Climate change in the Tuolumne River affects snow accumulation and melt, soil moisture and forests, and reservoir inflows, and potentially the water supplies available for all purposes. Table 7-1 summarizes the modeling results in terms of the change in simulated median annual runoff at O'Shaughnessy and Don Pedro dams for the climate change scenarios at the future climate dates.

Table 7-1. Change in median runoff volume for future climate conditions

Climate Change Scenario		O'Shaughnessy Runoff (% change from 2010)			Don Pedro Runoff (%change from 2010)		
		2040	2070	2100	2040	2070	2100
1A	low temperature increase no precipitation change	-0.7%	-1.5%	-2.6%	-1.1%	-2.4%	-3.6%
2A	moderate temperature increase no precipitation change	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2B	moderate temperature increase precipitation decrease	-7.6%	-15.8%	-24.7%	-9.5%	-19.1%	-28.7%
2C	moderate temperature increase precipitation increase	1.4%	2.2%	2.4%	1.1%	2.0%	2.8%
3A	high temperature increase no precipitation change	-2.1%	-5.6%	-10.2%	-3.0%	-6.5%	-10.1%
3B	high temperature increase precipitation decrease	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%

Note: The same results are shown in Table 6-3.

Simulated changes in median annual runoff do not fully describe how water supplies would be affected. When firm yield from reservoirs is evaluated, low runoff years are critical. Climate change effects are exacerbated in low runoff years. Table 7-2 summarizes the modeling results in terms of the change in simulated 5 (dry), 50 (the median runoff shown in Table 7-1) and 95% percent exceedance annual runoff for two climate change scenarios (2A moderate temperature increases with no precipitation and 3B high temperature increases with precipitation decreases).

Table 7-2. Change in runoff volume for future climate conditions at 5%, 50%, and 95% exceedance level

Climate Change Scenario		Exceed Prob	O'Shaughnessy Runoff (% change from 2010)			Don Pedro Runoff (% change from 2010)		
			2040	2070	2100	2040	2070	2100
2A	moderate temperature increase no precipitation change	5%	-0.6%	-1.4%	-2.4%	-1.1%	-2.6%	-3.7%
2A	moderate temperature increase no precipitation change	50%	-1.2%	-2.9%	-5.4%	-1.8%	-4.0%	-6.4%
2A	moderate temperature increase no precipitation change	95%	-3.4%	-8.8%	-15.1%	-4.2%	-9.8%	-16.1%
3B	high temperature increase precipitation decrease	5%	-7.1%	-14.3%	-21.8%	-8.7%	-16.7%	-24.3%
3B	high temperature increase precipitation decrease	50%	-8.6%	-18.6%	-29.4%	-10.7%	-21.6%	-32.3%
3B	high temperature increase precipitation decrease	95%	-14.7%	-30.9%	-46.5%	-16.6%	-33.3%	-48.1%

Note: The same results are shown in Table 6-4.

Runoff timing within the water year changes under the future climate conditions. Figure 7-1 shows the average monthly median runoff volume at O'Shaughnessy for the current climate and at the 2040, 2070 and 2100 future climate dates for two climate change scenarios, 2A moderate temperature increases with no precipitation and 2B moderate temperature increases with precipitation decreases. Under climate change scenario 2A in 2100 at O'Shaughnessy, the May through August runoff would decrease by 45% from the current condition (31% of current condition annual runoff), the September through April runoff would increase by 81% (26% of annual runoff), and 5% of the annual runoff would be lost to additional evapotranspiration. Reservoir operations would need to be revised to manage increased runoff in November through April, and decreased runoff in May for most climate change scenarios, and in June and July for all climate change scenarios.

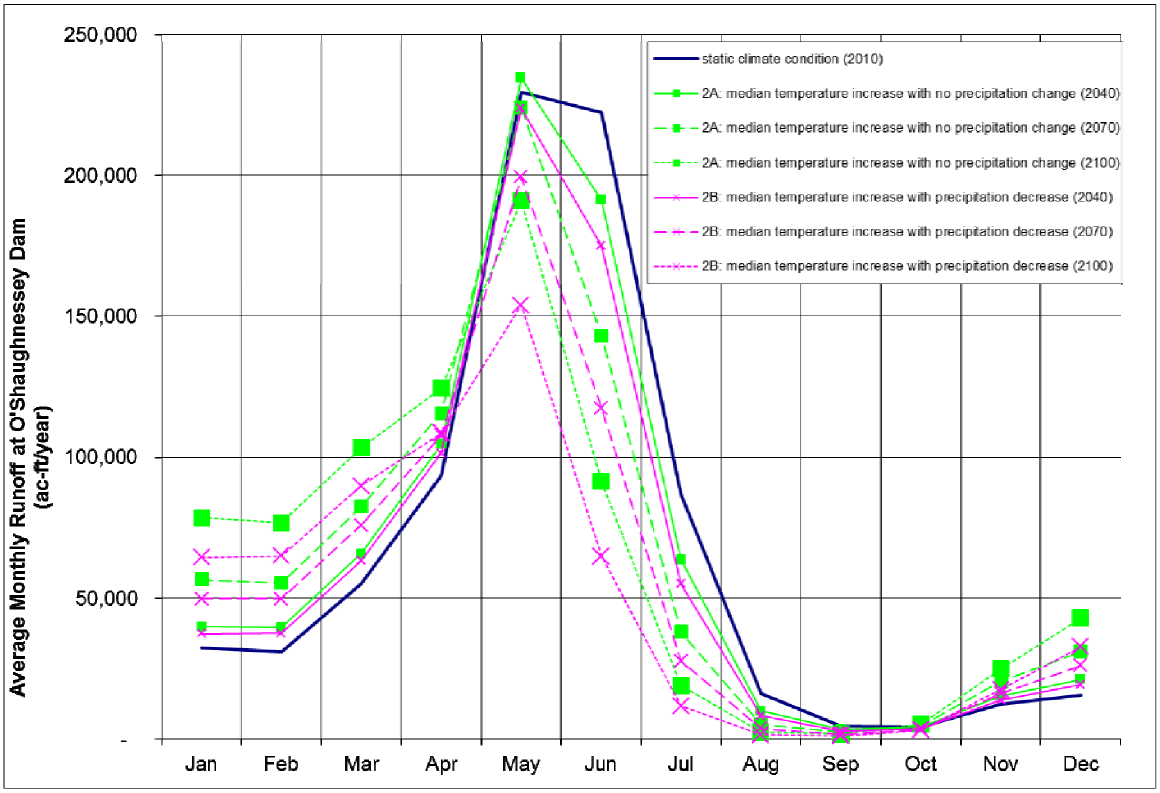


Figure 7-1. Average monthly runoff at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios at future climate dates

The simulated change in future hydrologic conditions based on the climate change scenarios results in a significantly altered snow and runoff regime in the watershed. Snow accumulation is reduced and snow melts earlier in the spring. Fall and early winter runoff increases and late spring and summer runoff decreases.

The reliability of projected changes in reservoir inflows for the climate change scenarios is good because the model is physically-based and has been calibrated over a 34-year period to accurately represent hydrologic conditions in the Tuolumne watershed during a range of temperature and precipitation conditions. The temperature and precipitation timeseries used for the climate change scenarios are within the range of temperatures experienced in the Tuolumne during the calibration period. For example, a climate change scenario may have higher temperatures than experienced in the same period historically but similar temperatures would have been observed at other times in the calibration period.

Reduced snow accumulation and a resulting shift of runoff from the spring to the winter runoff in the Tuolumne were expected due to the temperature increases of the climate change scenarios. In addition, the climate change scenario results showed that:

- Climate change effects are most exacerbated in low runoff years because of increased evapotranspiration results, particularly when expressed as a percent of runoff. This result is important for reservoir 'firm yield' analysis. This study created daily reservoir inflow data during the 34-year analysis period (water years 1974 to 2008) for all climate change scenarios which can be used for subsequent operations studies by TID and SFPUC.

- Soil moisture reductions in summer would be very significant by 2070 and 2100. The predicted reduction in summer soil moistures would be expected to change vegetation distribution within the watershed. The potential changes in vegetation might cause a secondary change in the hydrologic response of some land segments but this effect was not modeled in this study.

- The future climate condition in year 2040 of climate change scenario 3B (moderate temperature increases with precipitation decrease) results in reductions in median runoff of -8.6% at O'Shaughnessy Dam and -10.7% at Don Pedro Dam, so relatively large reductions in runoff may take place in 30 years if both temperature rise and precipitation decrease occur.

- The future climate condition in year 2040 of climate change scenario 2A (moderate temperature increase and no precipitation change) results in insignificant runoff reductions of 0.6% at O'Shaughnessy Dam and 1.1% at Don Pedro Dam. The 2A results in terms of runoff and timing changes are small compared to the year-to-year variation that is currently experienced.

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APPENDIX A

Future Climate Condition Simulation Results

APPENDIX A

Future Climate Condition Simulation Results

A.1 Changes in Simulated Runoff Timing and Volume

A.1.1 Simulated Annual Runoff Comparisons

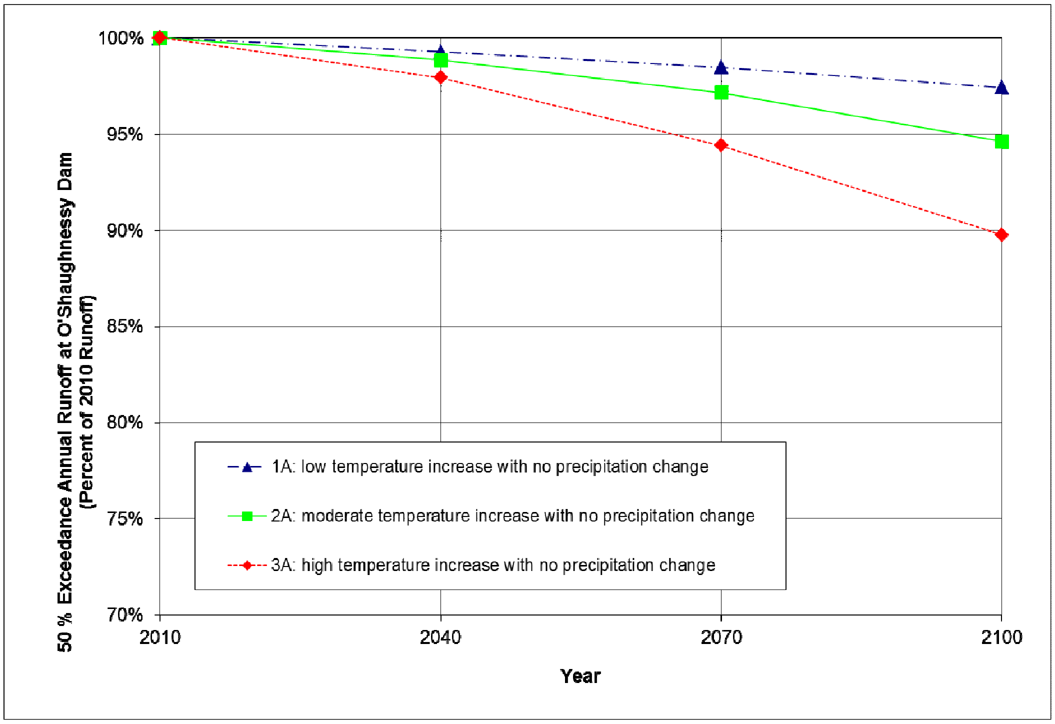


Figure A-1. Annual runoff at O'Shaughnessy Dam for temperature change scenarios

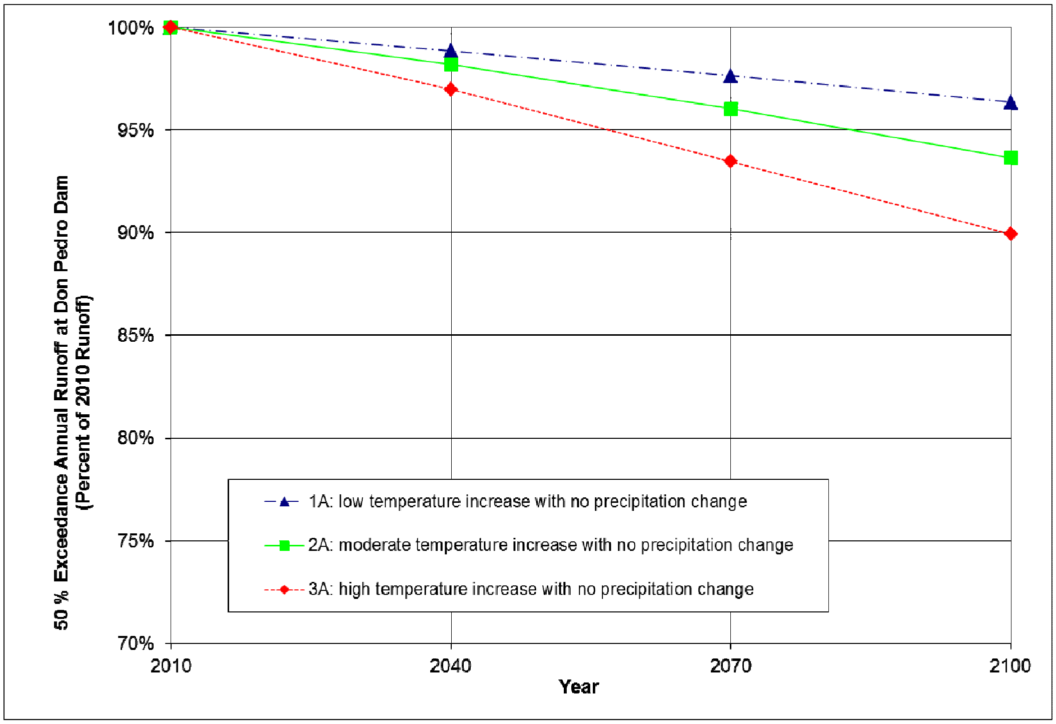


Figure A-2. Annual runoff at Don Pedro Dam for temperature change scenarios

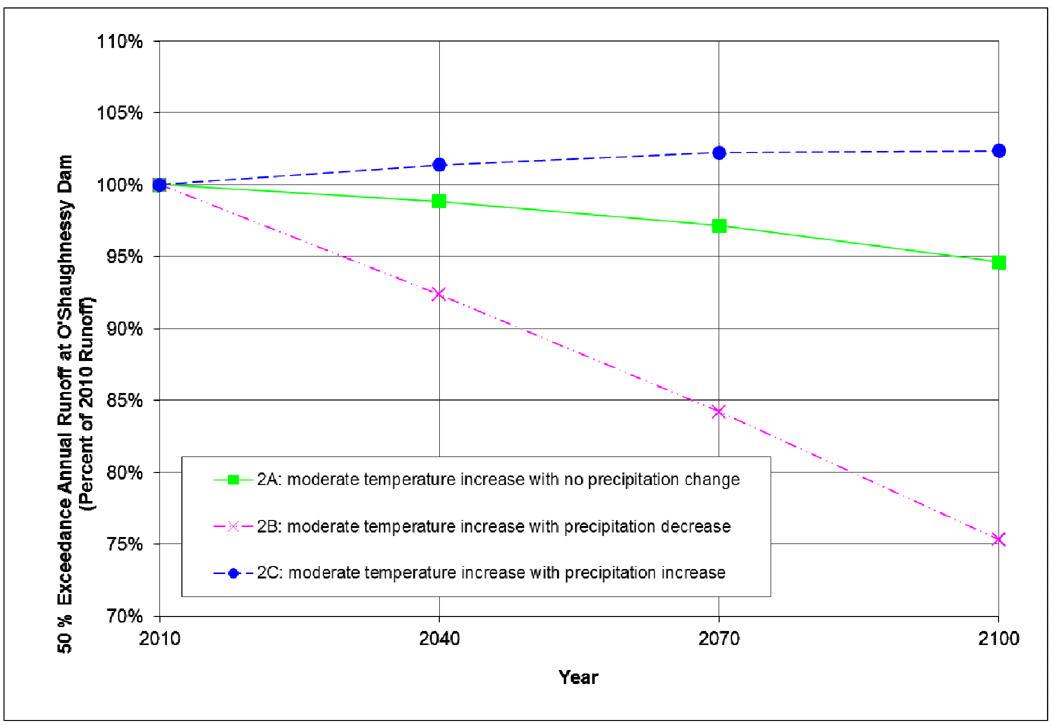


Figure A-3. Annual runoff at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios

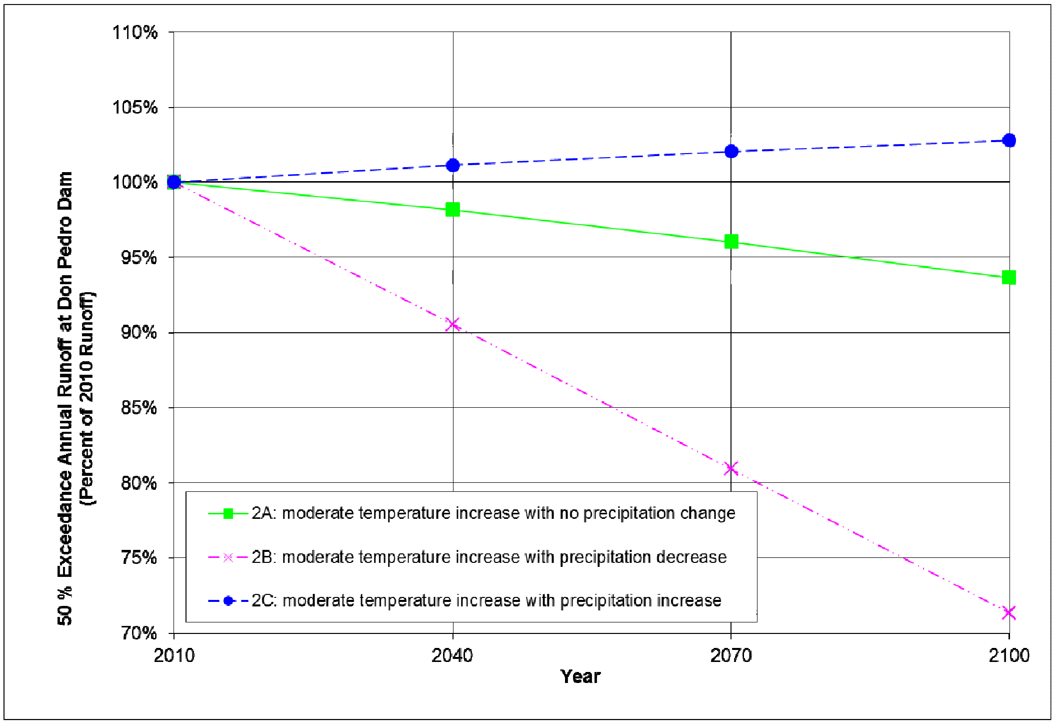


Figure A-4. Annual runoff at Don Pedro Dam for moderate temperature increase and precipitation change scenarios

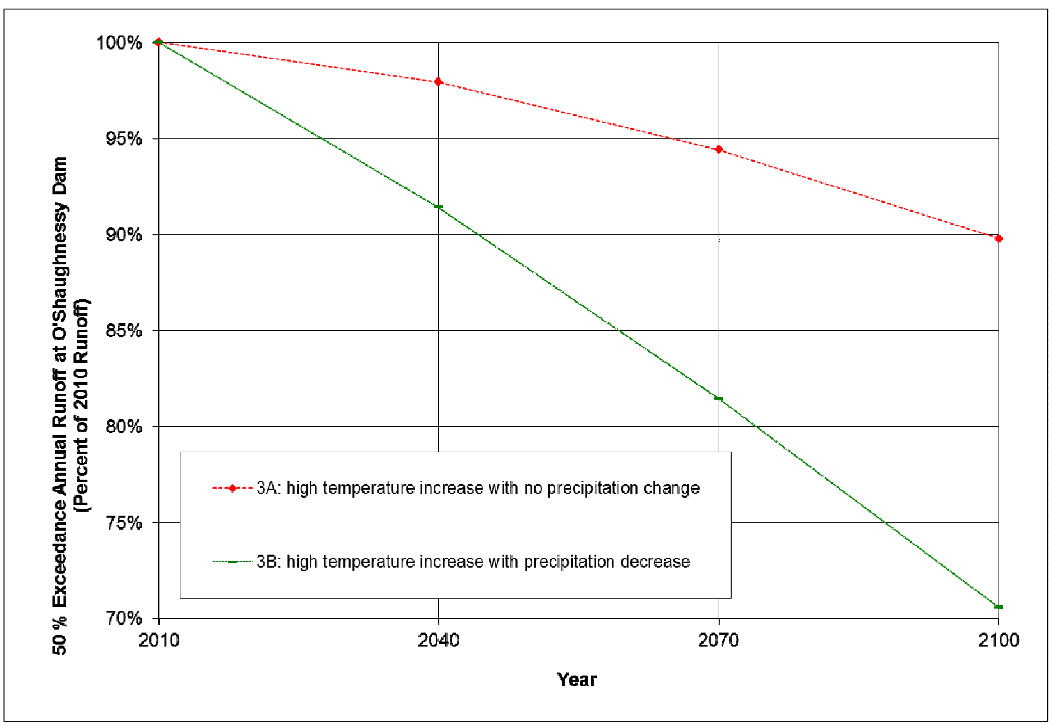


Figure A-5. Annual runoff at O'Shaughnessy Dam for high temperature increase and precipitation change scenarios

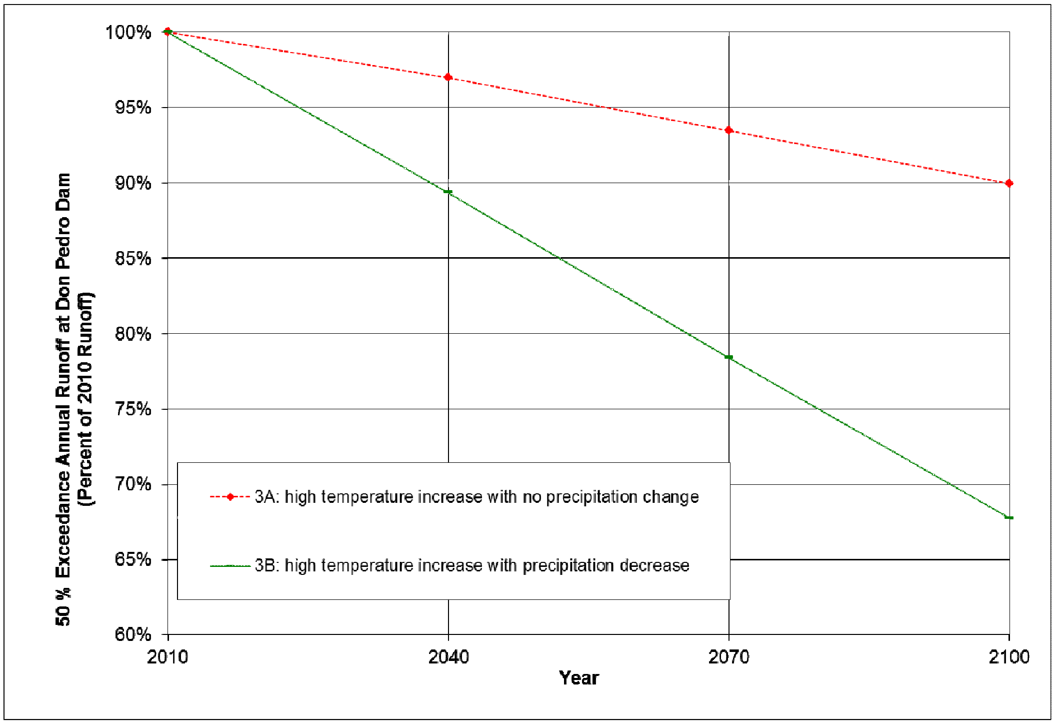


Figure A-6. Annual runoff at Don Pedro Dam for high temperature increase and precipitation change scenarios

A.1.2 Simulated Annual Runoff in Low and High Runoff Years

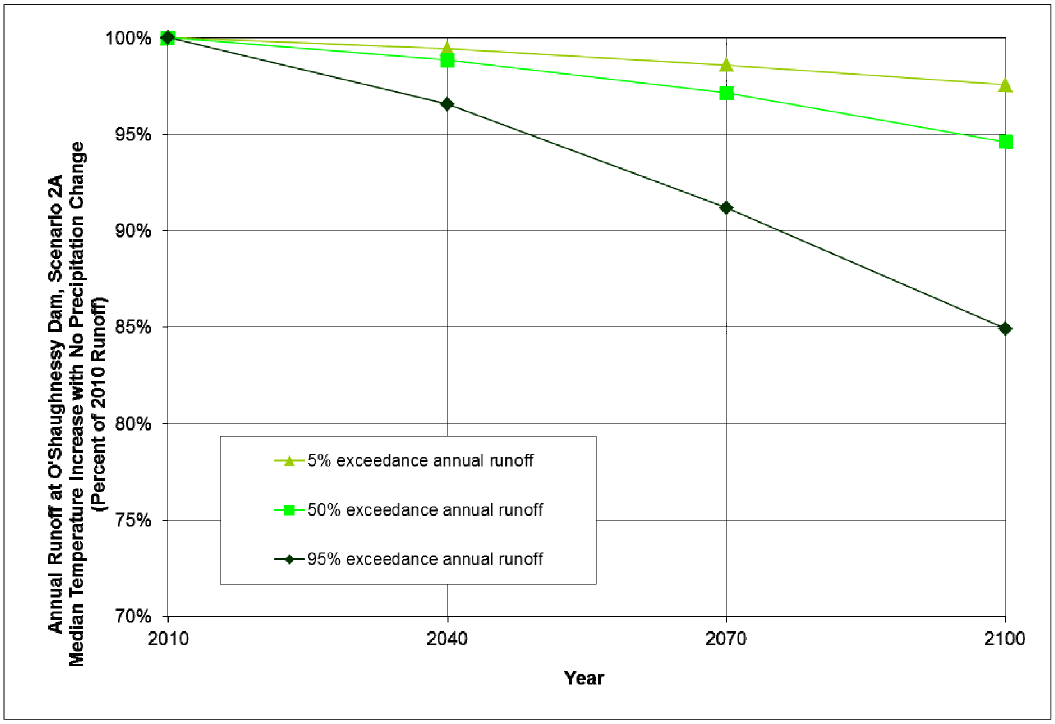


Figure A-7. Annual runoff at O'Shaughnessy Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

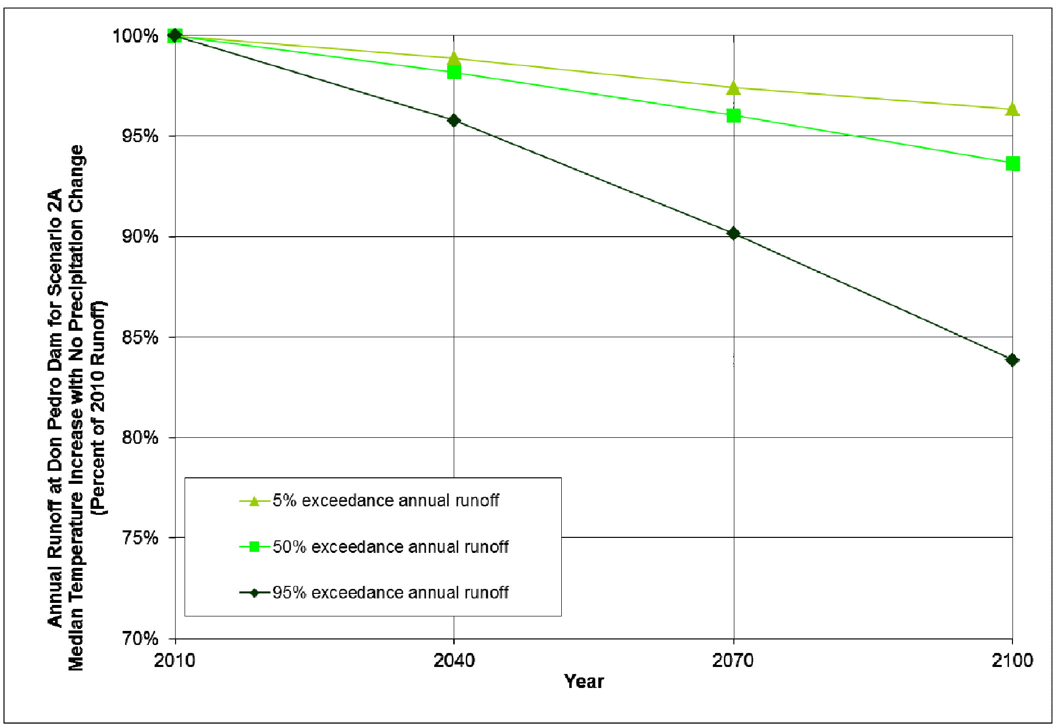


Figure A-8. Annual runoff at Don Pedro Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

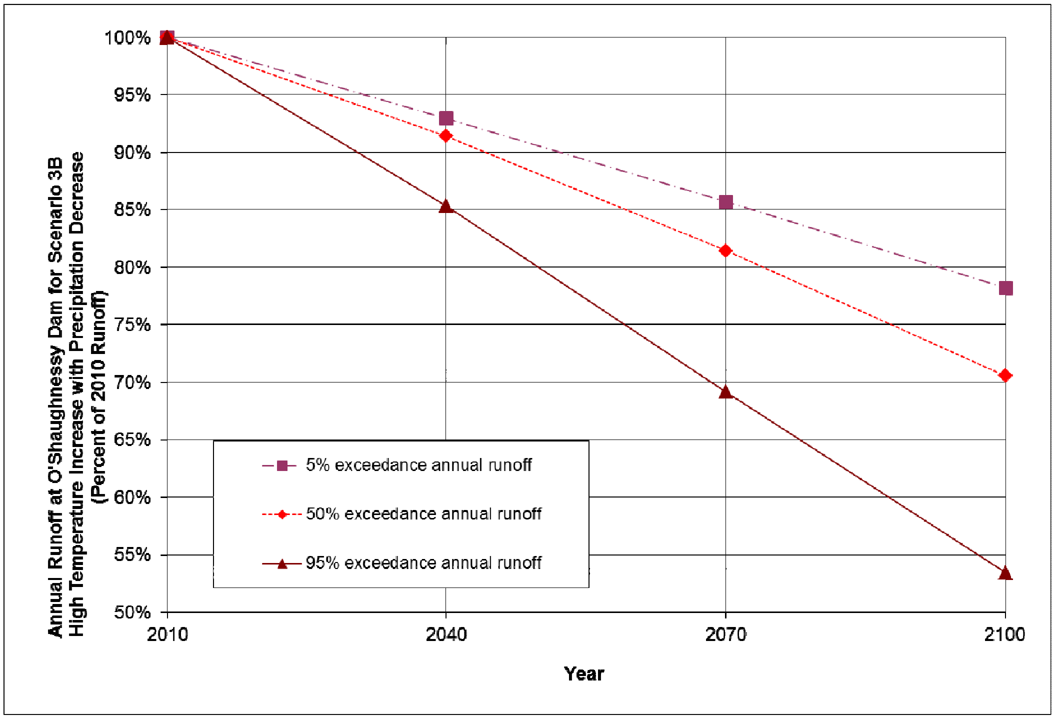


Figure A-9. Annual runoff at O'Shaughnessy Dam for scenario 3B (high temperature increase with precipitation decrease) for 5%, 50% and 95% exceedance

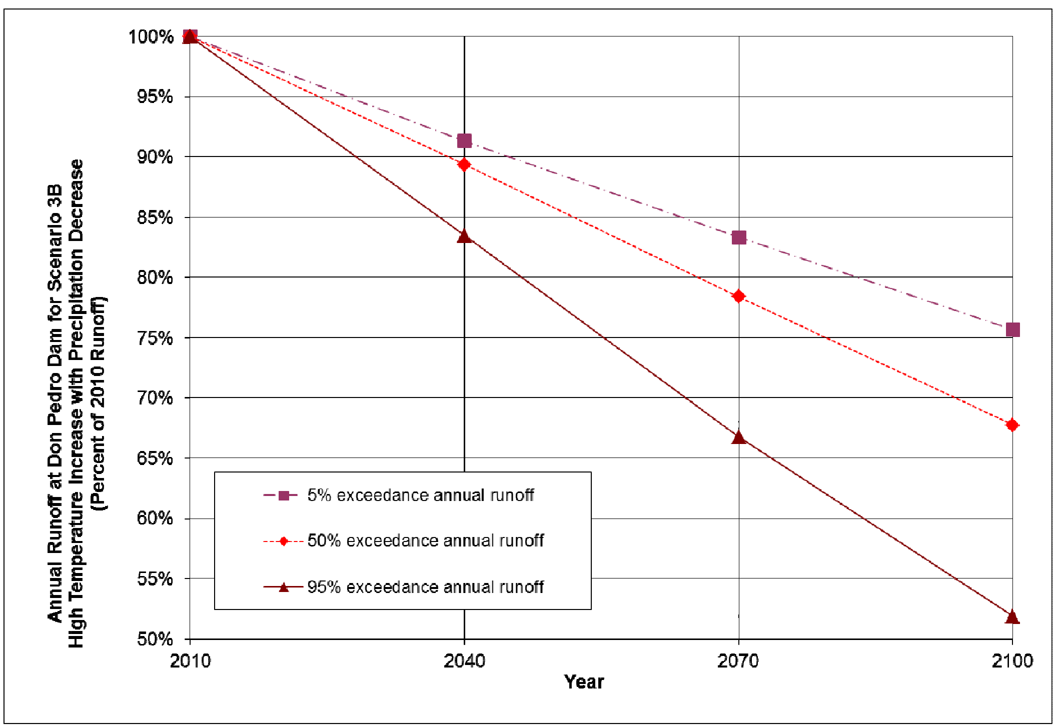


Figure A-10. Annual runoff at Don Pedro Dam for scenario 3B (high temperature increase with precipitation decrease) for 5%, 50% and 95% exceedance

A.1.3 Monthly Runoff Timing Comparisons

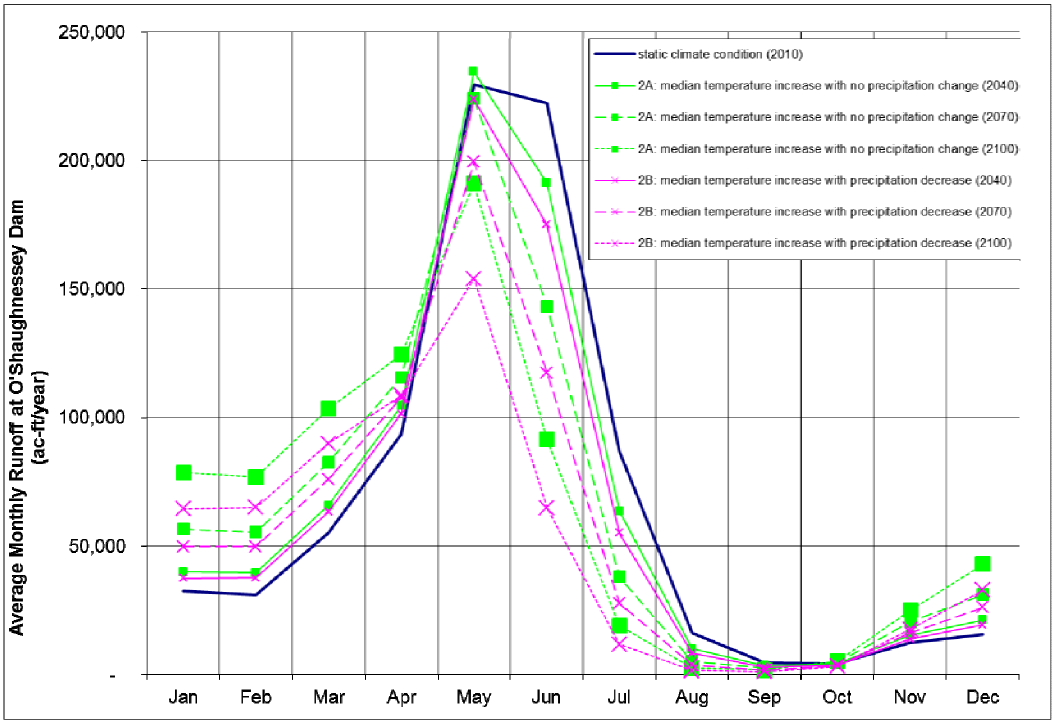


Figure A-11. Average monthly runoff at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios at future climate dates

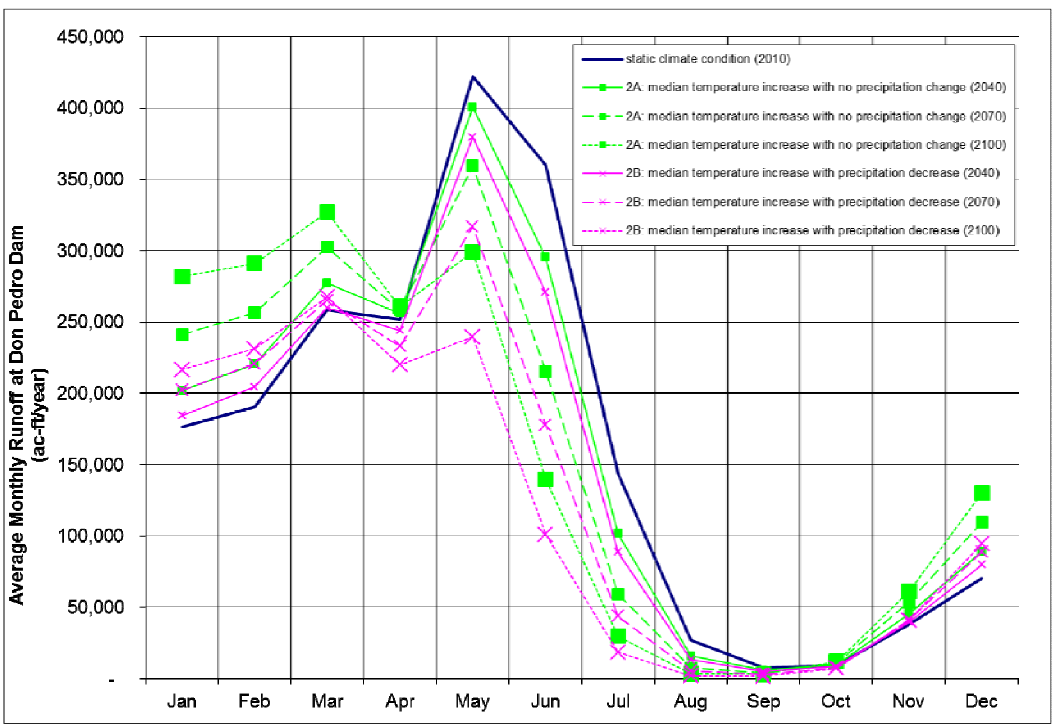


Figure A-12. Average monthly runoff at Don Pedro Dam for moderate temperature increase and precipitation change scenarios at future climate dates

A.1.4 Drought Period Comparison

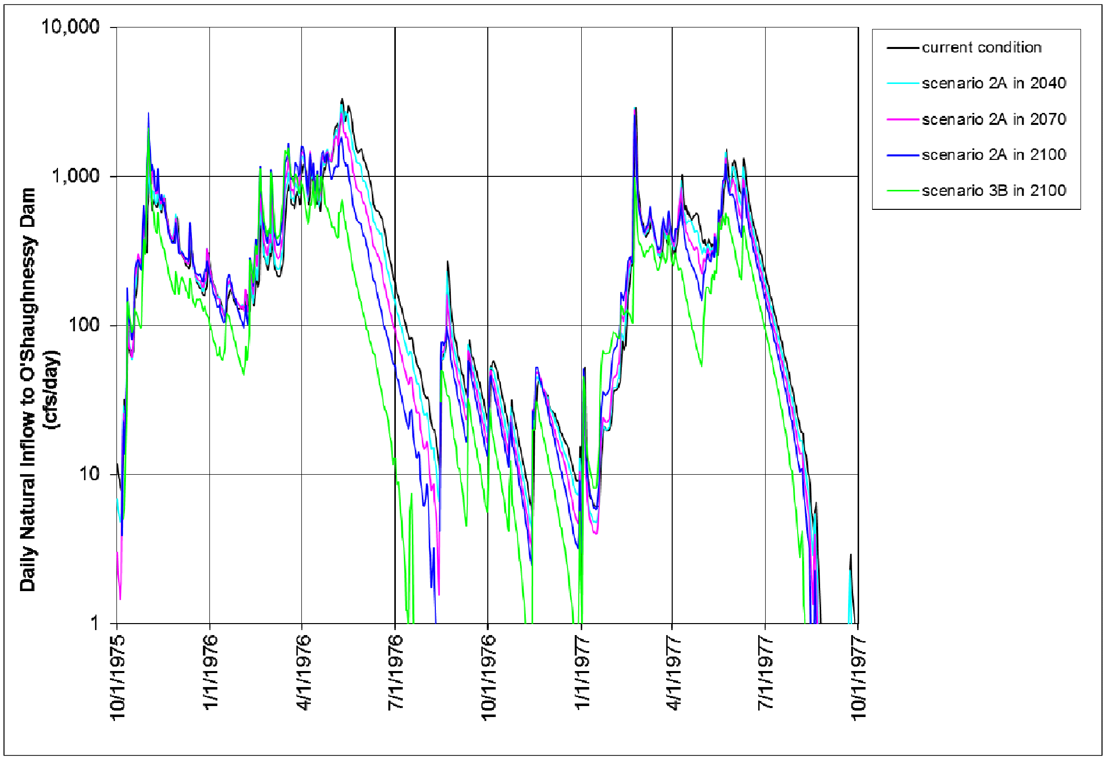


Figure A-13. Daily natural inflow to O'Shaughnessy Dam, water years 1976 and 1977 on log scale

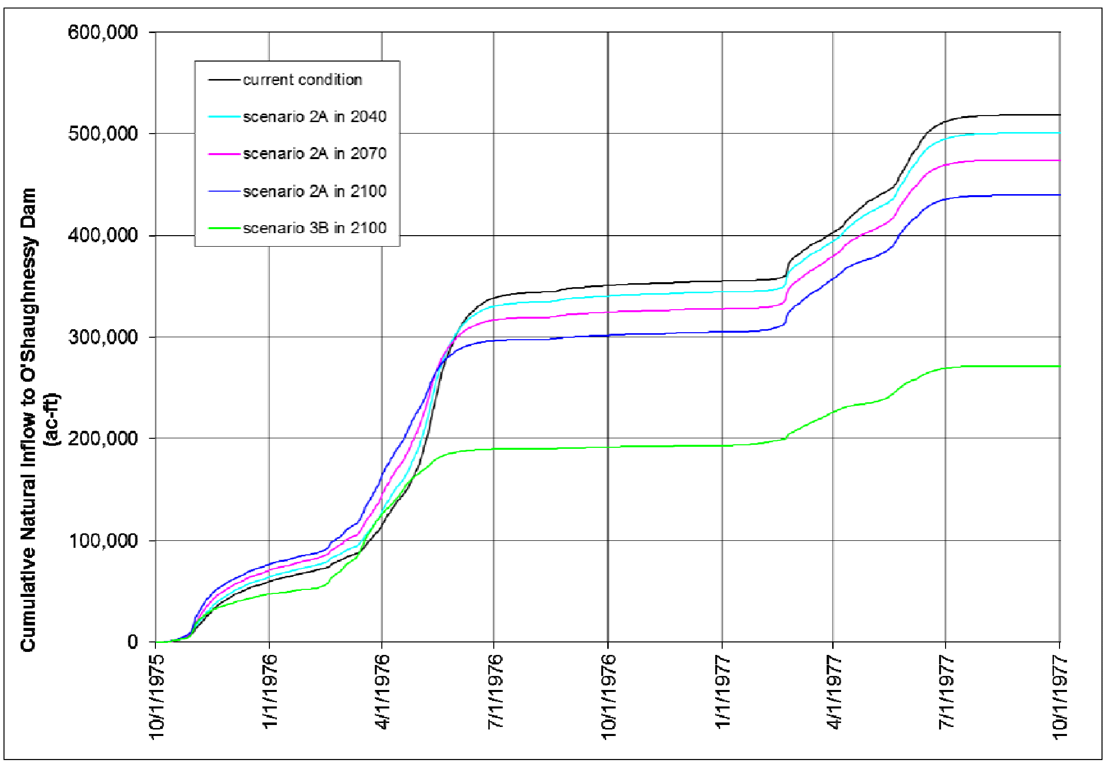


Figure A-14. Cumulative natural inflow to O'Shaughnessy Dam, water years 1976 and 1977

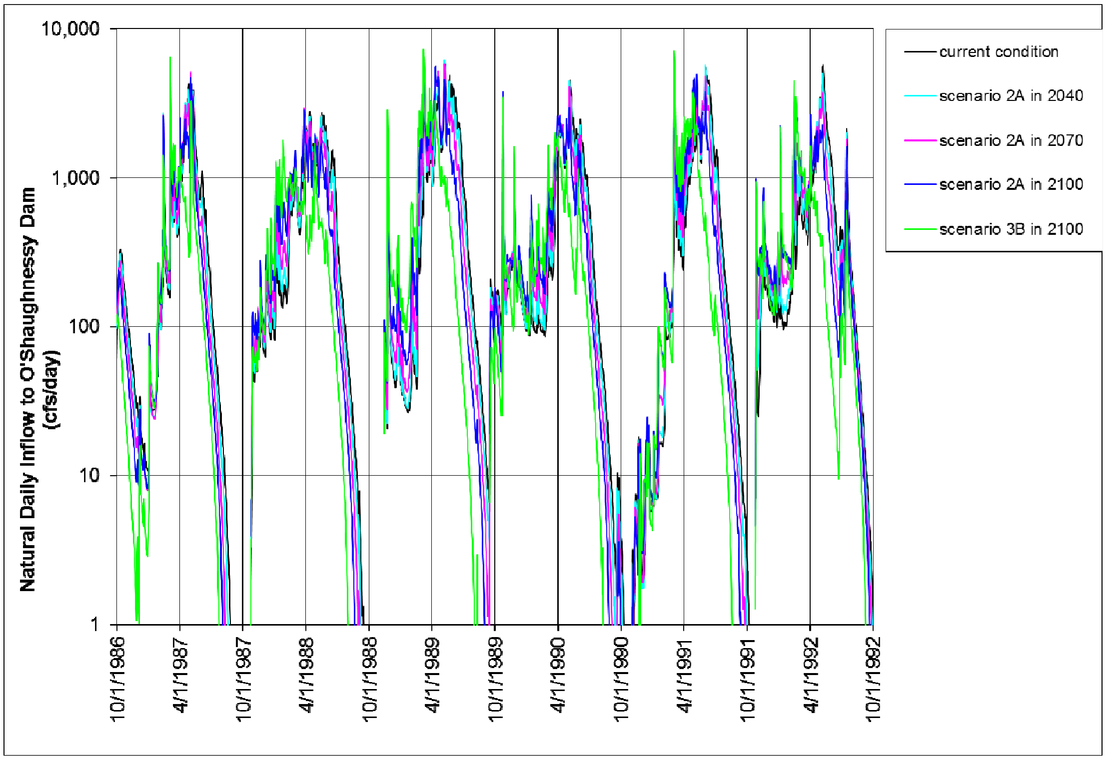


Figure A-15. Daily natural inflow to O'Shaughnessy Dam, water years 1987 to 1992 on log scale

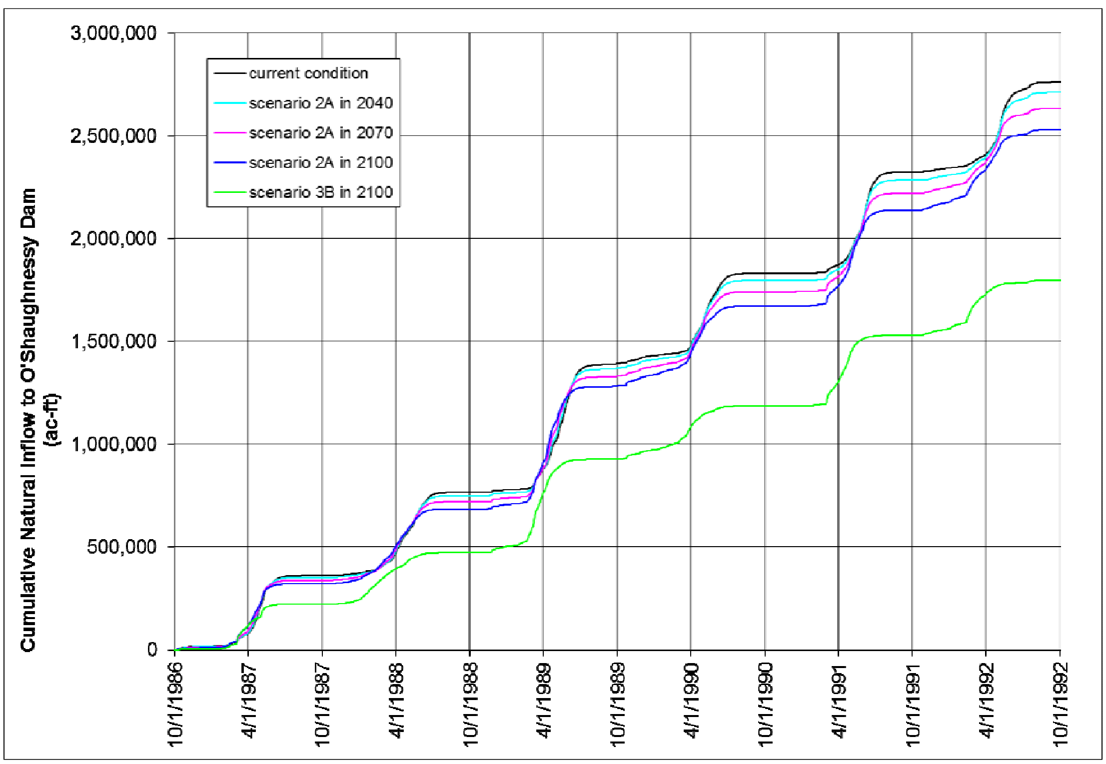


Figure A-16. Cumulative natural inflow to O'Shaughnessy Dam, water years 1987 to 1992

A.2 Changes in Simulated Actual Evapotranspiration

A.2.1 Simulated Annual Actual Evapotranspiration Comparisons

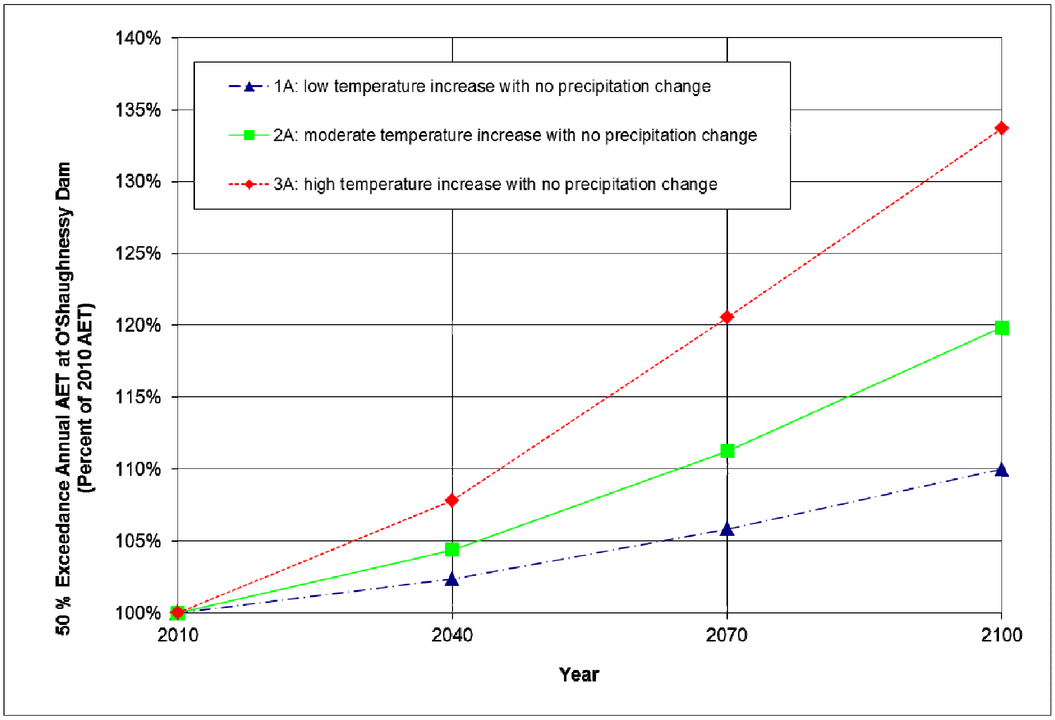


Figure A-17. Annual AET at O'Shaughnessy Dam for temperature change scenarios

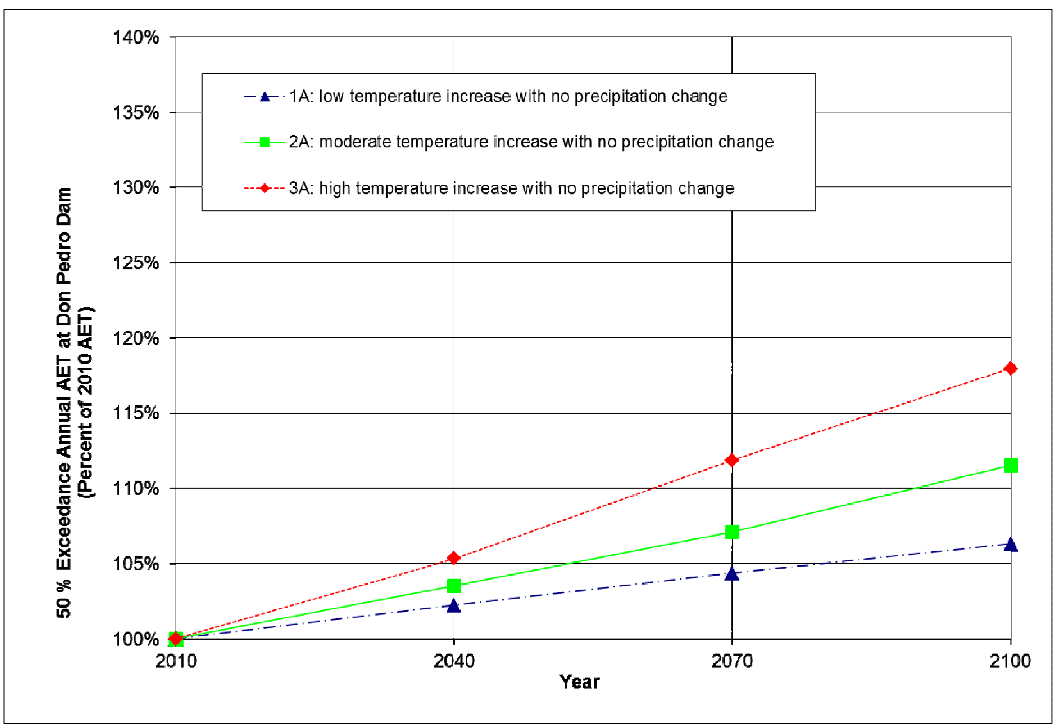


Figure A-18. Annual AET at Don Pedro Dam for temperature change scenarios

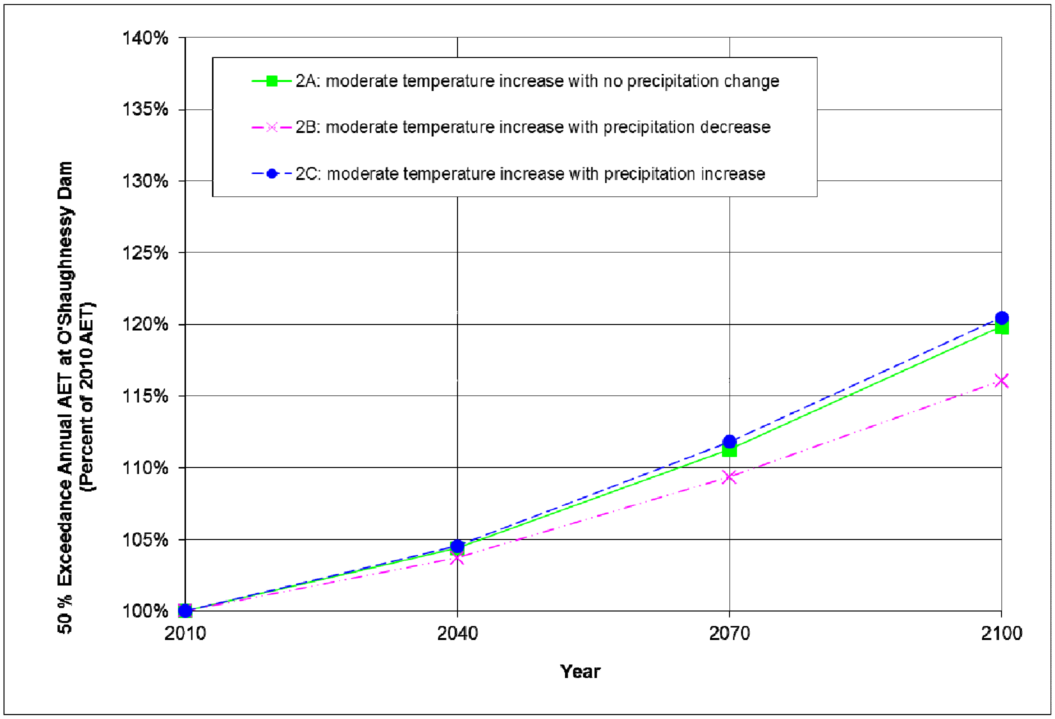


Figure A-19. Annual AET at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios

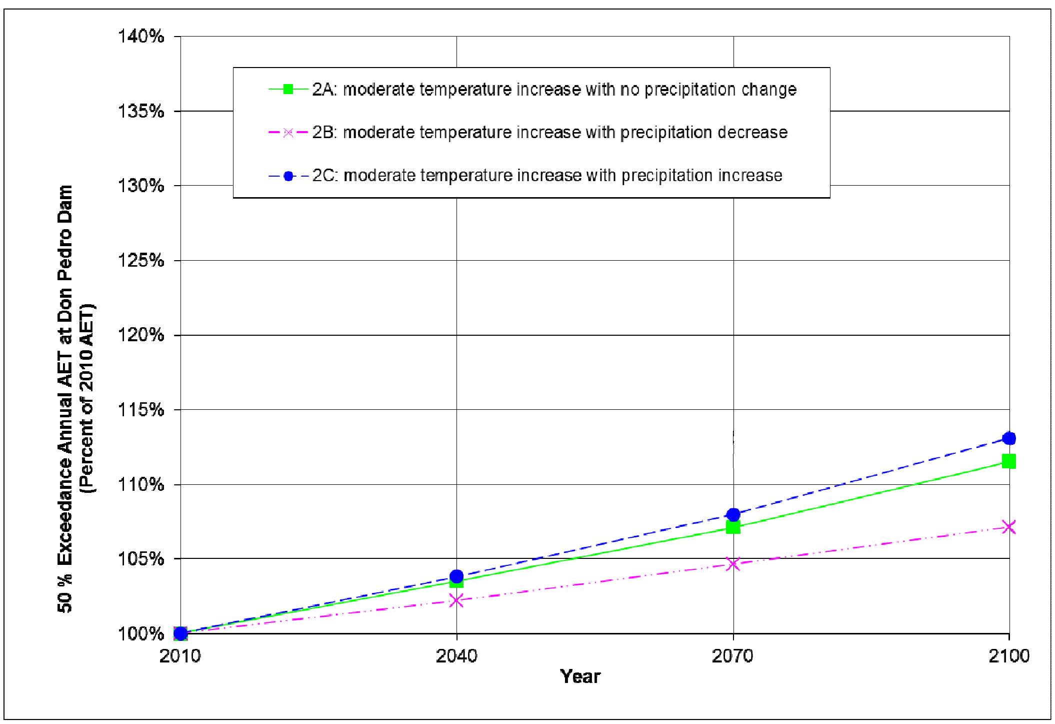


Figure A-20. Annual AET at Don Pedro Dam for moderate temperature increase and precipitation change scenarios

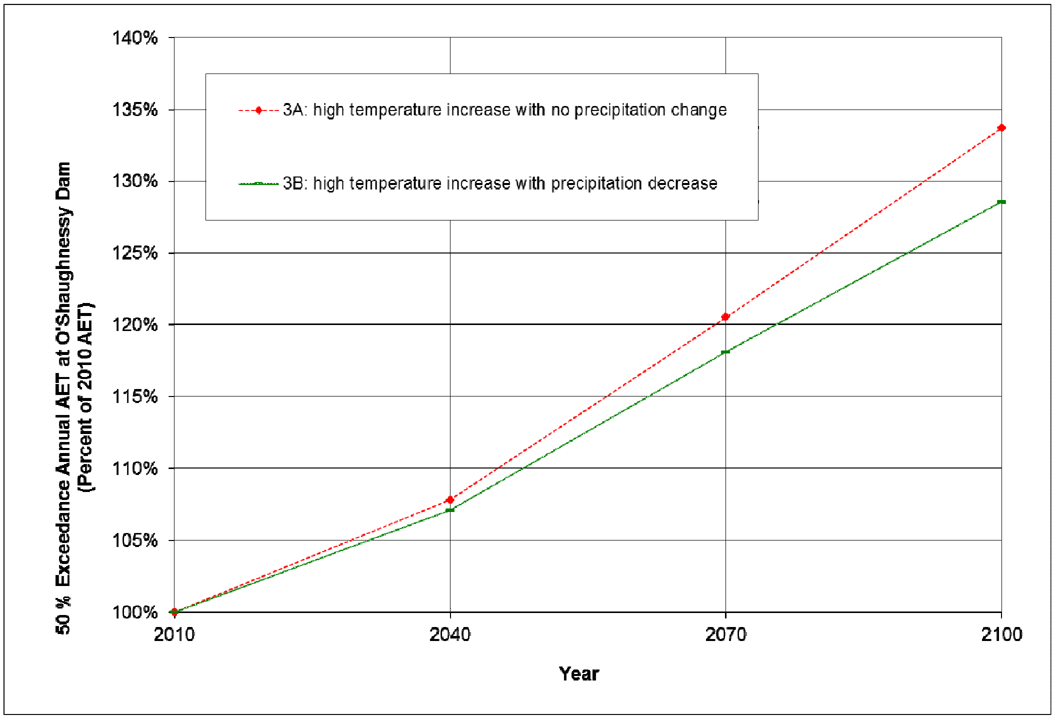
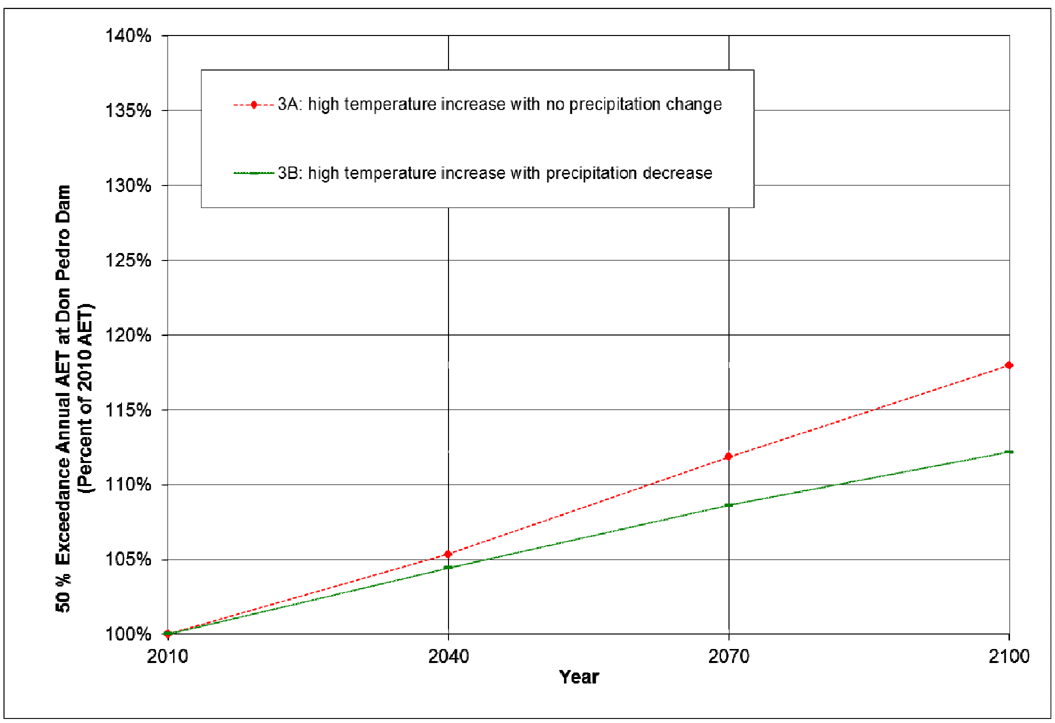


Figure A-21. Annual AET at O'Shaughnessy Dam for high temperature increase and precipitation change scenarios



FigureA-22. Annual AET at Don Pedro Dam for high temperature increase and precipitation change scenarios

A.2.2 Simulated Annual Actual Evapotranspiration in Low and High Runoff Years

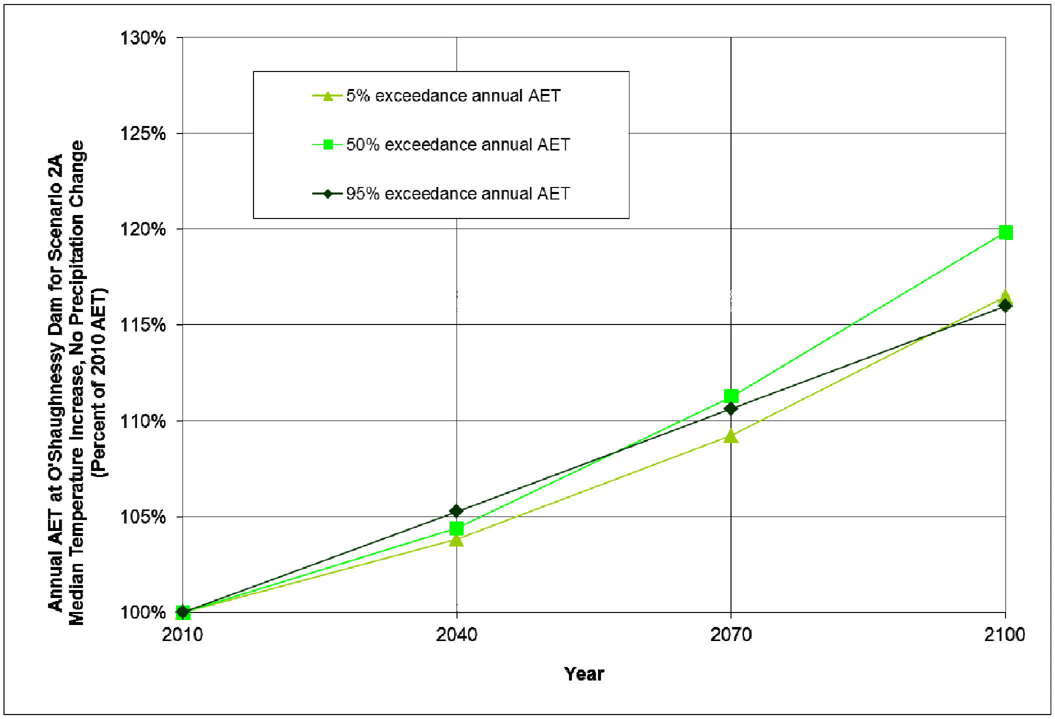


Figure A-23. Annual AET at O'Shaughnessy Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

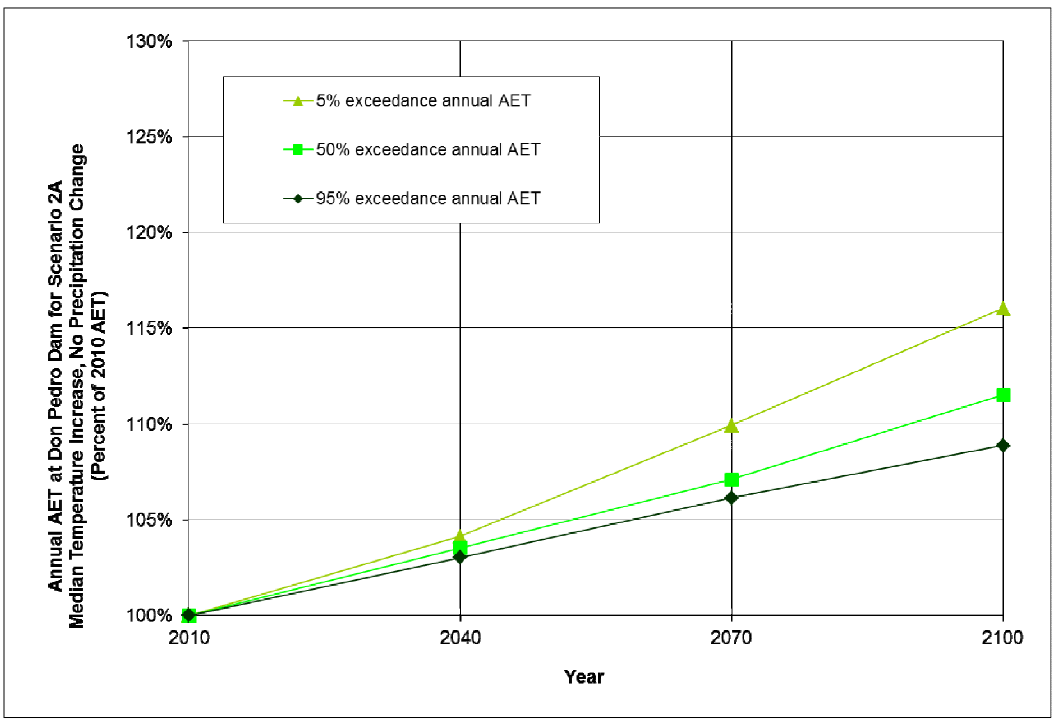


Figure A-24. Annual AET at Don Pedro Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

A.3 Changes in Simulated Snow Water Equivalent

A.3.1 Simulated Annual Maximum Snow Water Equivalent Comparisons

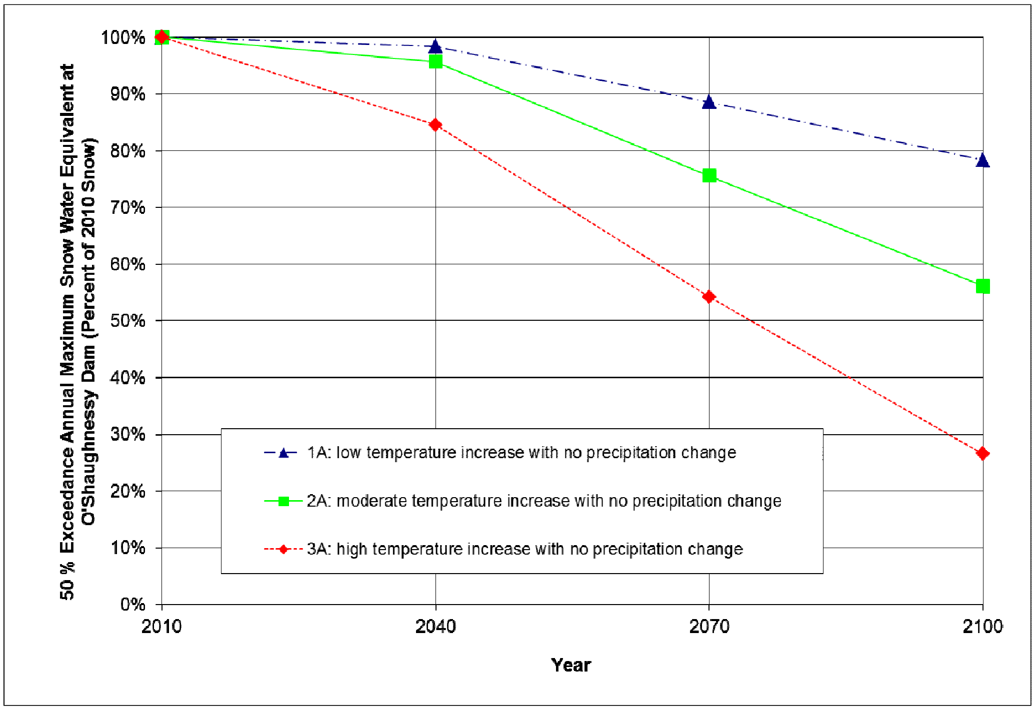


Figure A-25. Annual maximum snow water equivalent at O'Shaughnessy Dam for temperature change scenarios

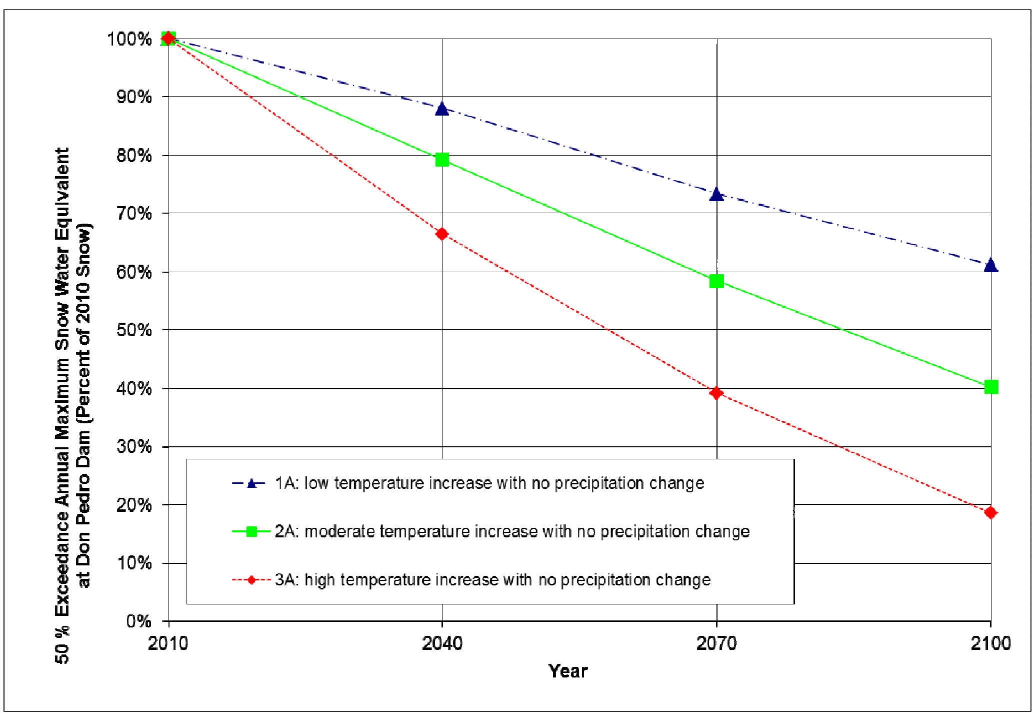


Figure A-26. Annual maximum snow water equivalent at Don Pedro Dam for temperature change scenarios

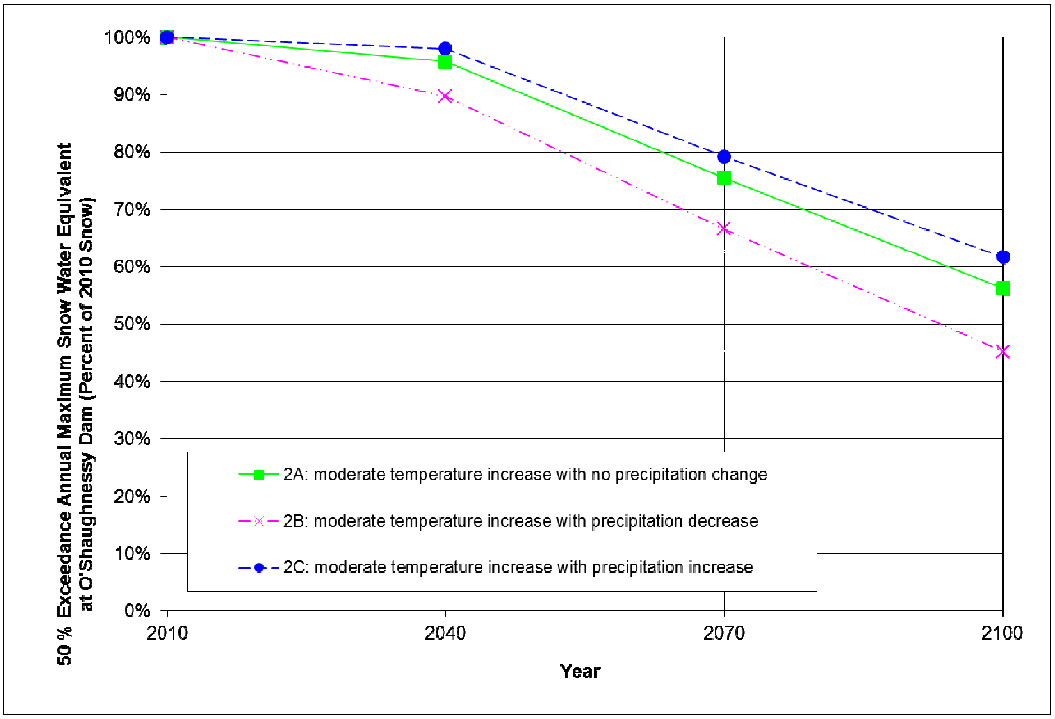


Figure A-27. Annual maximum snow water equivalent at O'Shaughnessy Dam for moderate temperature increase and precipitation change scenarios

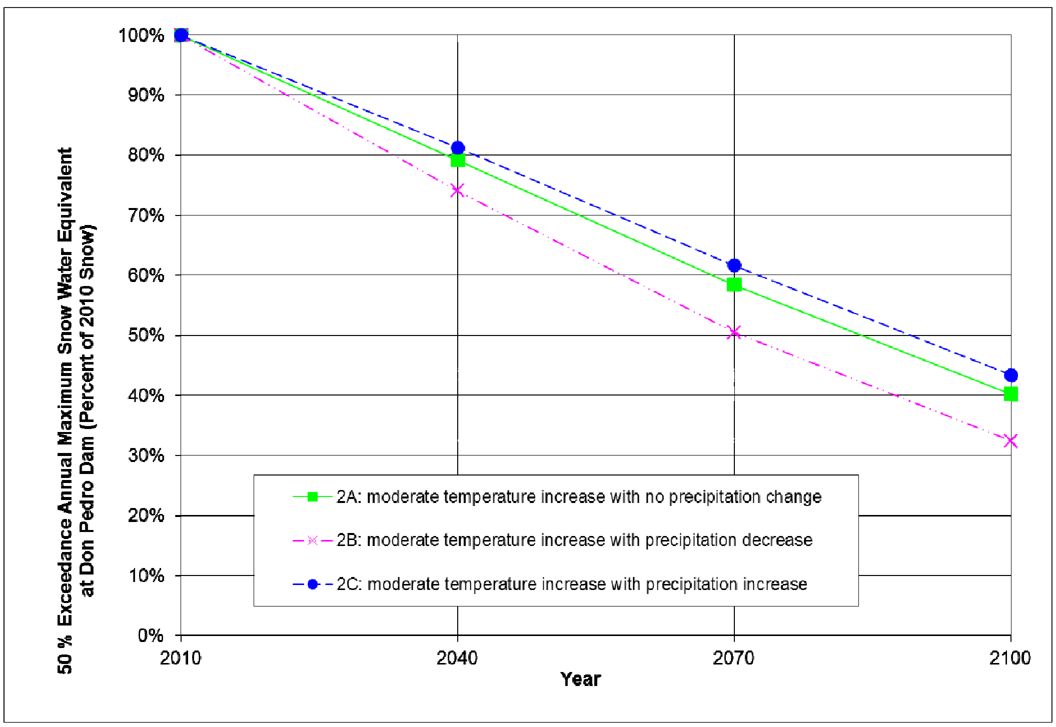


Figure A-28. Annual maximum snow water equivalent at Don Pedro Dam for moderate temperature increase and precipitation change scenarios

A.2.2 Simulated Annual Maximum Snow Water Equivalent in Low and High Runoff Years

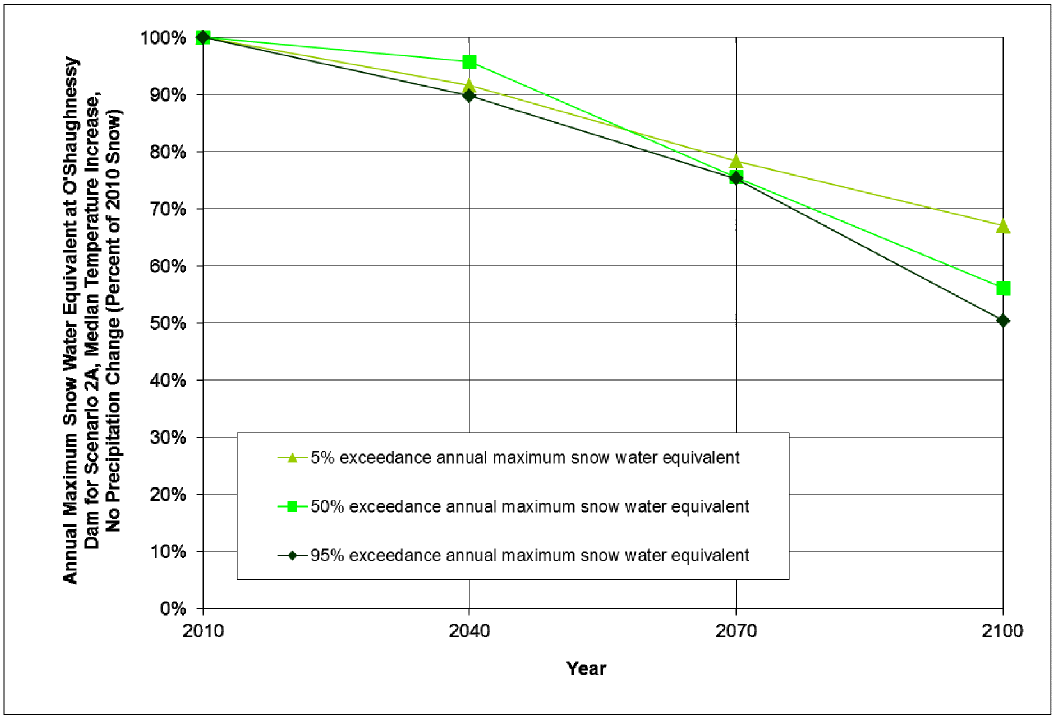


Figure A-29. Annual maximum snow water equivalent at O'Shaughnessy Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

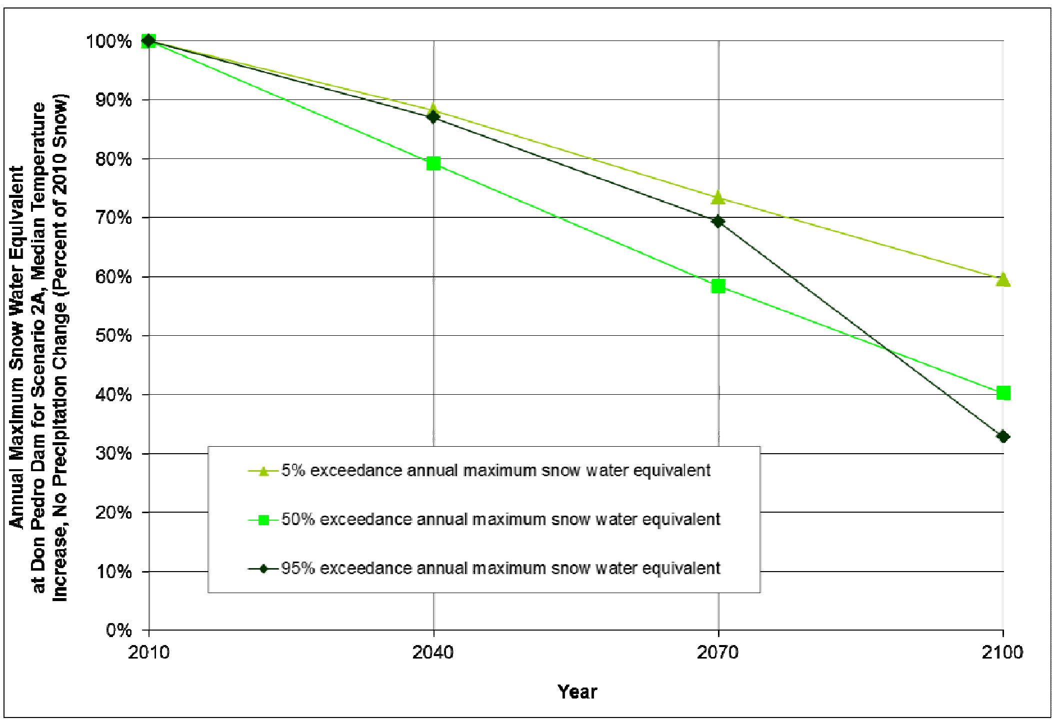


Figure A-30. Annual maximum snow water equivalent at Don Pedro Dam for scenario 2A (moderate temperature increase with no precipitation change) for 5%, 50% and 95% exceedance

APPENDIX B

Calibration Results

APPENDIX B

Calibration Results

This appendix provides daily hydrographs of HFAM simulated and estimated actual natural inflow to Hetch Hetchy and Don Pedro reservoirs for each year in the calibration period, water years 1975 to 2008.

Hetch Hetchy flows are plotted with a maximum Y-axis of 20,000 cfs. Flows higher than 20,000 cfs only occurred during the January 1997 storm; HFAM simulated daily average peak flow during this storm is 44,788 cfs and estimated actual peak flow is 37,685 cfs.

La Grange flows are plotted with a minimum Y-axis of 0 cfs and a maximum Y-axis of 40,000 cfs. Flows higher than 40,000 cfs occurred during the January 1997 storm; HFAM simulated average daily peak flow during this storm is 107,212 and estimated actual peak flow is 117,706 cfs. The estimated natural inflows to Don Pedro reservoir include negative values due to the method of calculation and are needed for correct inflow volumes however negative inflows would not actually occur.

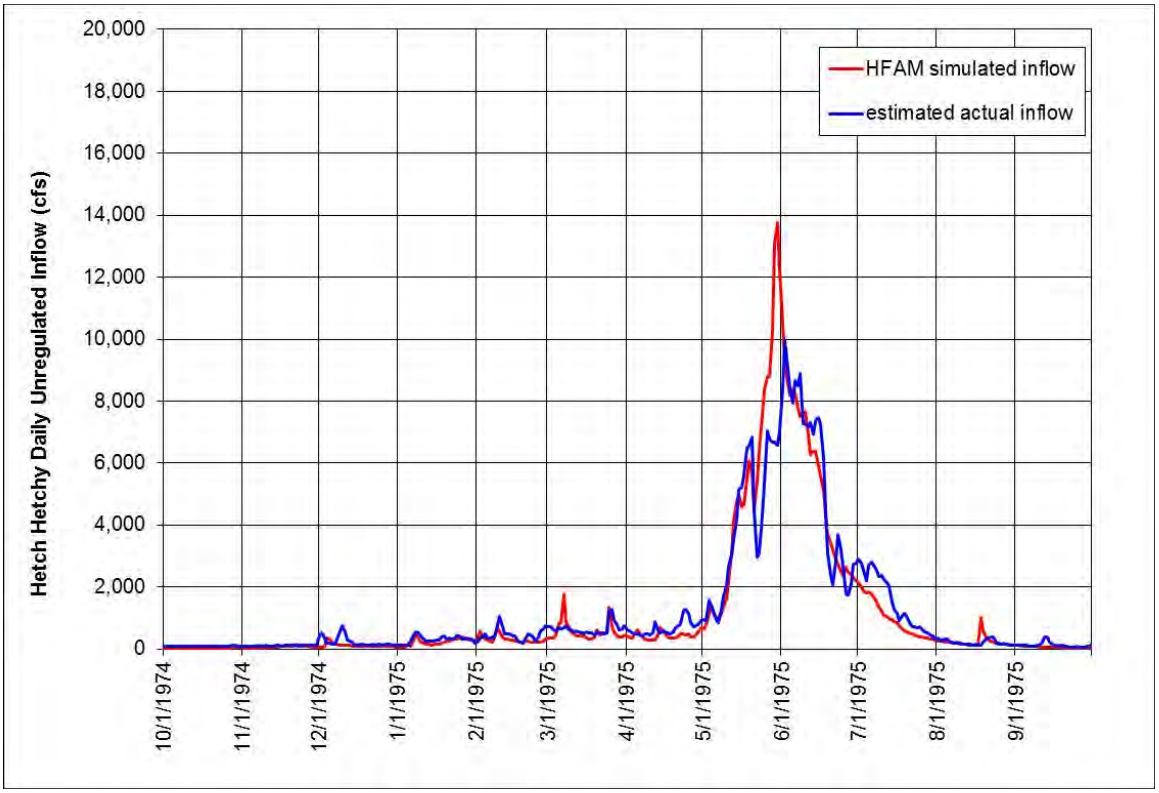


Figure B.1a Hetch Hetchy Daily Unregulated Inflow, water year 1975

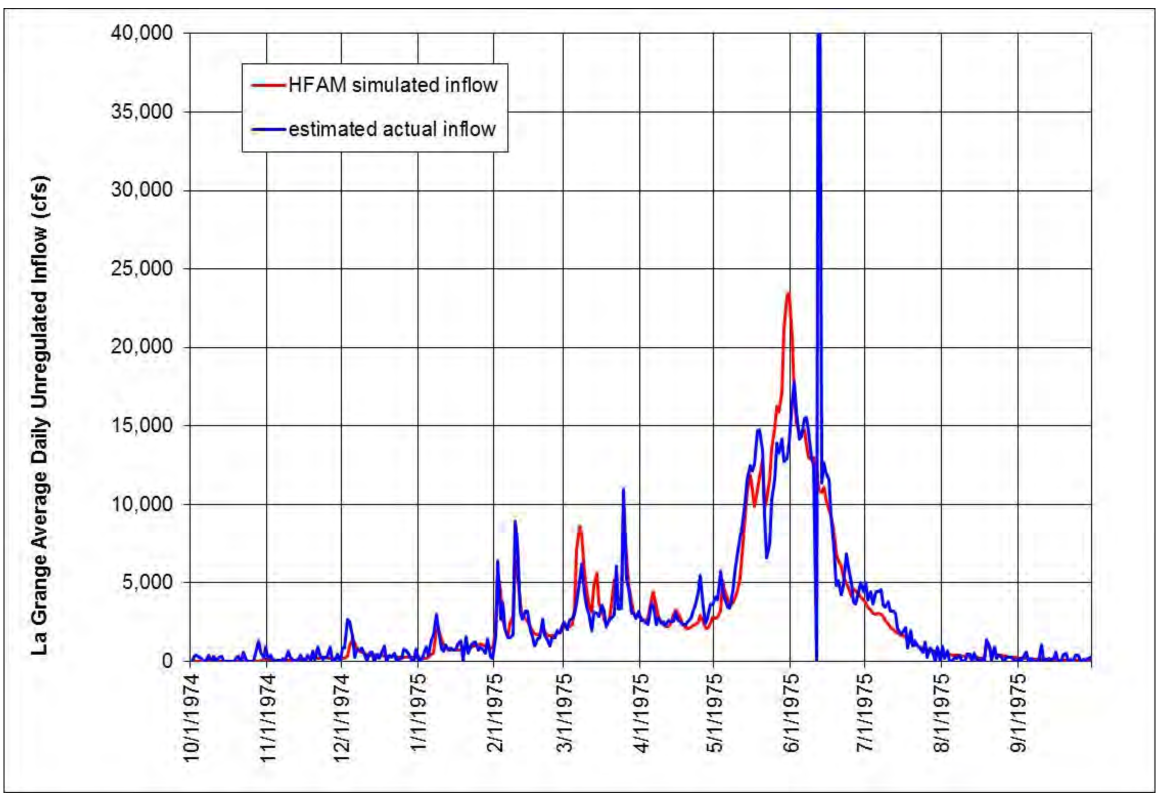


Figure B.1b La Grange Daily Unregulated Inflow, water year 1975

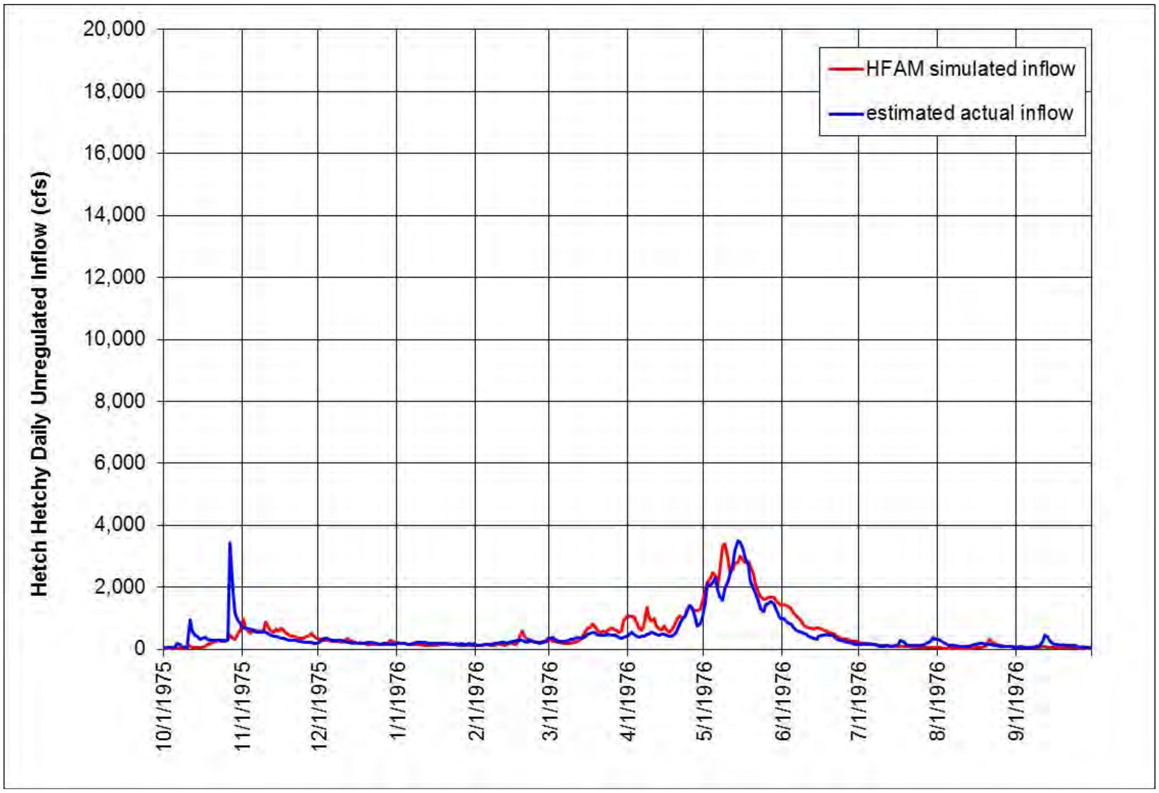


Figure B.2a Hetch Hetchy Daily Unregulated Inflow, water year 1976

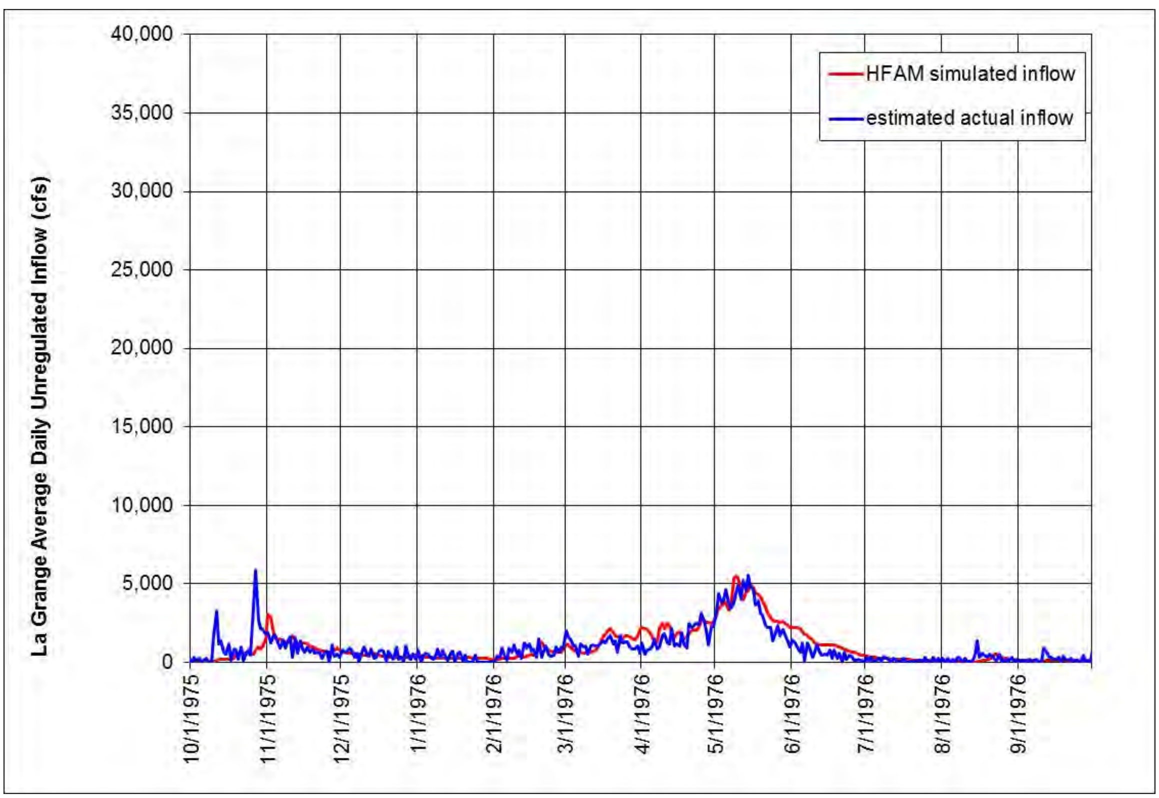


Figure B.2b La Grange Daily Unregulated Inflow, water year 1976

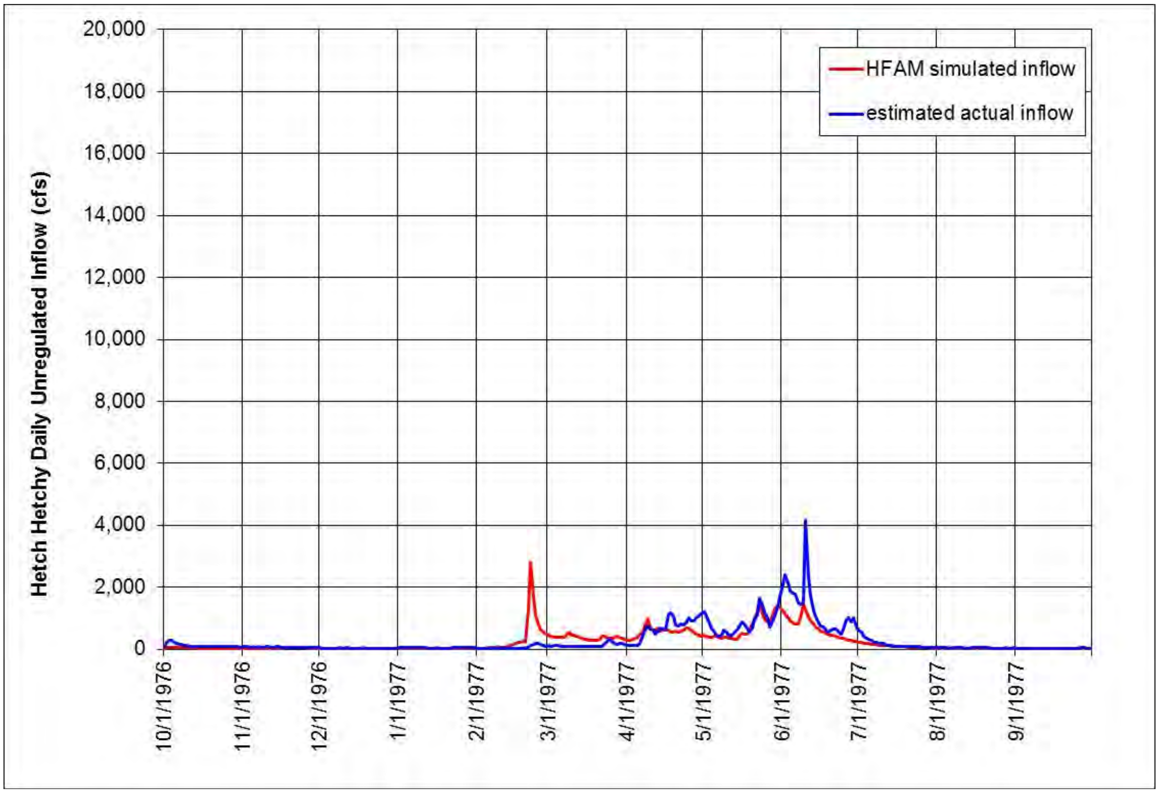


Figure B.3a Hetch Hetchy Daily Unregulated Inflow, water year 1977

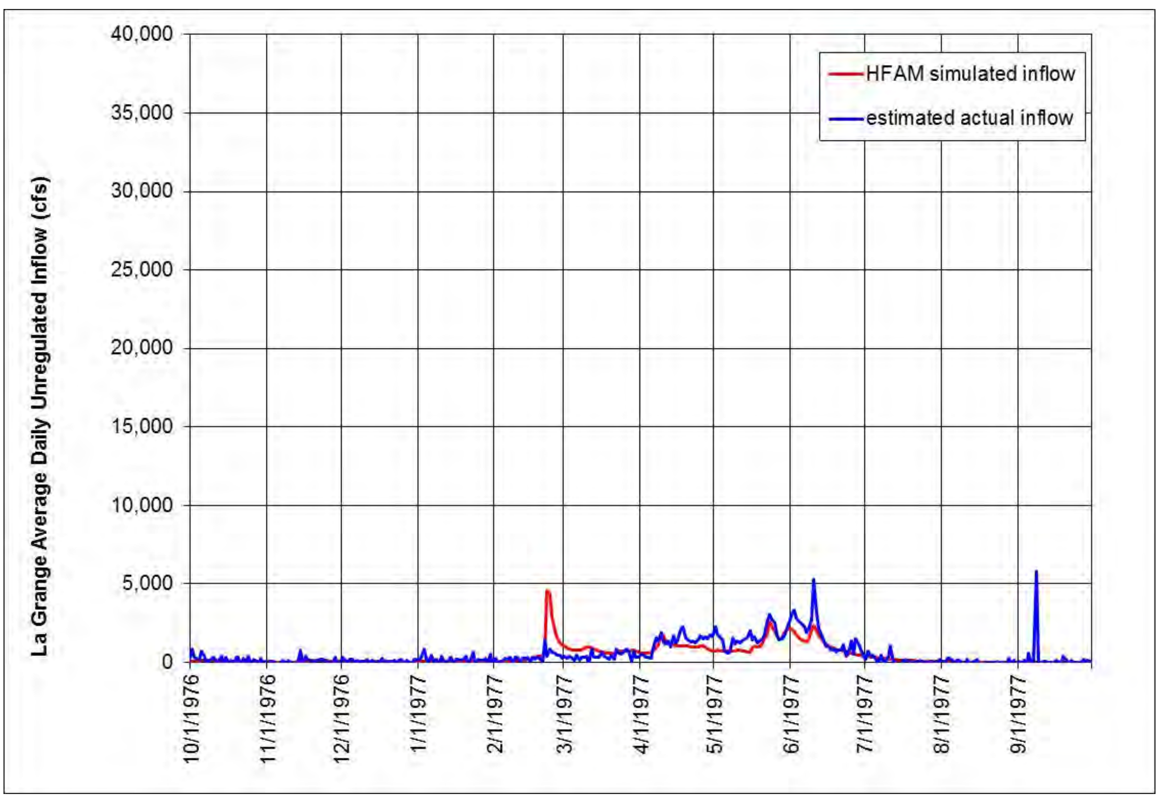


Figure B.3b La Grange Daily Unregulated Inflow, water year 1977

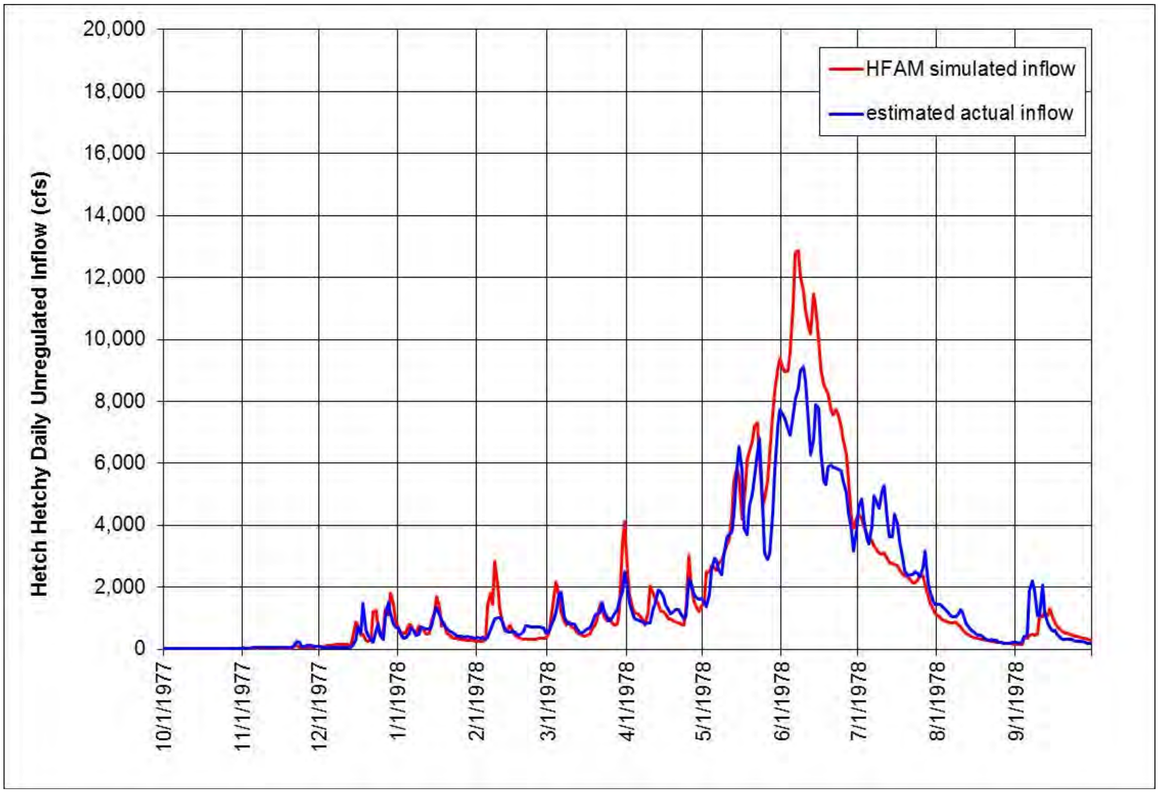


Figure B.4a Hetch Hetchy Daily Unregulated Inflow, water year 1978

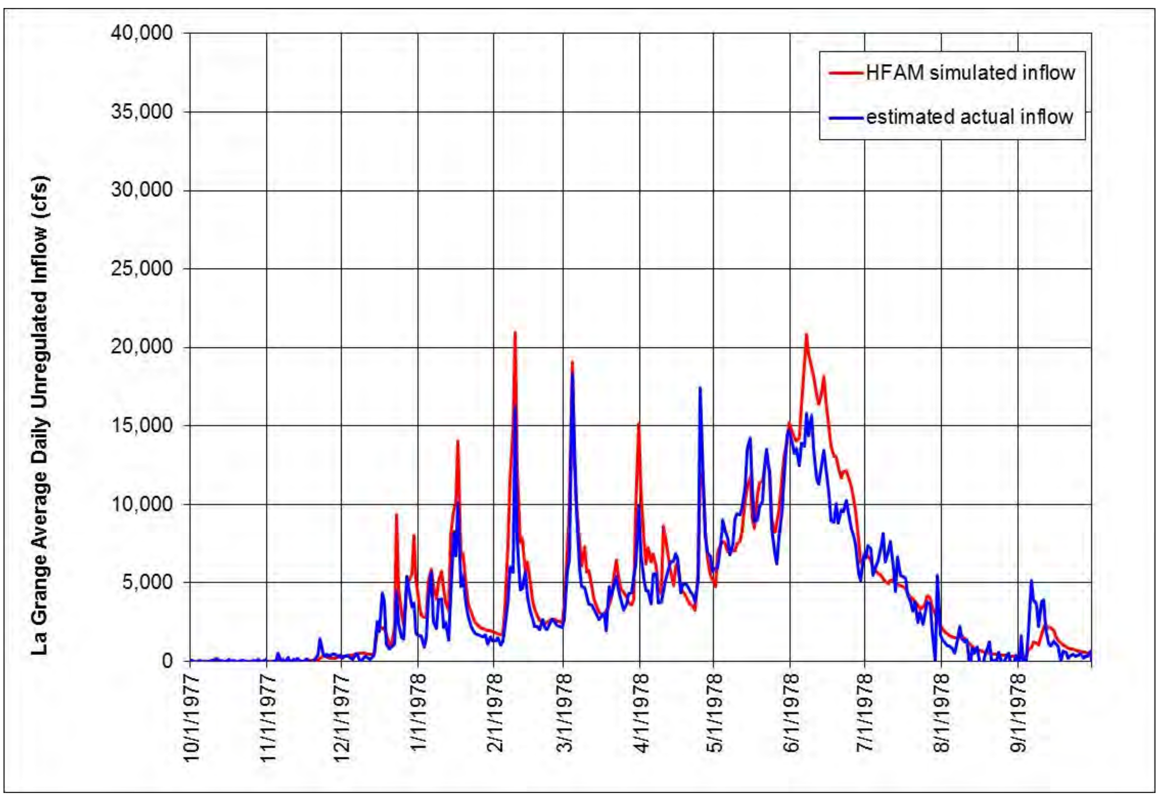


Figure B.4b La Grange Daily Unregulated Inflow, water year 1978

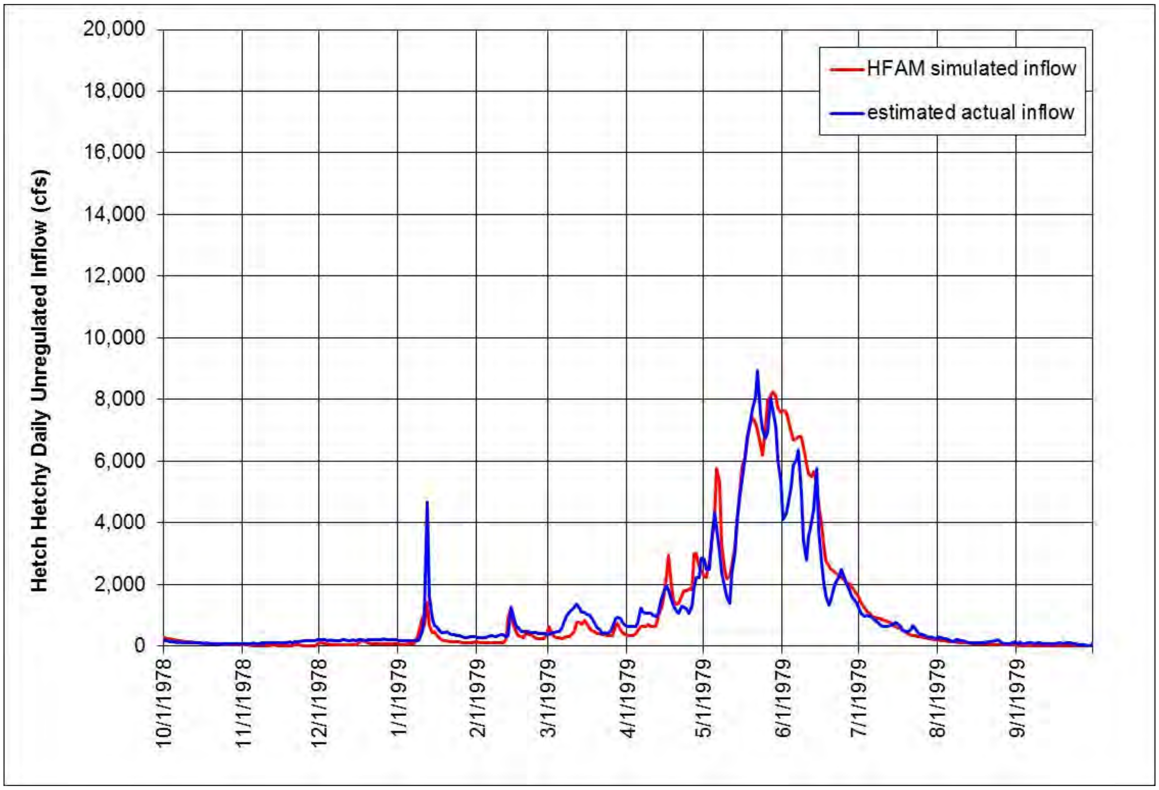


Figure B.5a Hetch Hetchy Daily Unregulated Inflow, water year 1979

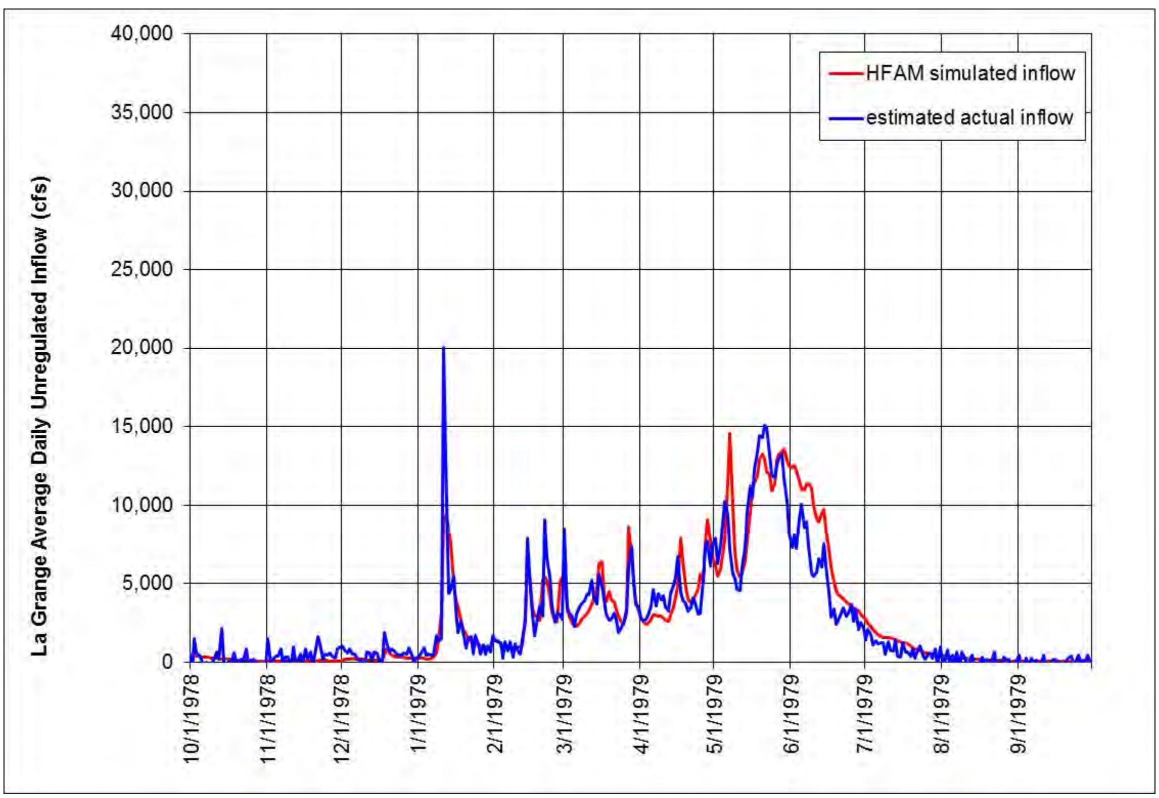


Figure B.5b La Grange Daily Unregulated Inflow, water year 1979

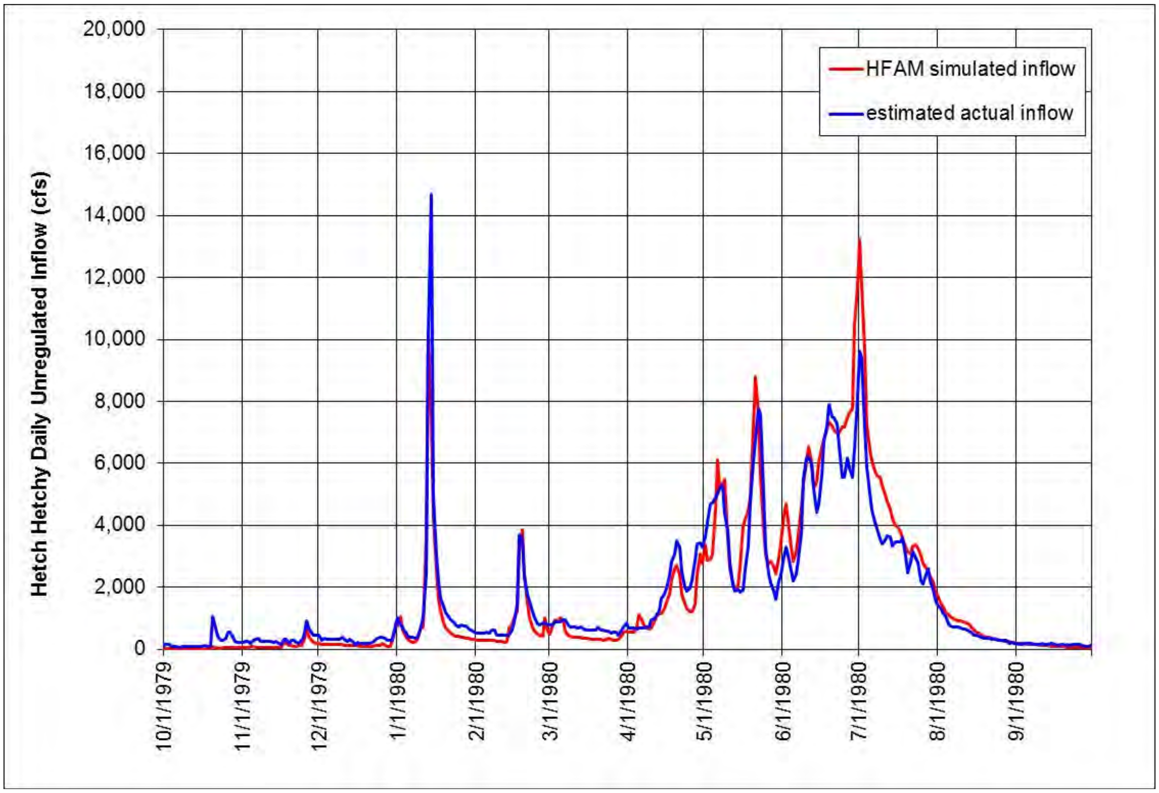


Figure B.6a Hetch Hetchy Daily Unregulated Inflow, water year 1980

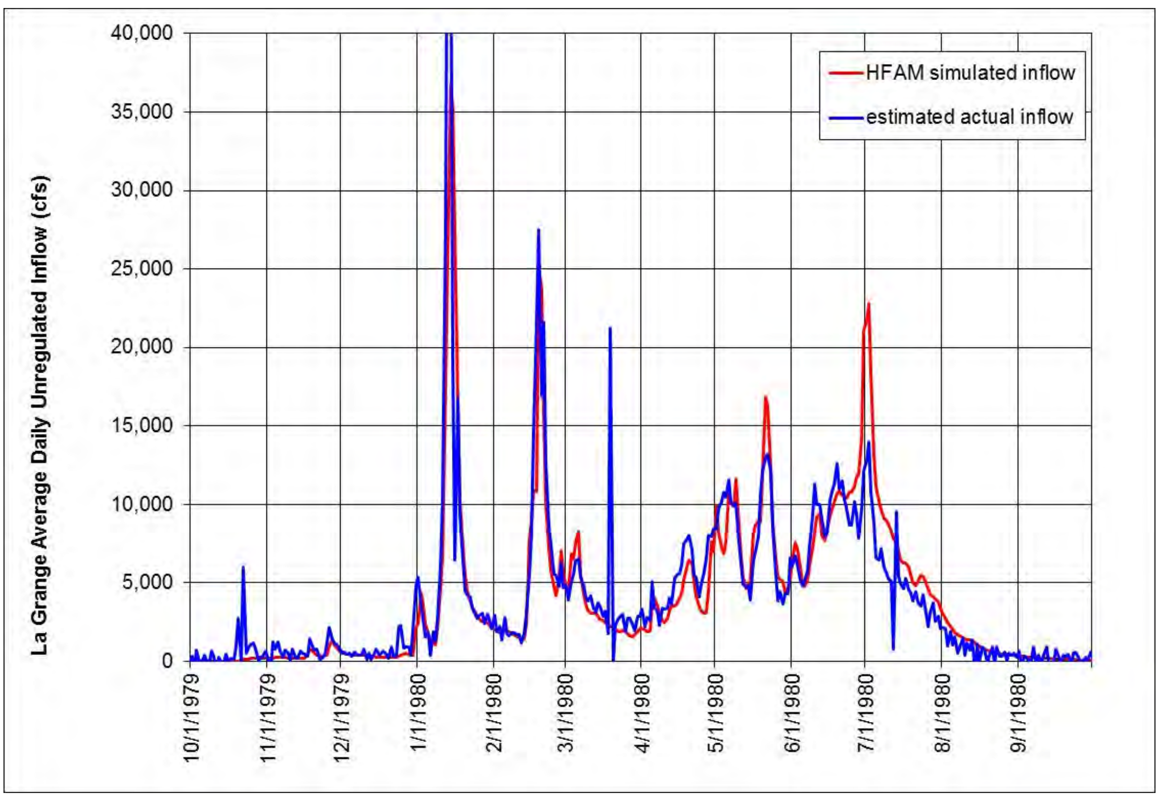


Figure B.6b La Grange Daily Unregulated Inflow, water year 1980

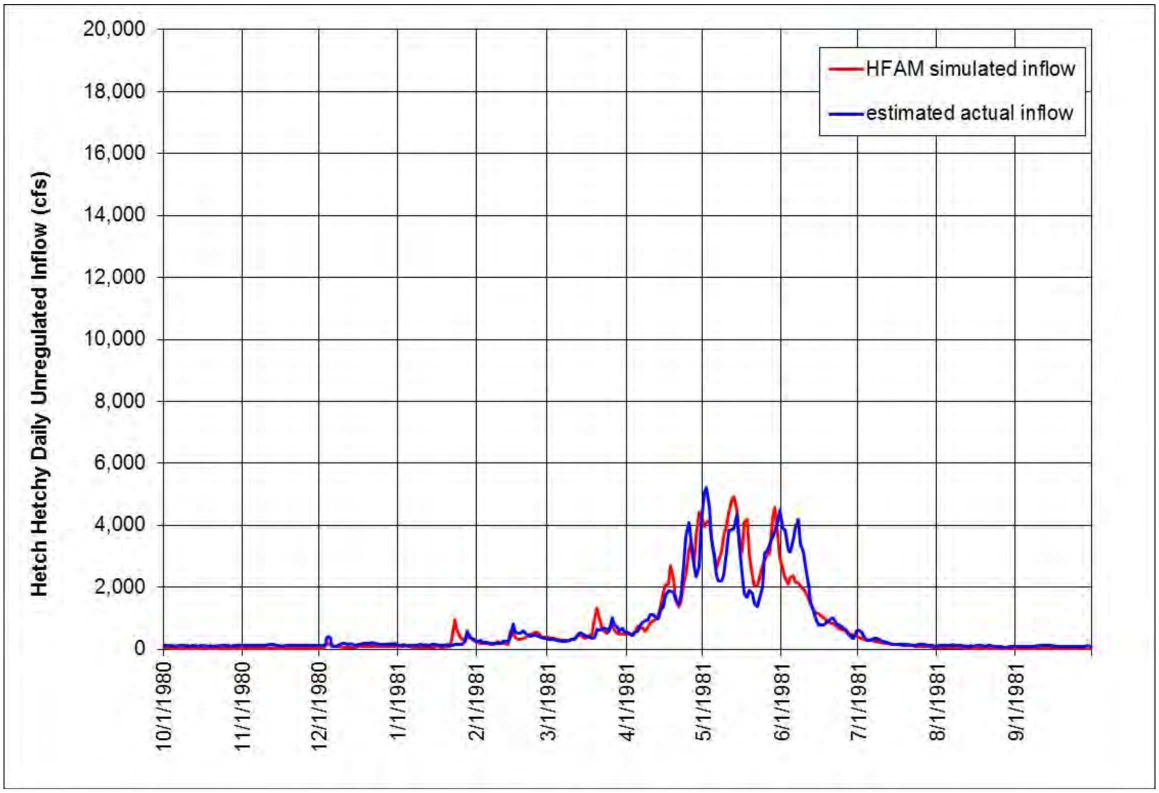


Figure B.7a Hetch Hetchy Daily Unregulated Inflow, water year 1981

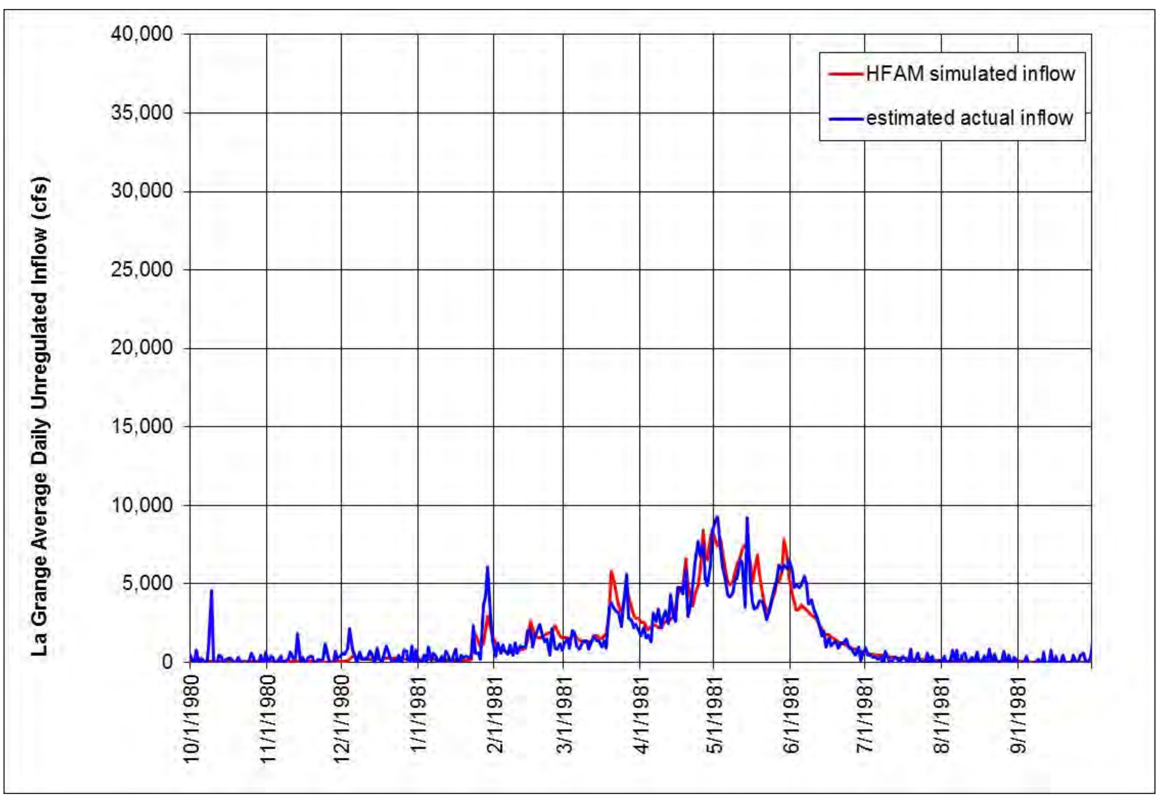


Figure B.7b La Grange Daily Unregulated Inflow, water year 1981

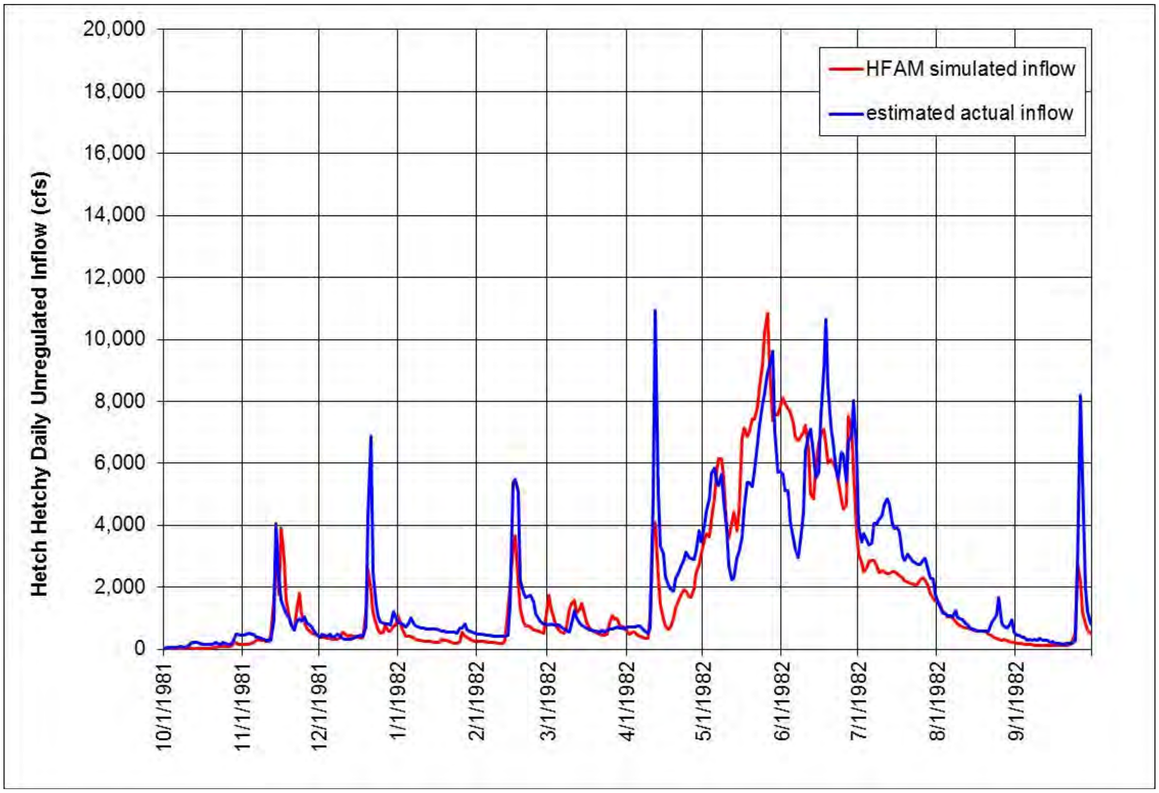


Figure B.8a Hetch Hetchy Daily Unregulated Inflow, water year 1982

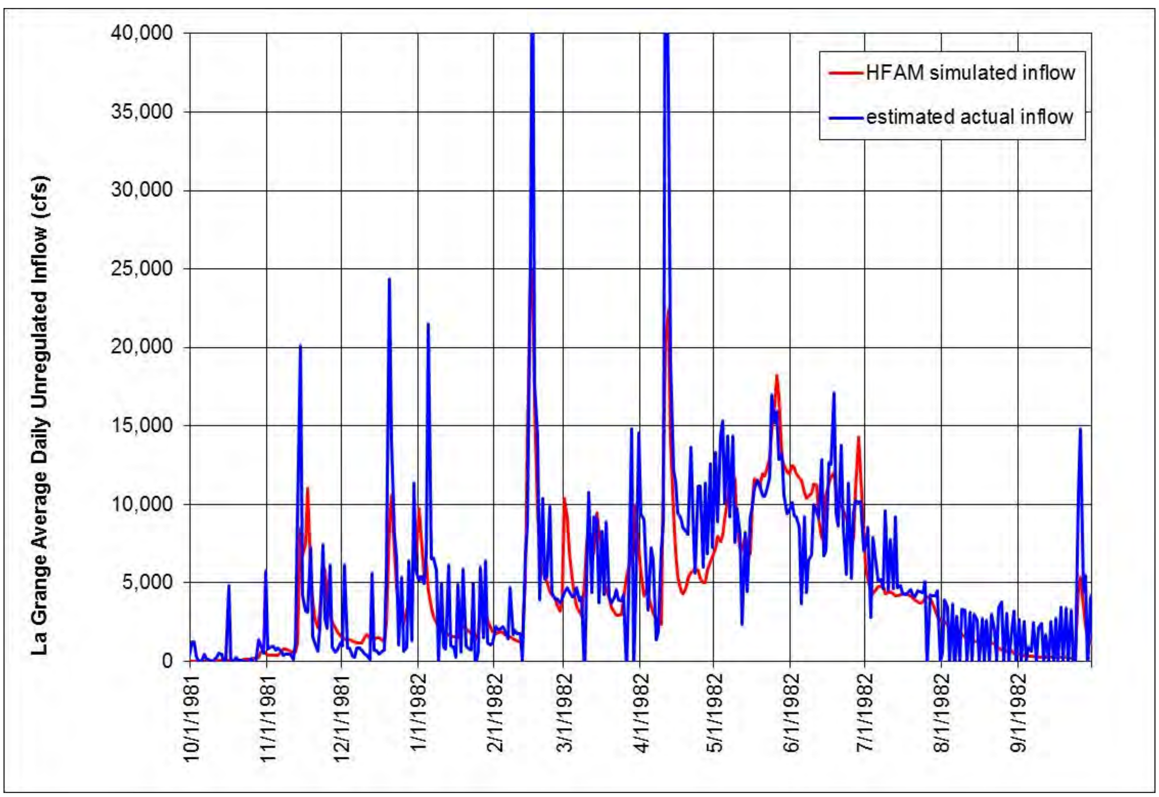


Figure B.8b La Grange Daily Unregulated Inflow, water year 1982

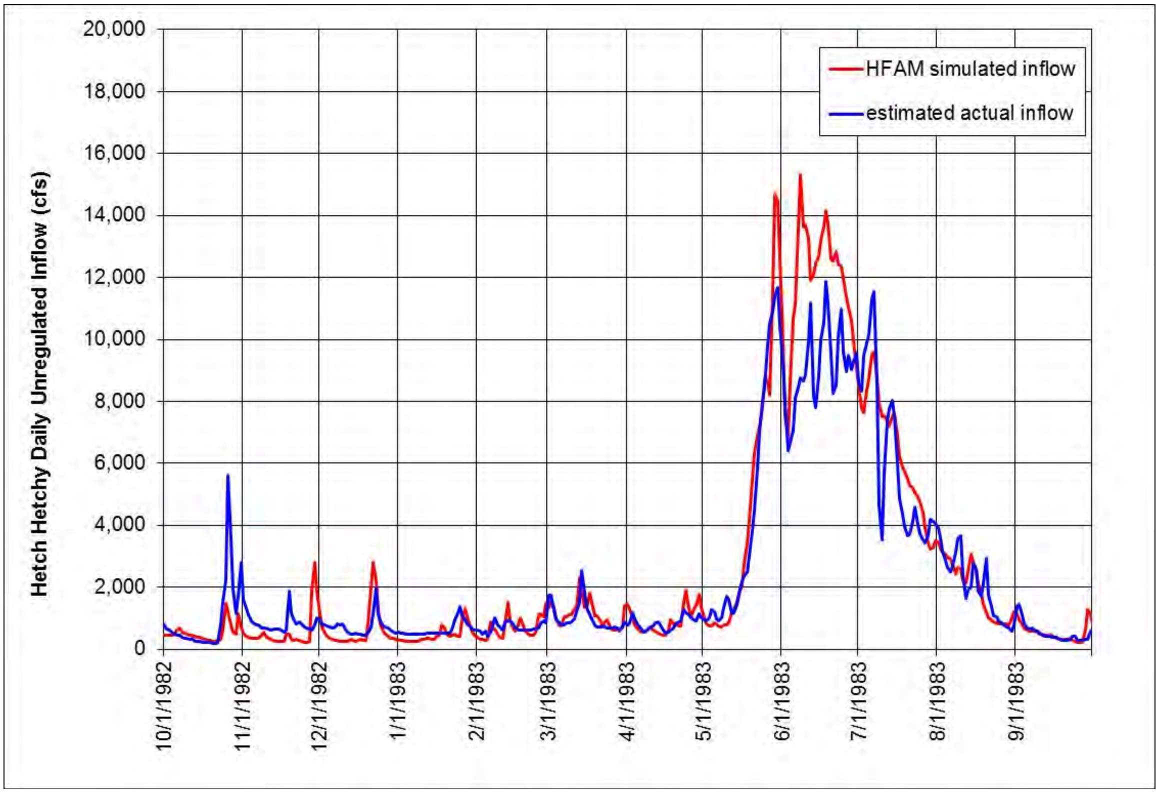


Figure B.9a Hetch Hetchy Daily Unregulated Inflow, water year 1983

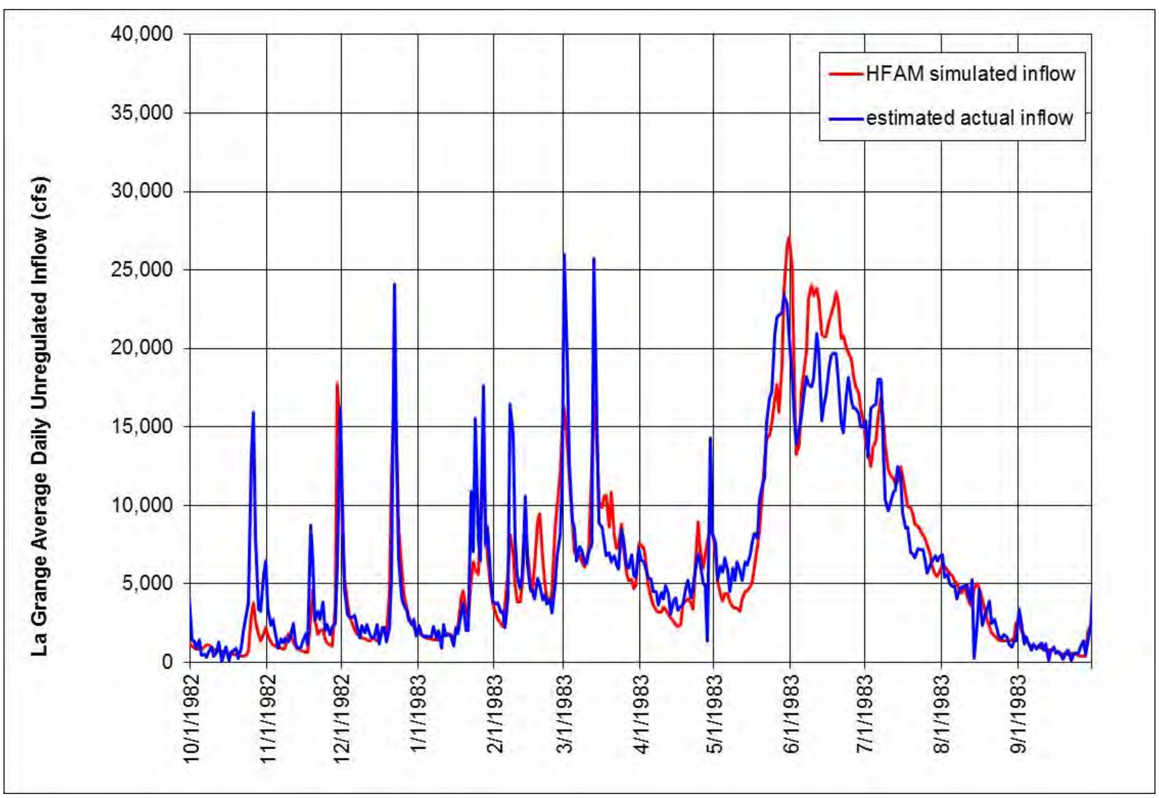


Figure B.9b La Grange Daily Unregulated Inflow, water year 1983

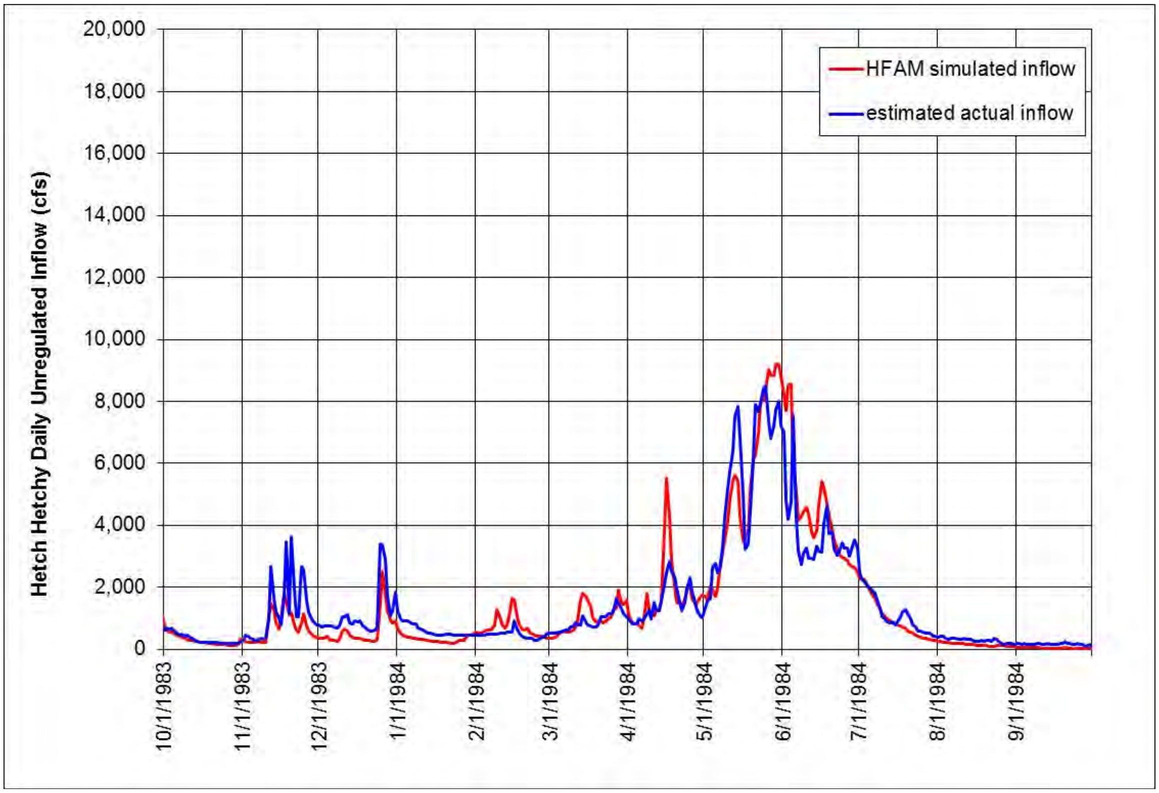


Figure B.10a Hetch Hetchy Daily Unregulated Inflow, water year 1984

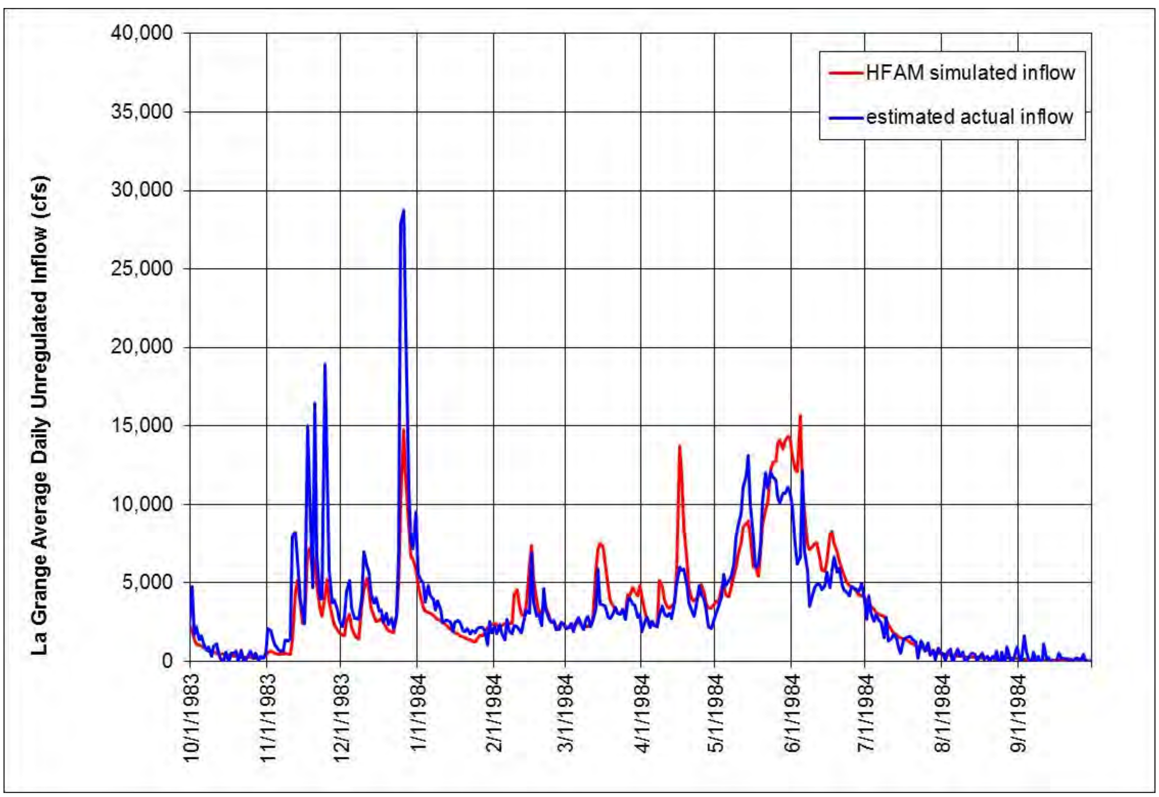


Figure B.10b La Grange Daily Unregulated Inflow, water year 1984

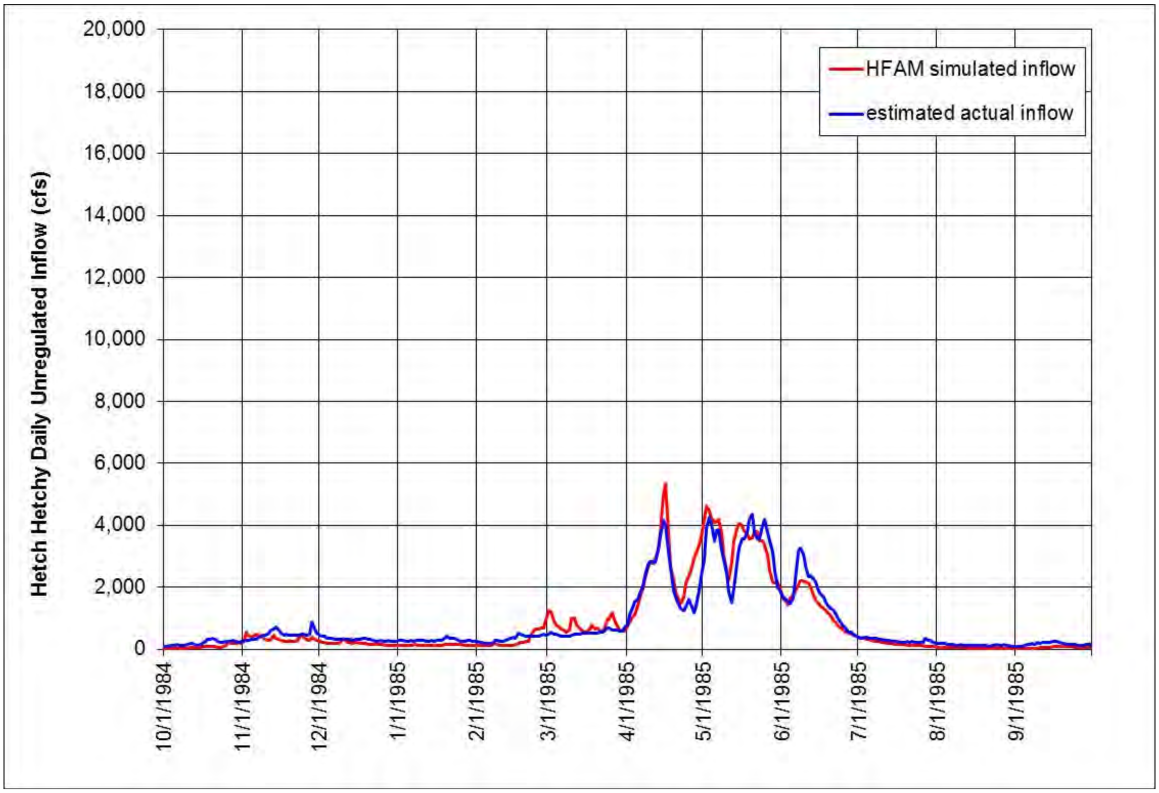


Figure B.11a Hetch Hetchy Daily Unregulated Inflow, water year 1985

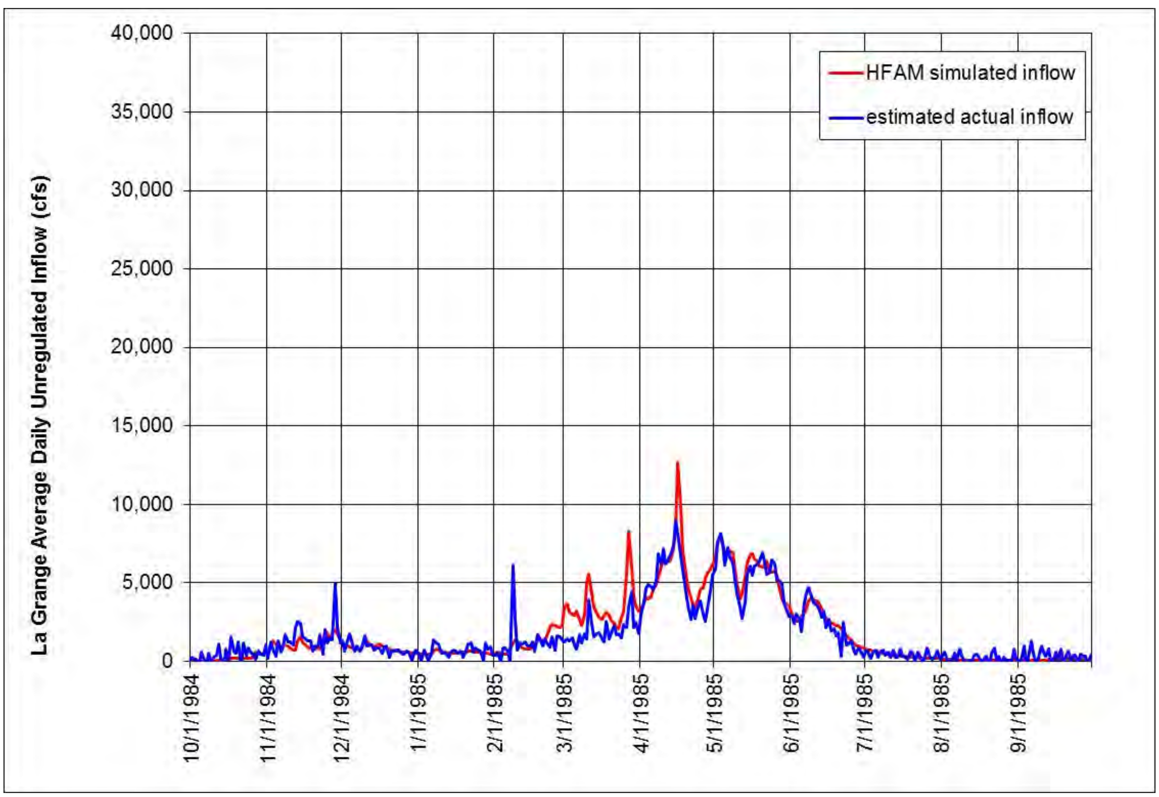


Figure B.11b La Grange Daily Unregulated Inflow, water year 1985

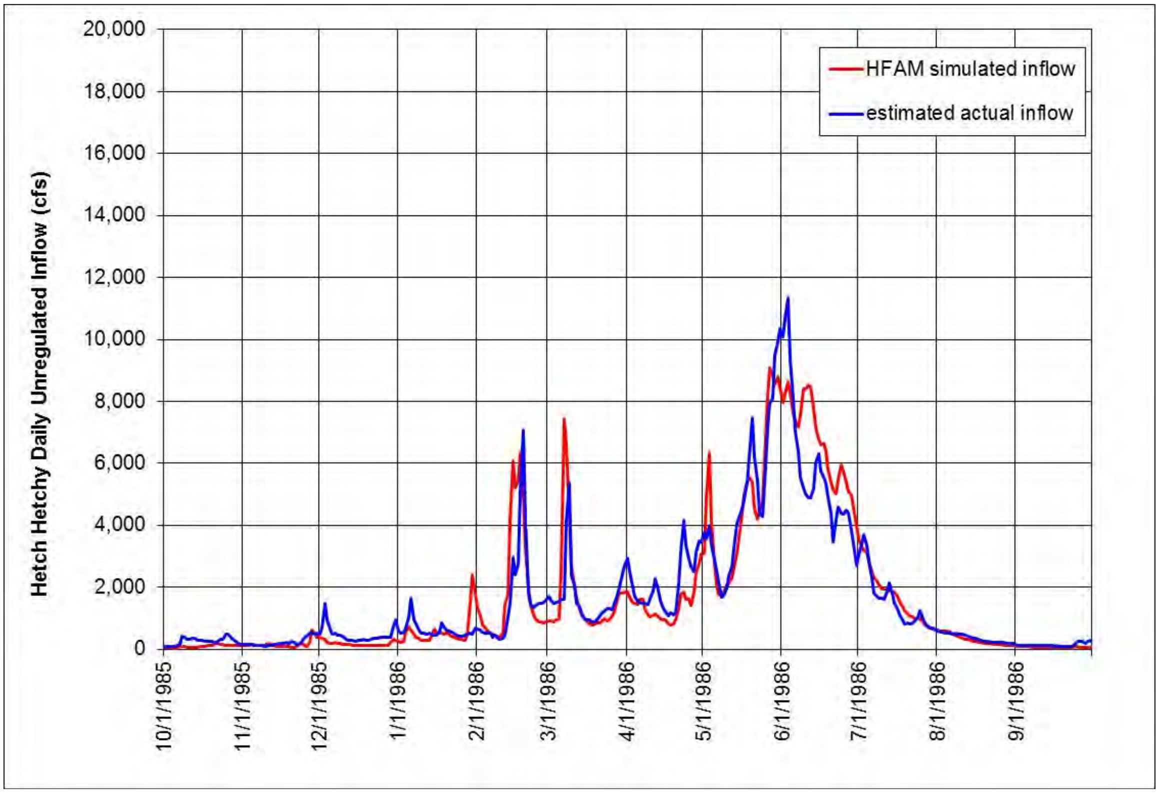


Figure B.12a Hetch Hetchy Daily Unregulated Inflow, water year 1986

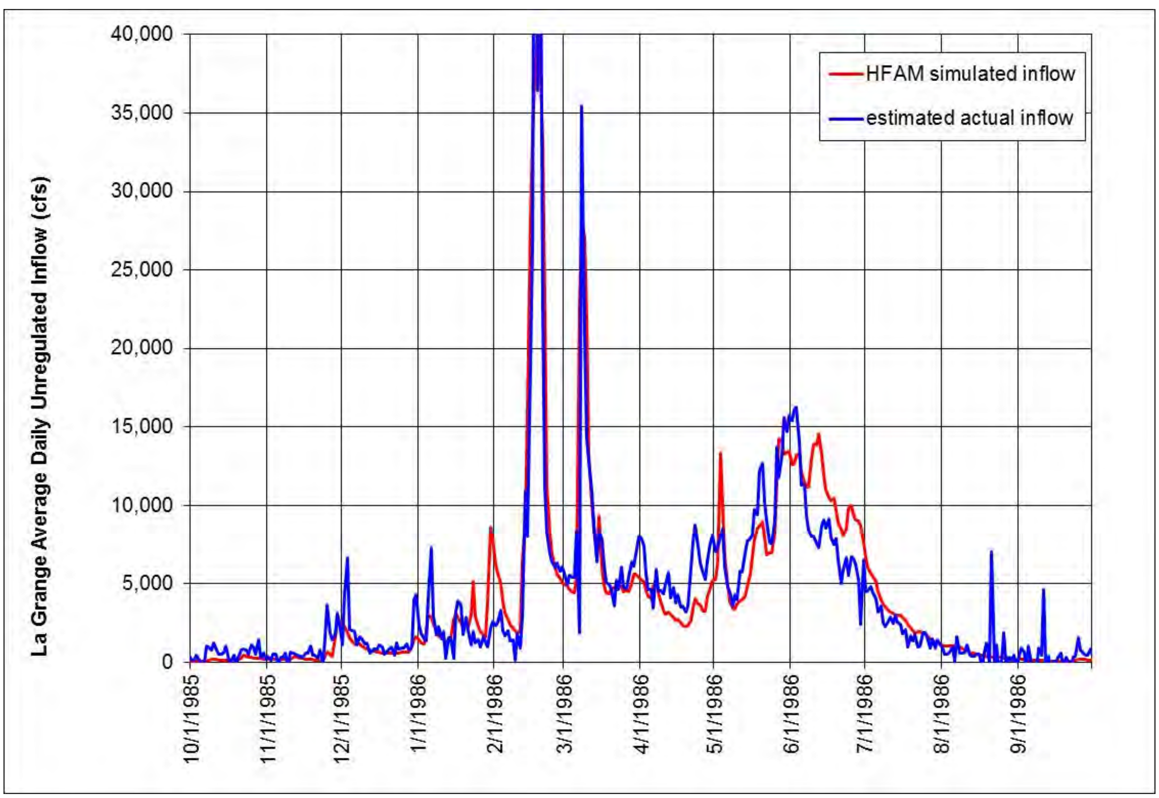


Figure B.12b La Grange Daily Unregulated Inflow, water year 1986

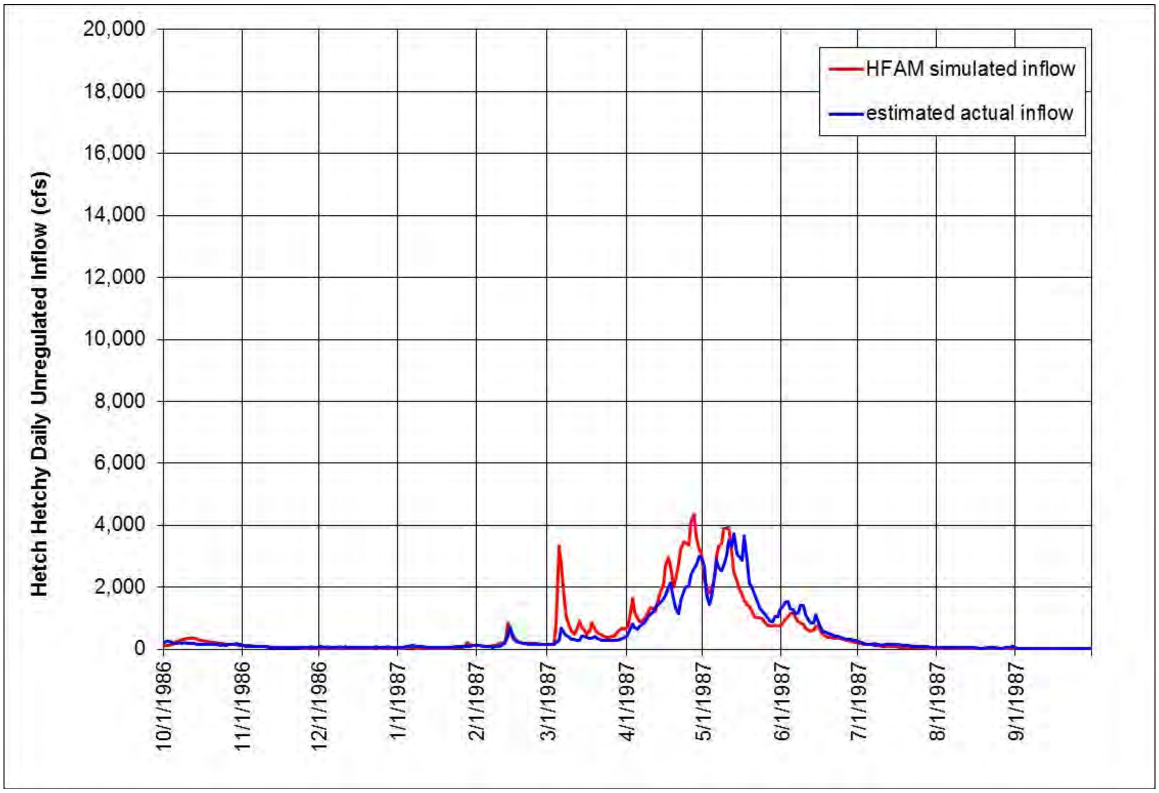


Figure B.13a Hetch Hetchy Daily Unregulated Inflow, water year 1987

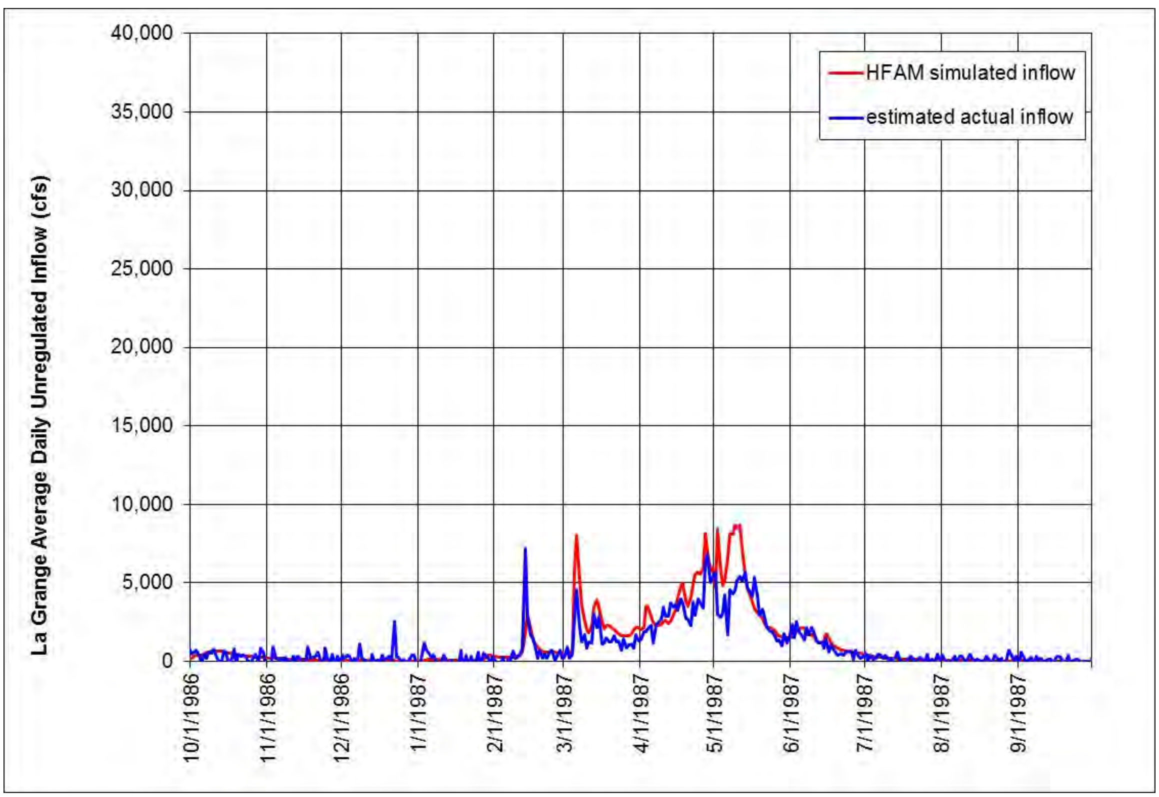


Figure B.13b La Grange Daily Unregulated Inflow, water year 1987

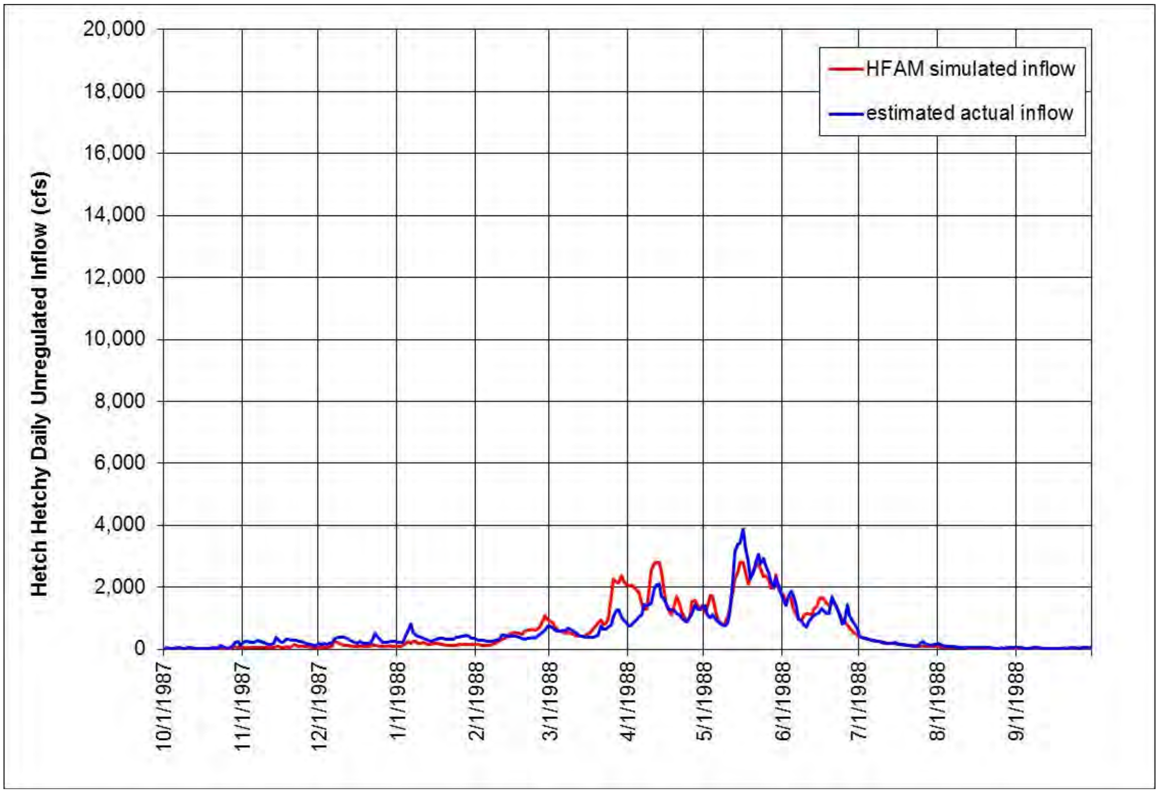


Figure B.14a Hetch Hetchy Daily Unregulated Inflow, water year 1988

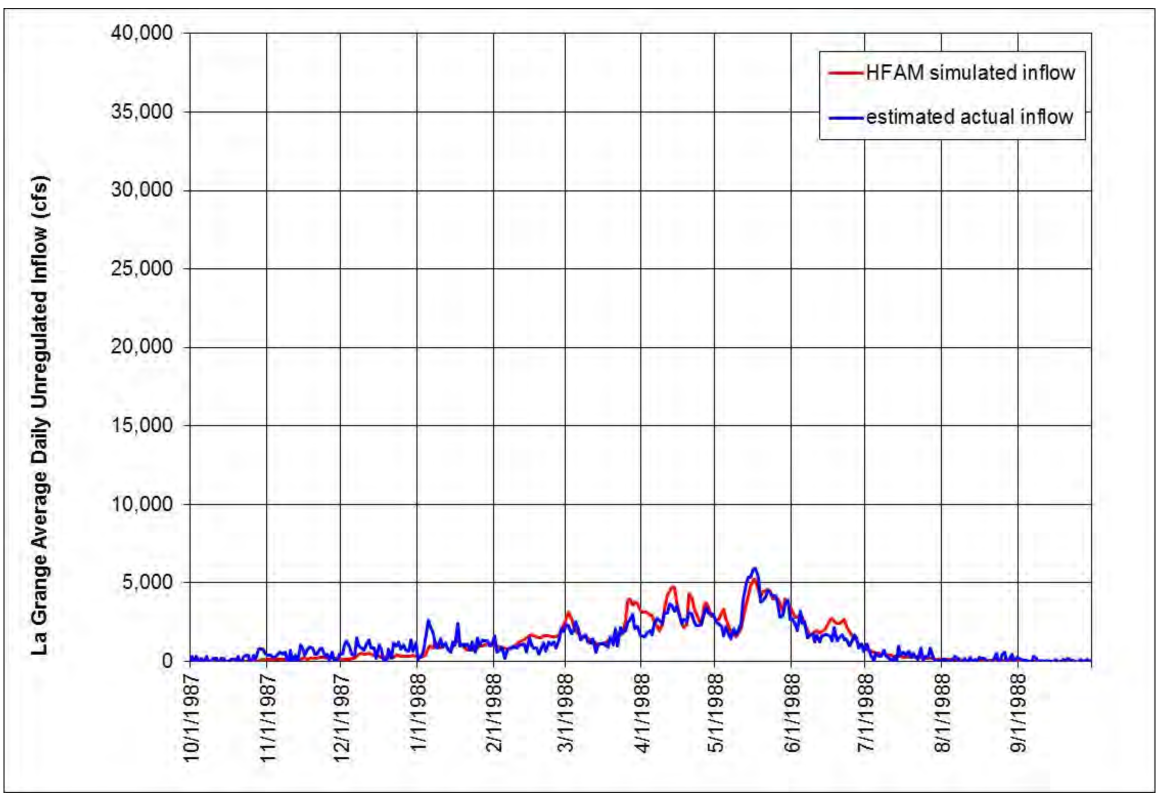


Figure B.14b La Grange Daily Unregulated Inflow, water year 1988

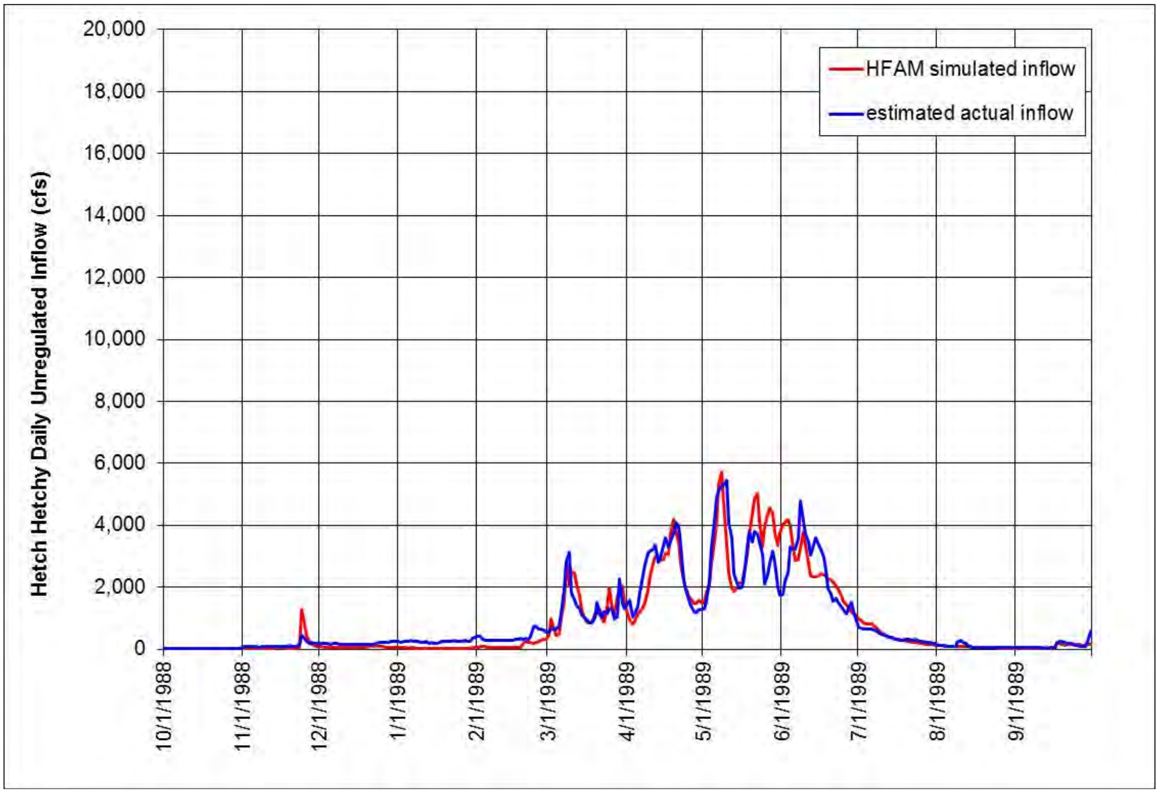


Figure B.15a Hetch Hetchy Daily Unregulated Inflow, water year 1989

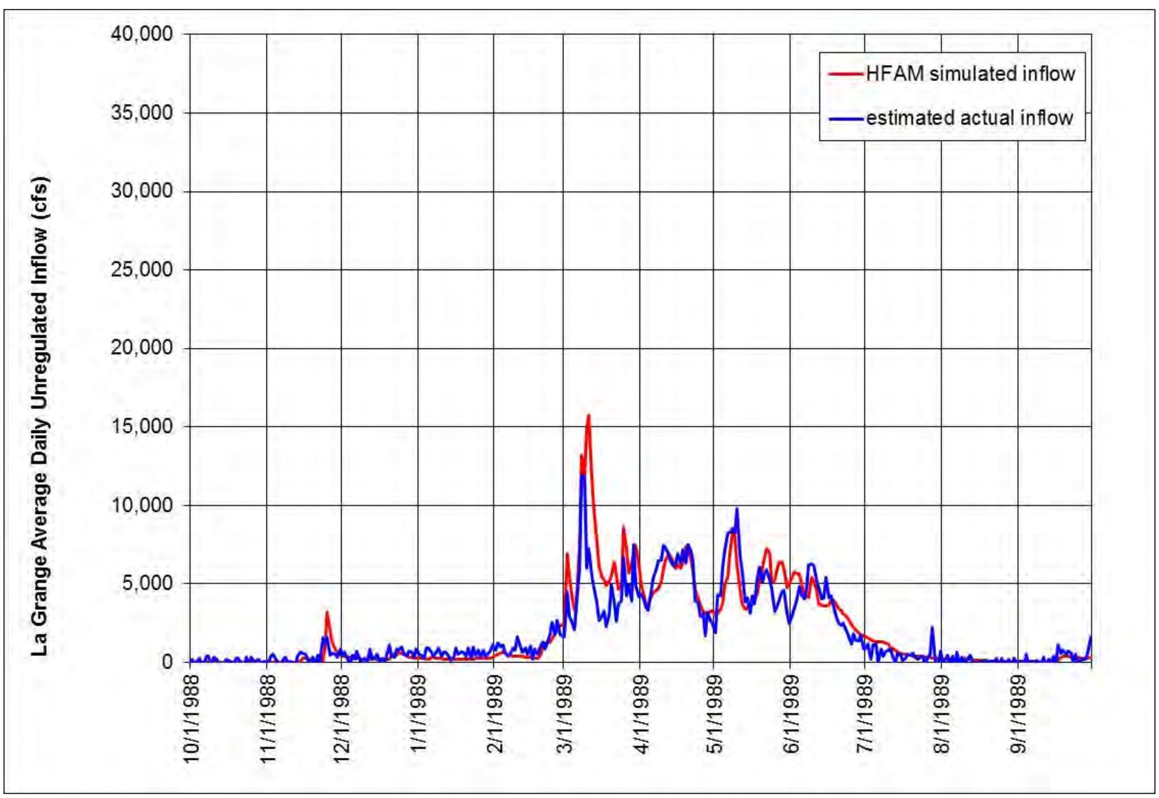


Figure B.15b La Grange Daily Unregulated Inflow, water year 1989

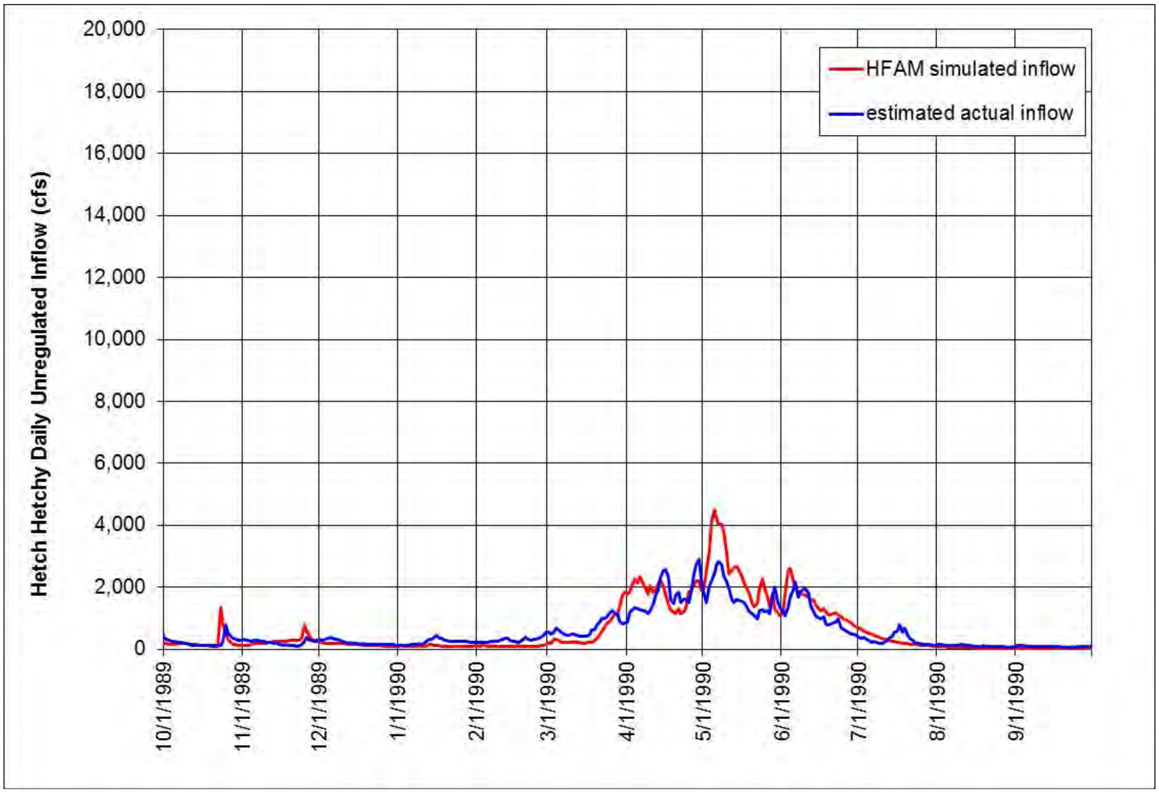


Figure B.16a Hetch Hetchy Daily Unregulated Inflow, water year 1990

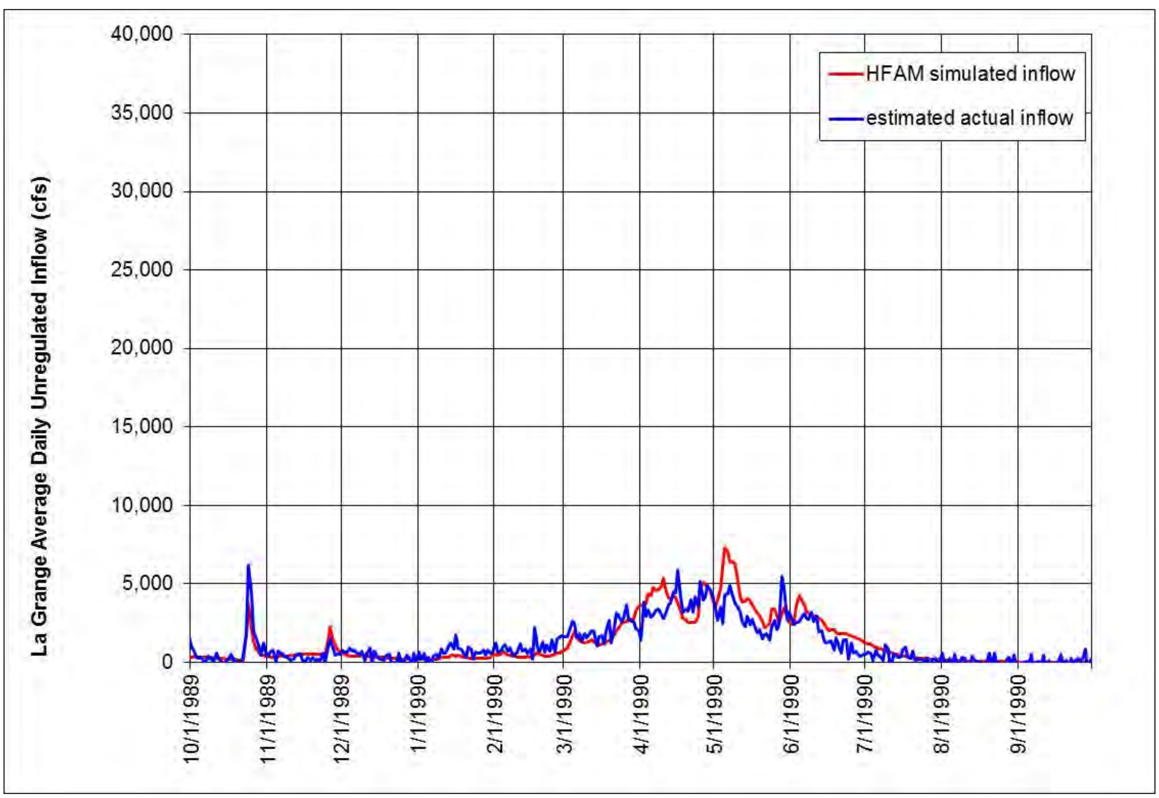


Figure B.16b La Grange Daily Unregulated Inflow, water year 1990

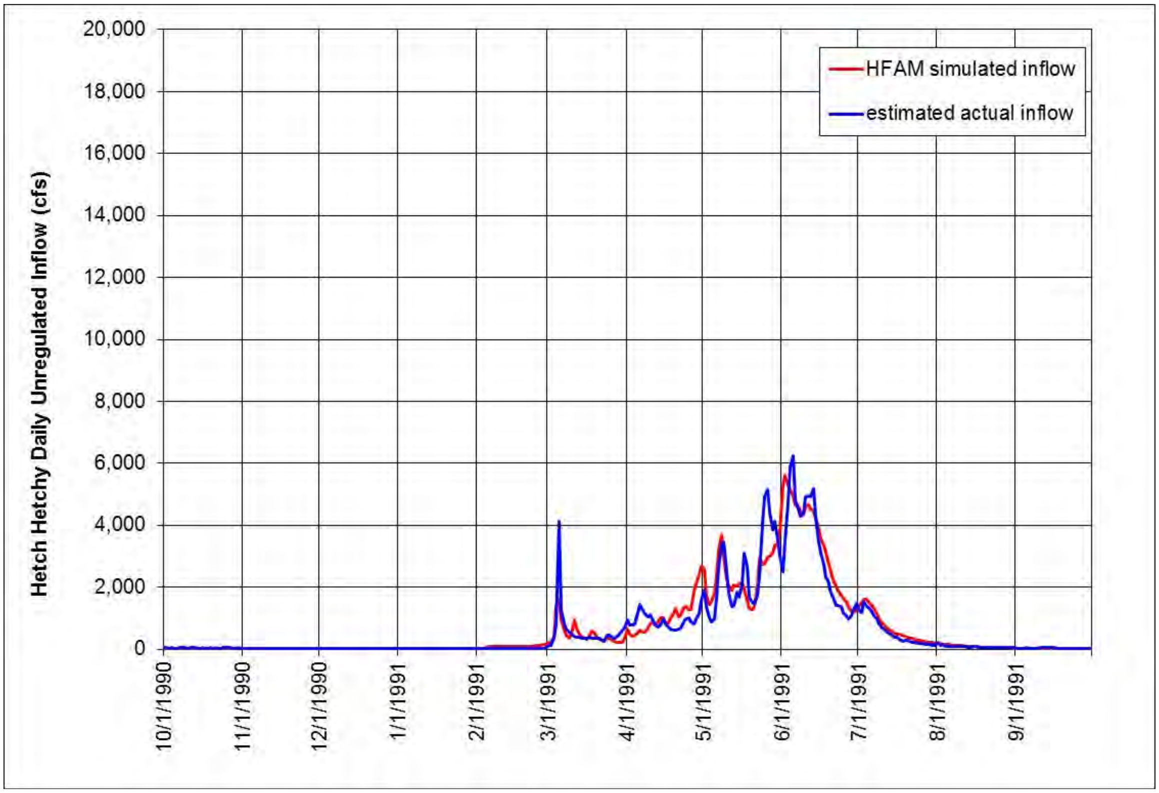


Figure B.17a Hetch Hetchy Daily Unregulated Inflow, water year 1991

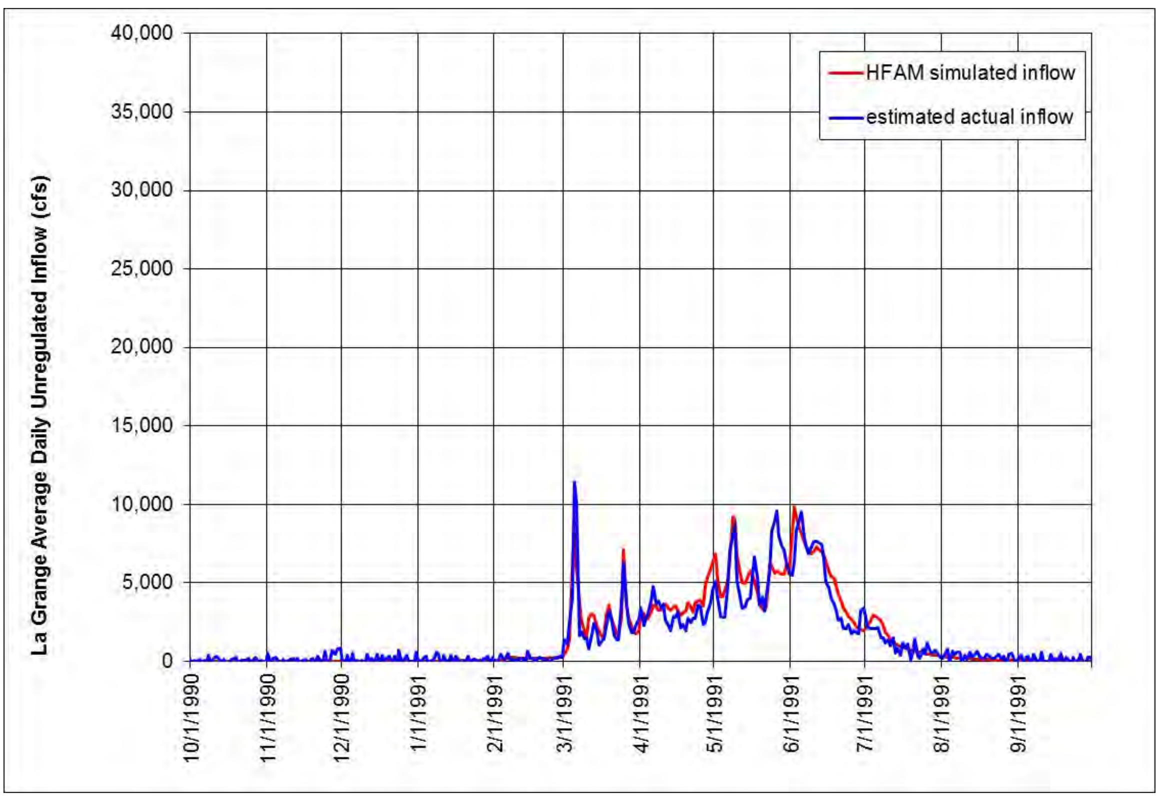


Figure B.17b La Grange Daily Unregulated Inflow, water year 1991

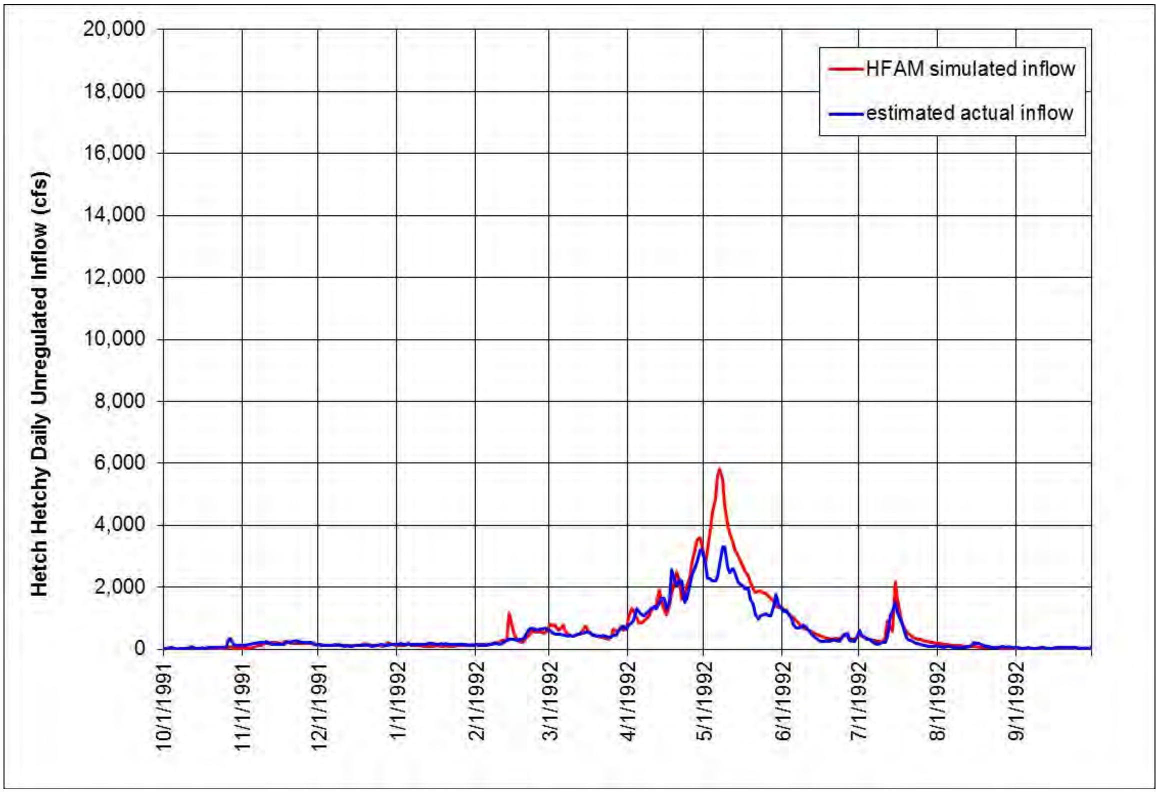


Figure B.18a Hetch Hetchy Daily Unregulated Inflow, water year 1992

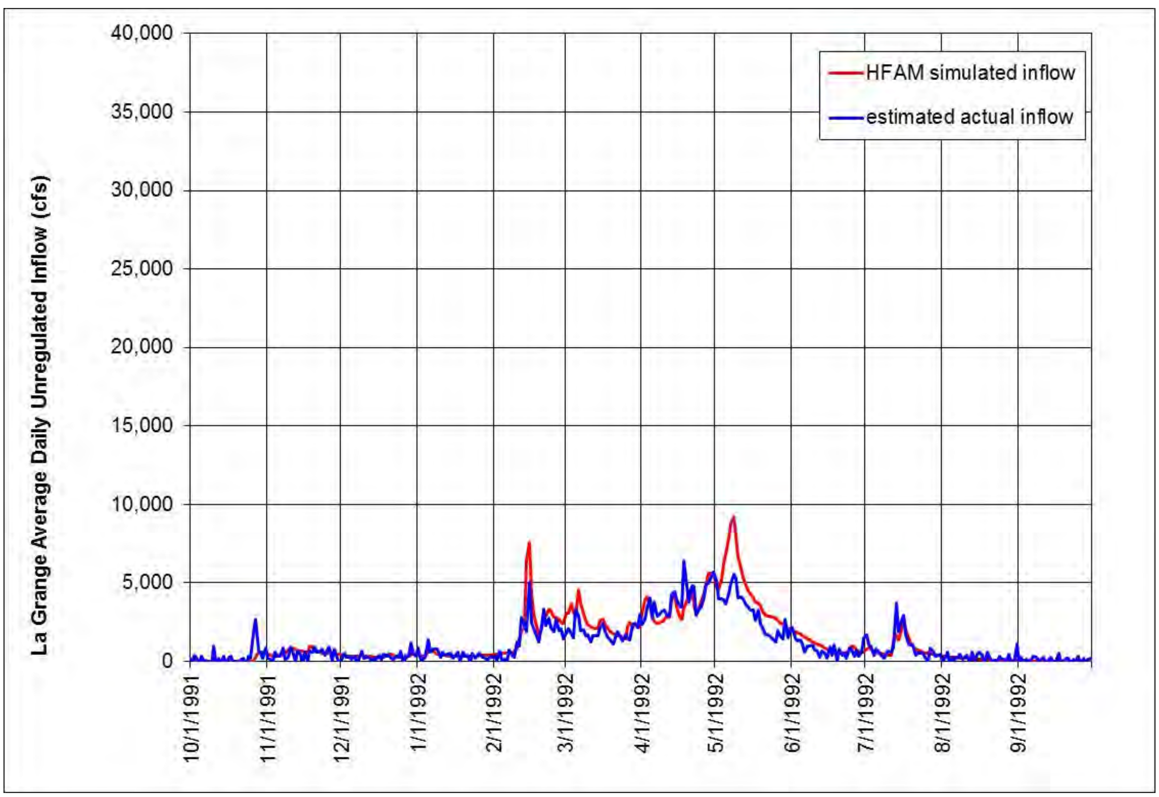


Figure B.18b La Grange Daily Unregulated Inflow, water year 1992

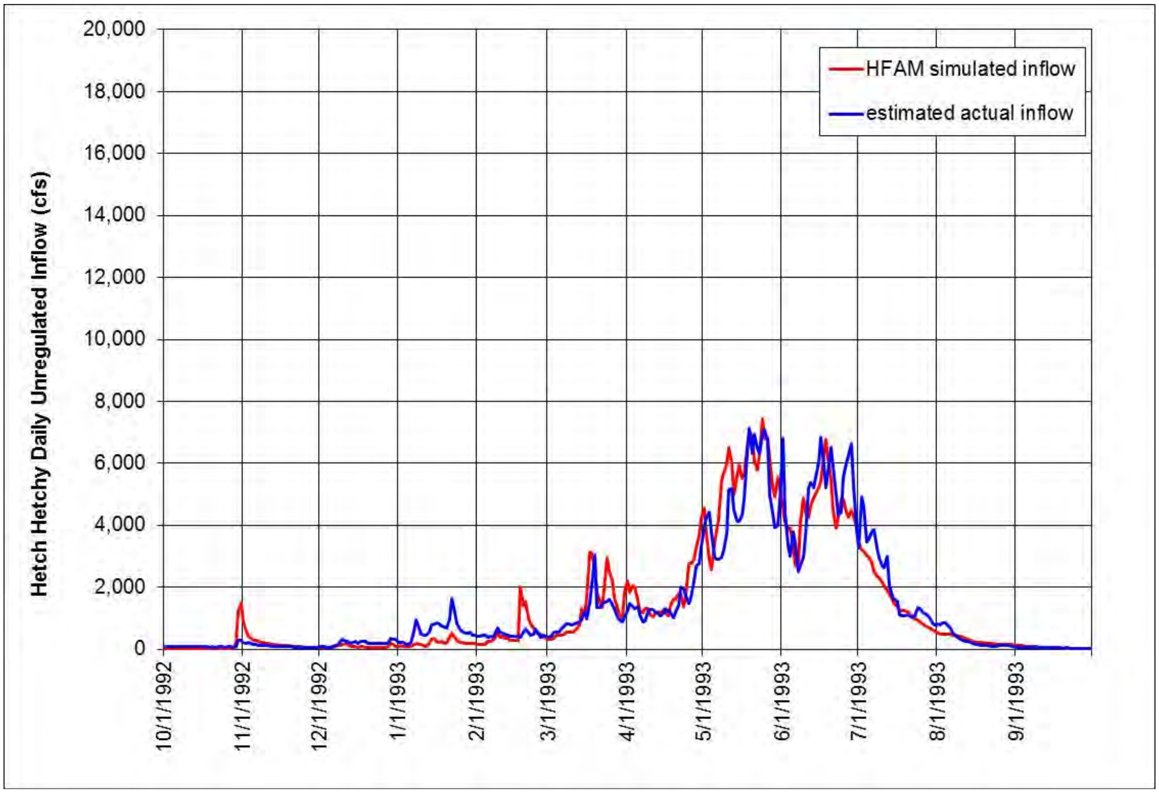


Figure B.19a Hetch Hetchy Daily Unregulated Inflow, water year 1993

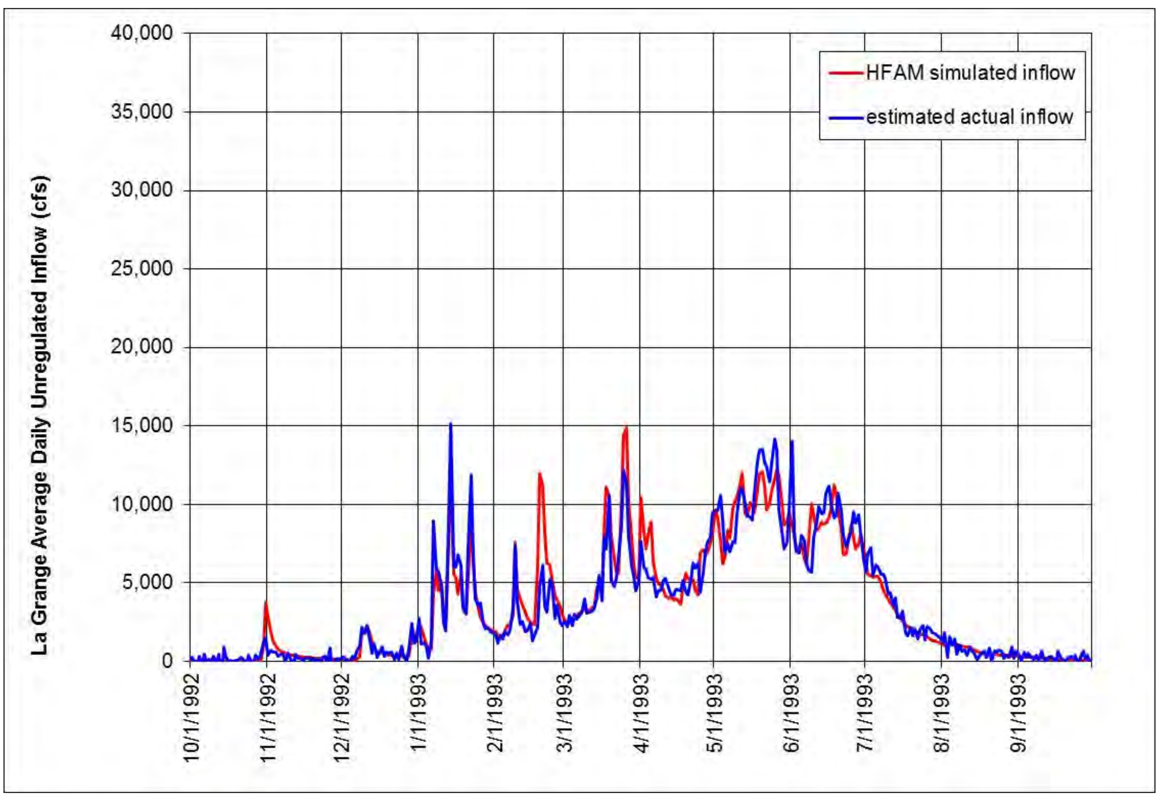


Figure B.19b La Grange Daily Unregulated Inflow, water year 1993

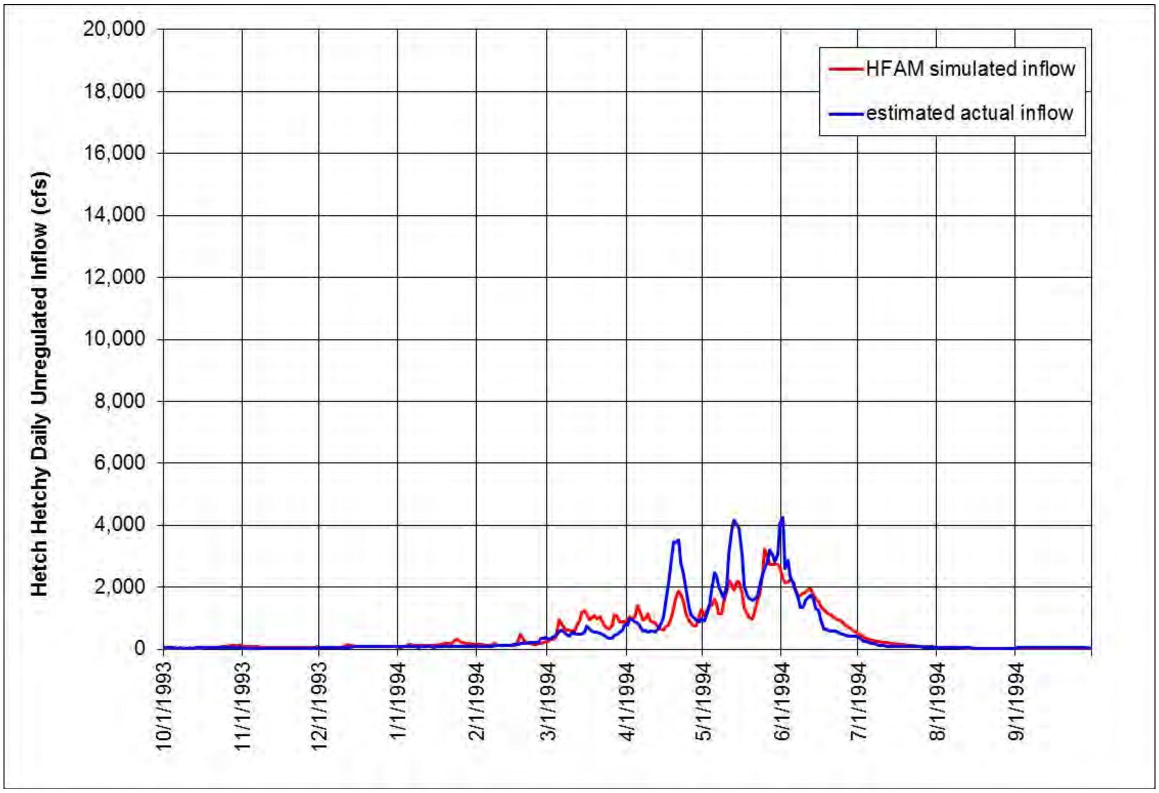


Figure B.20a Hetch Hetchy Daily Unregulated Inflow, water year 1994

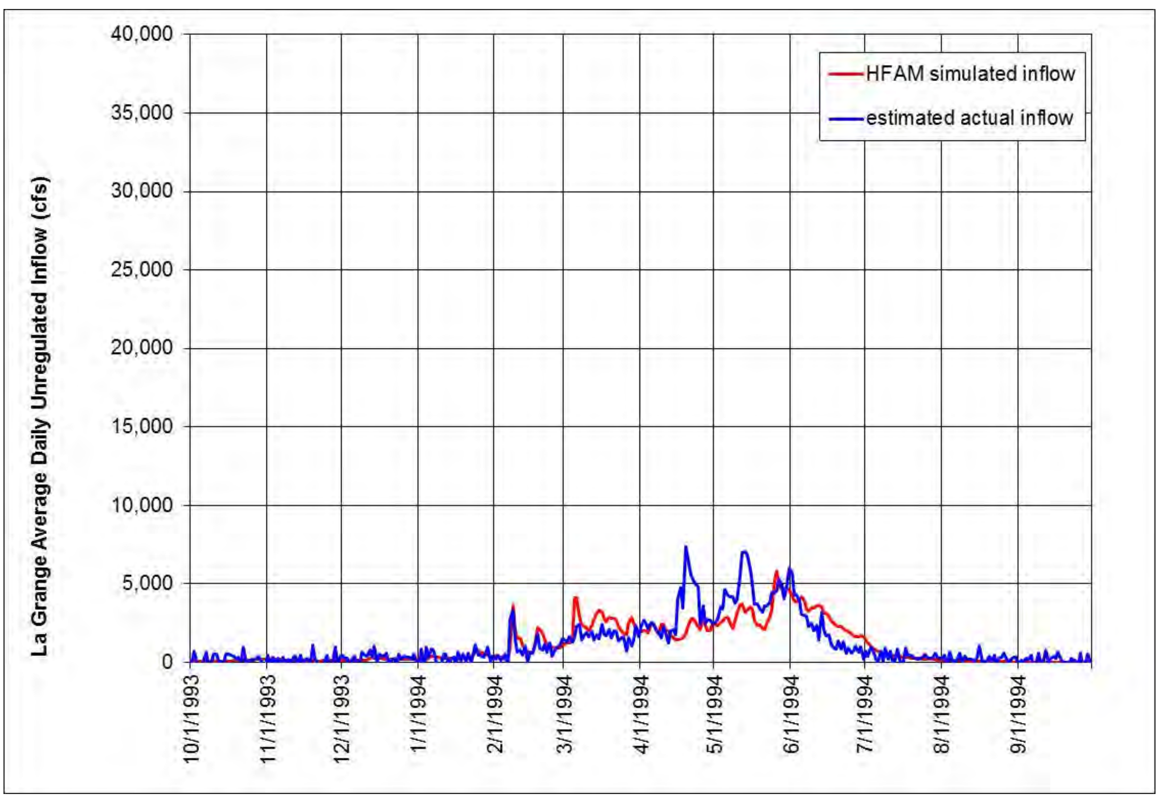


Figure B.20b La Grange Daily Unregulated Inflow, water year 1994

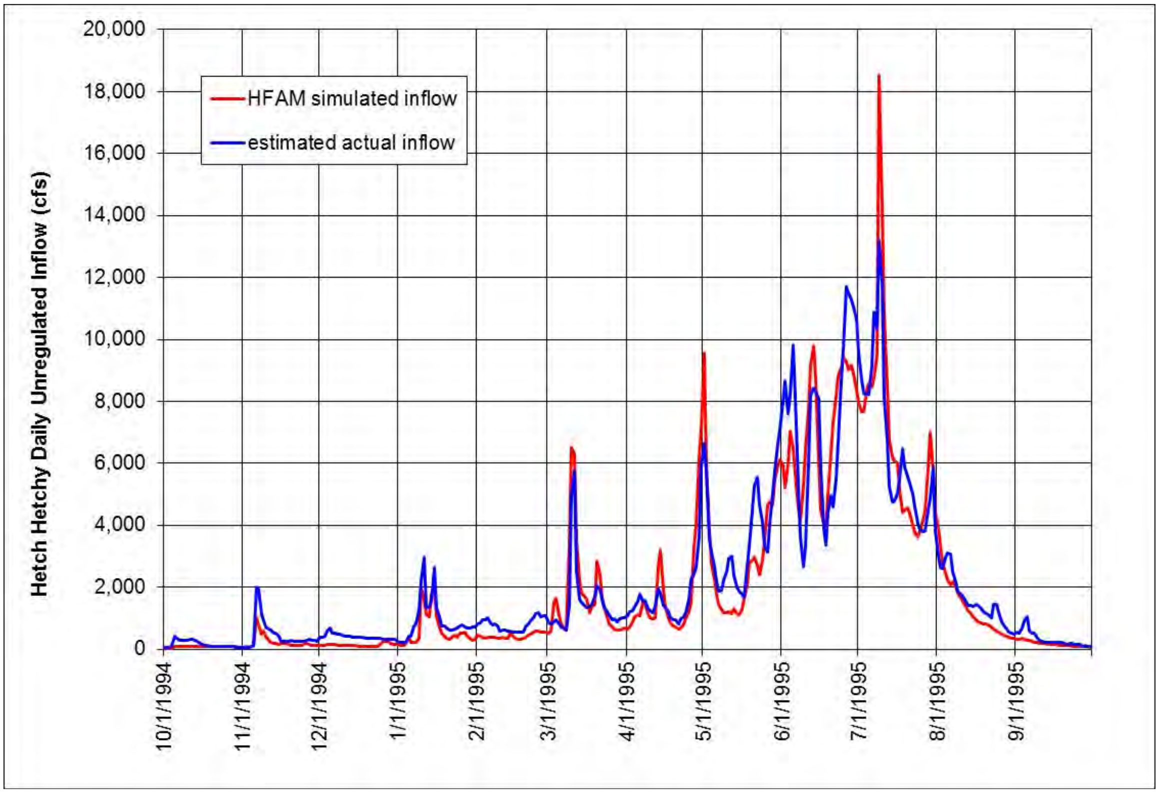


Figure B.21a Hetch Hetchy Daily Unregulated Inflow, water year 1995

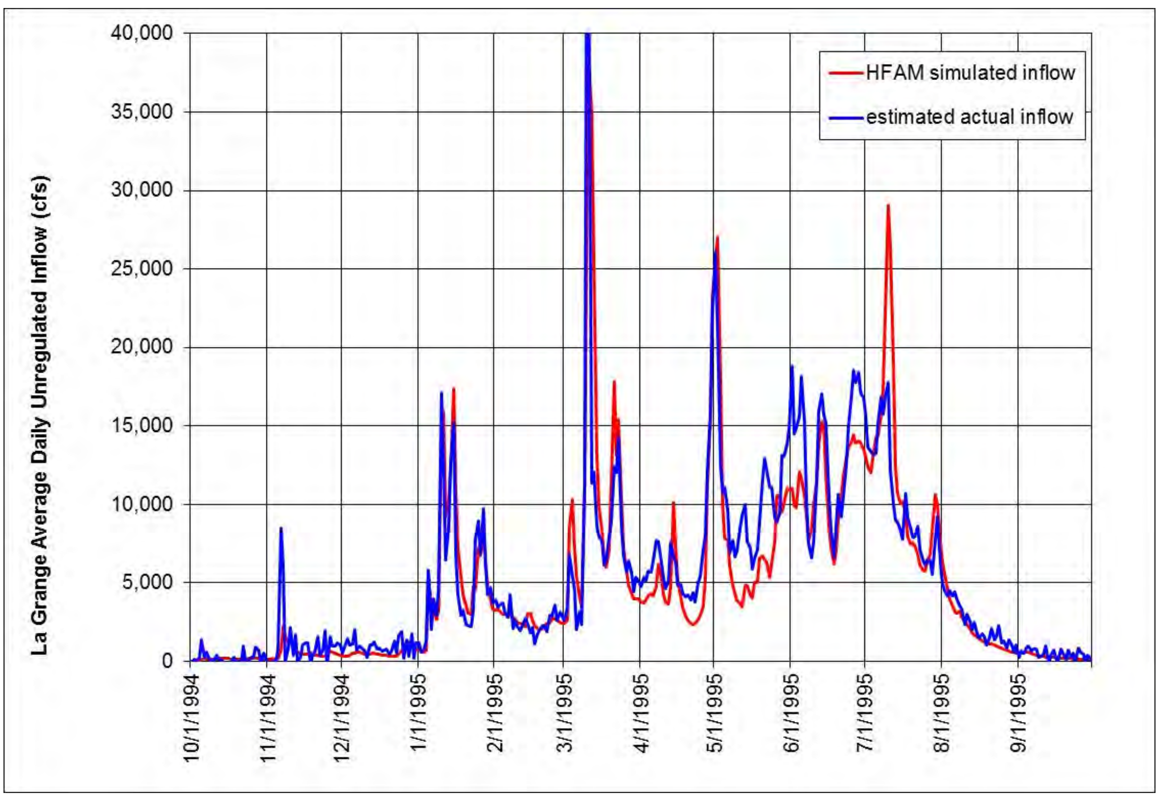


Figure B.21b La Grange Daily Unregulated Inflow, water year 1995

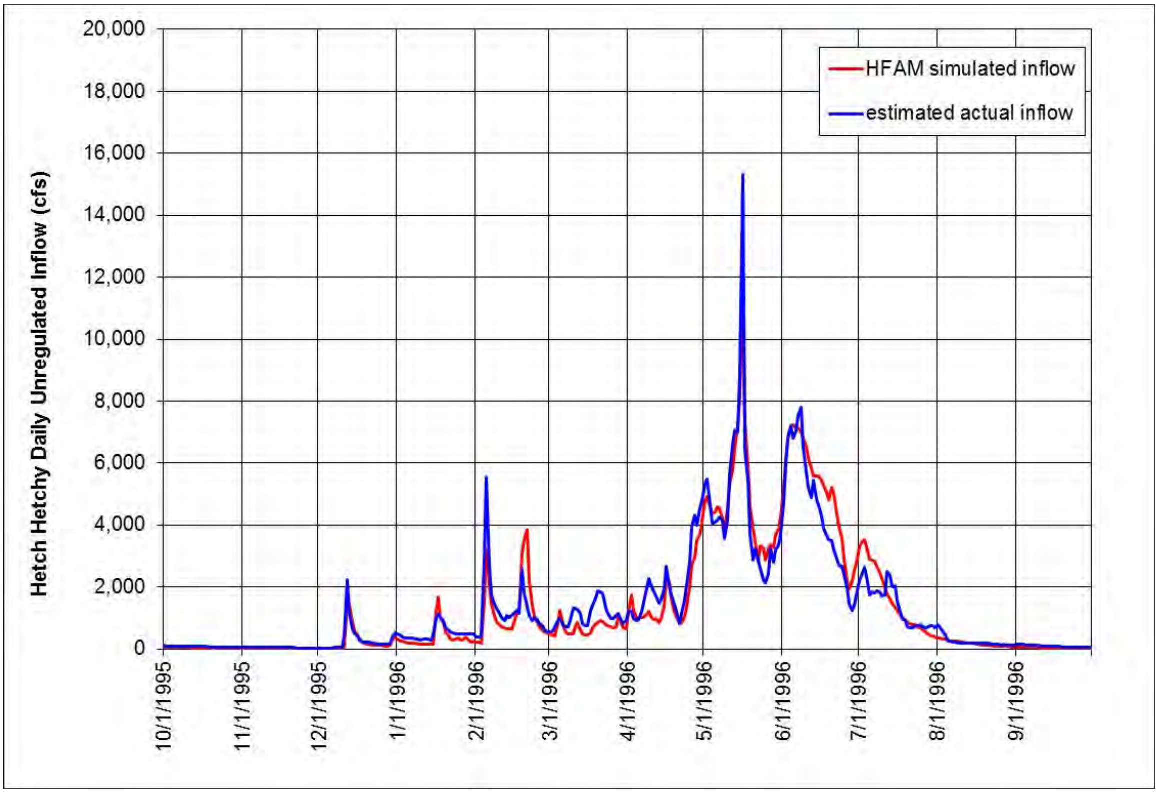


Figure B.22a Hetch Hetchy Daily Unregulated Inflow, water year 1996

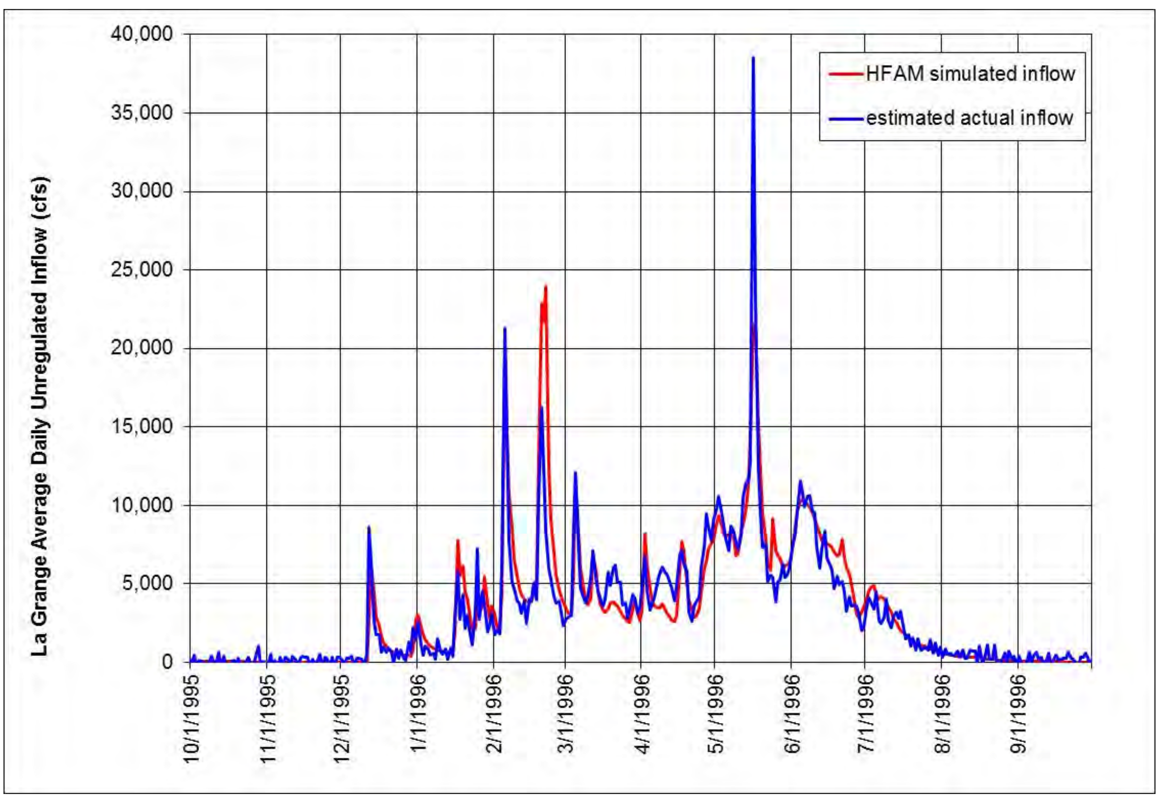


Figure B.22b La Grange Daily Unregulated Inflow, water year 1996

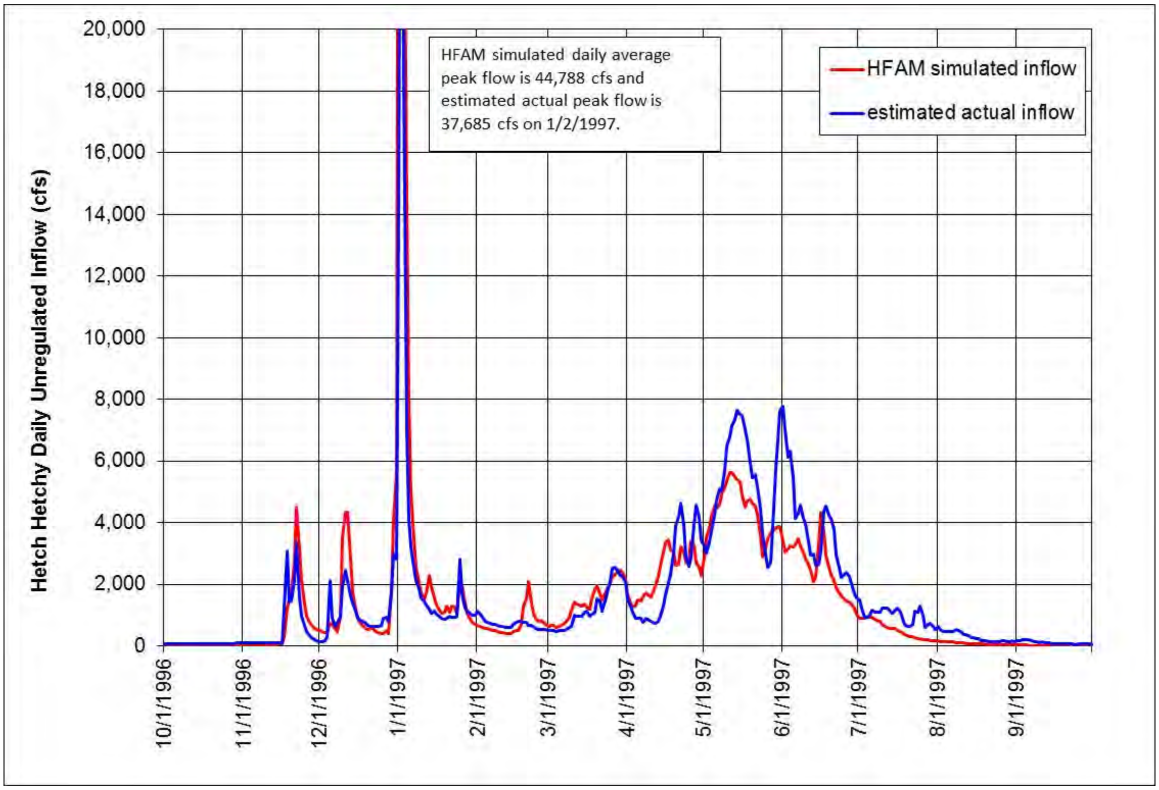


Figure B.23a Hetch Hetchy Daily Unregulated Inflow, water year 1997

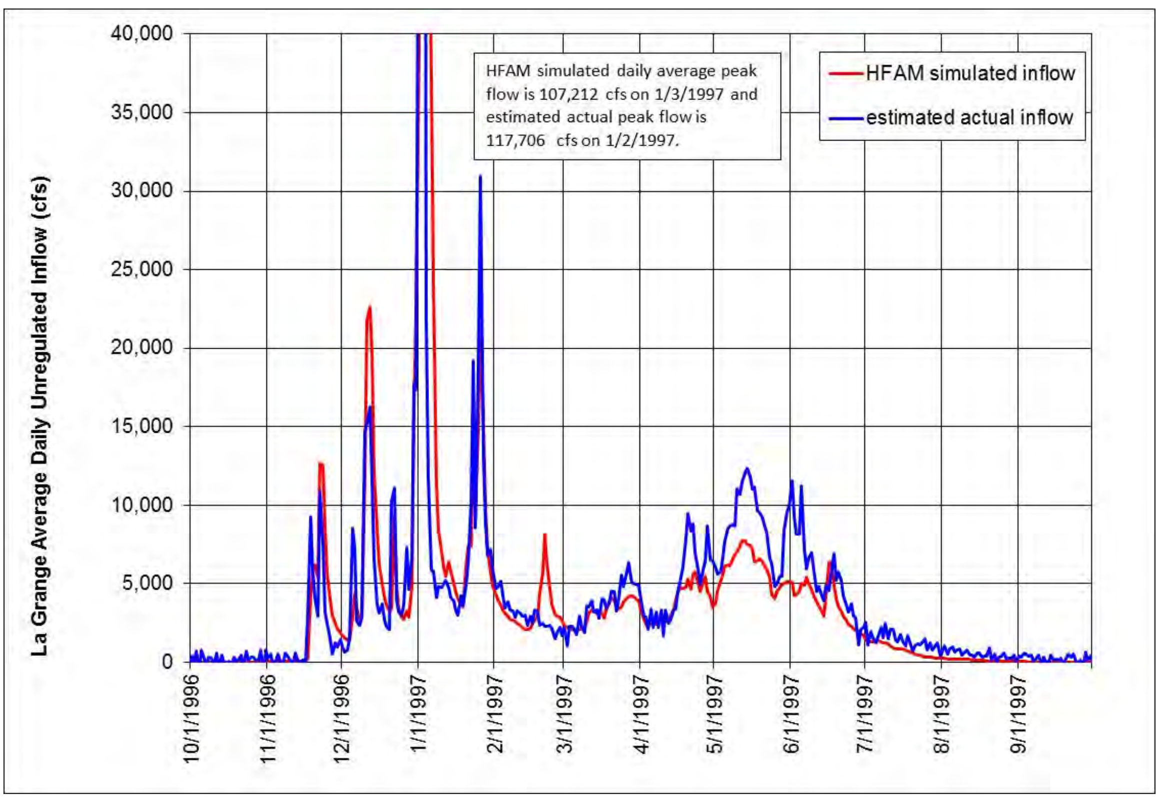


Figure B.23b La Grange Daily Unregulated Inflow, water year 1997

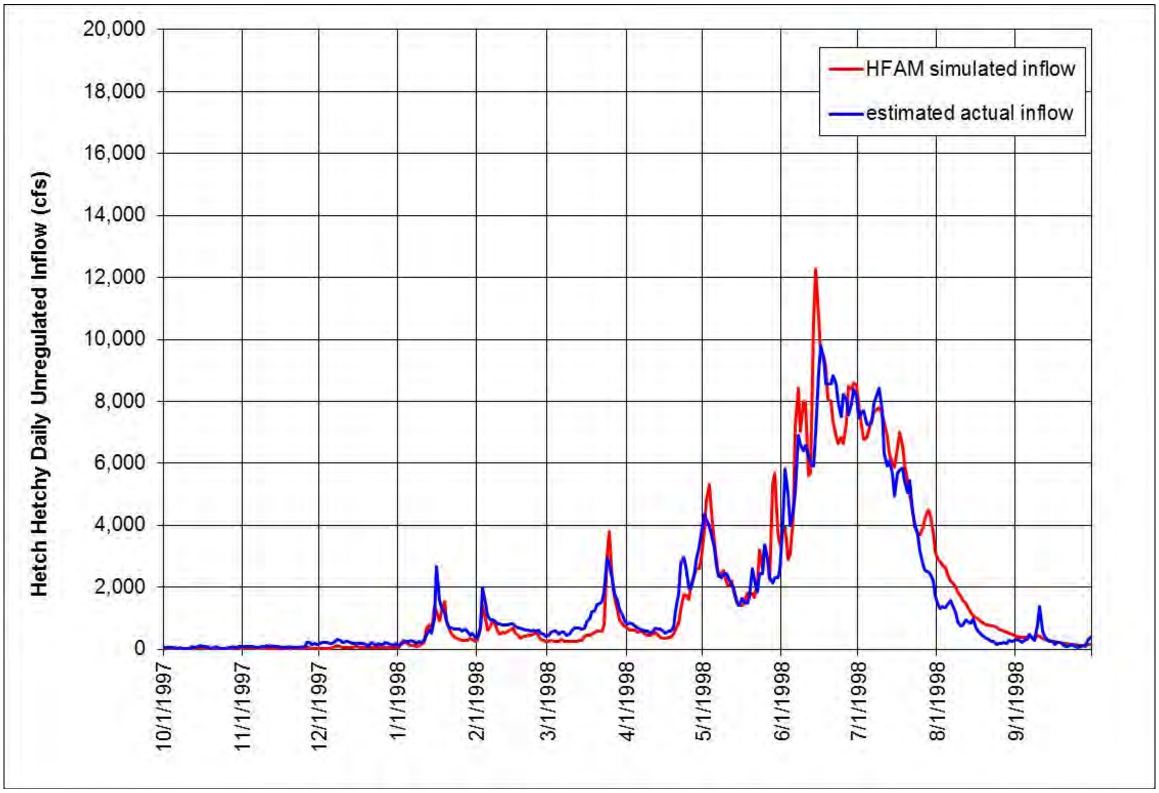


Figure B.24a Hetch Hetchy Daily Unregulated Inflow, water year 1998

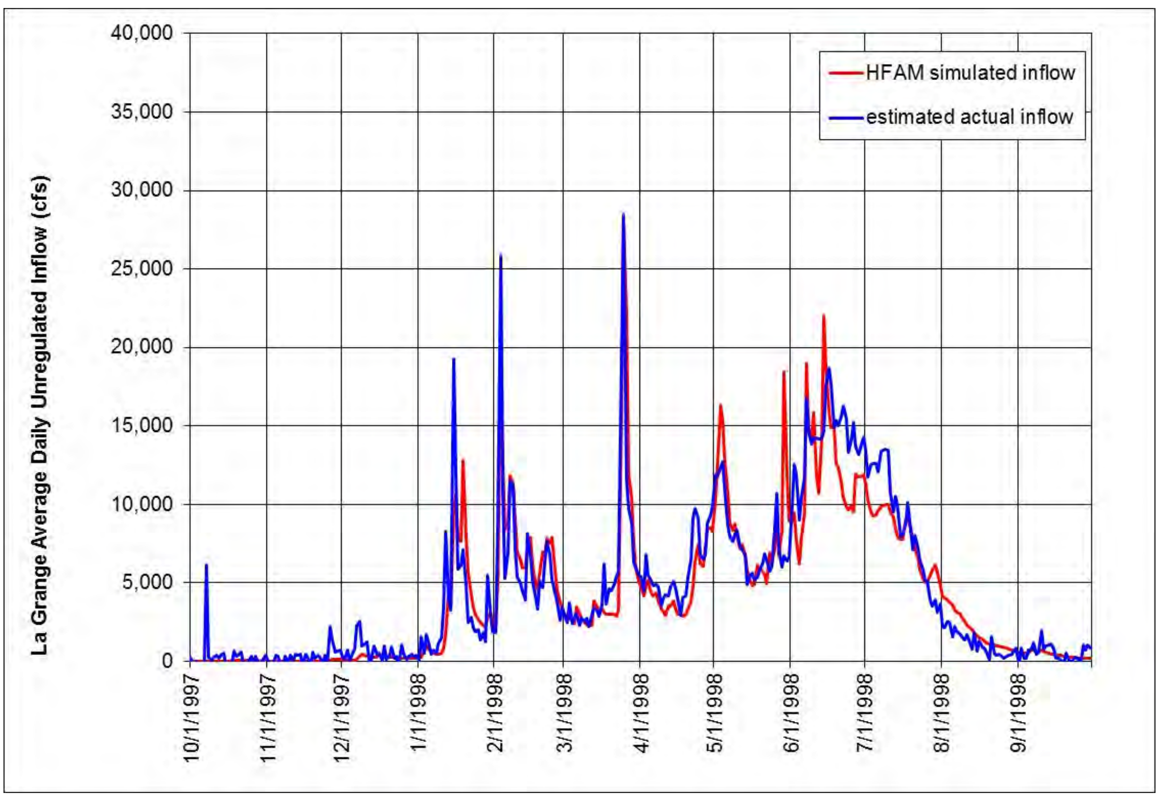


Figure B.24b La Grange Daily Unregulated Inflow, water year 1998

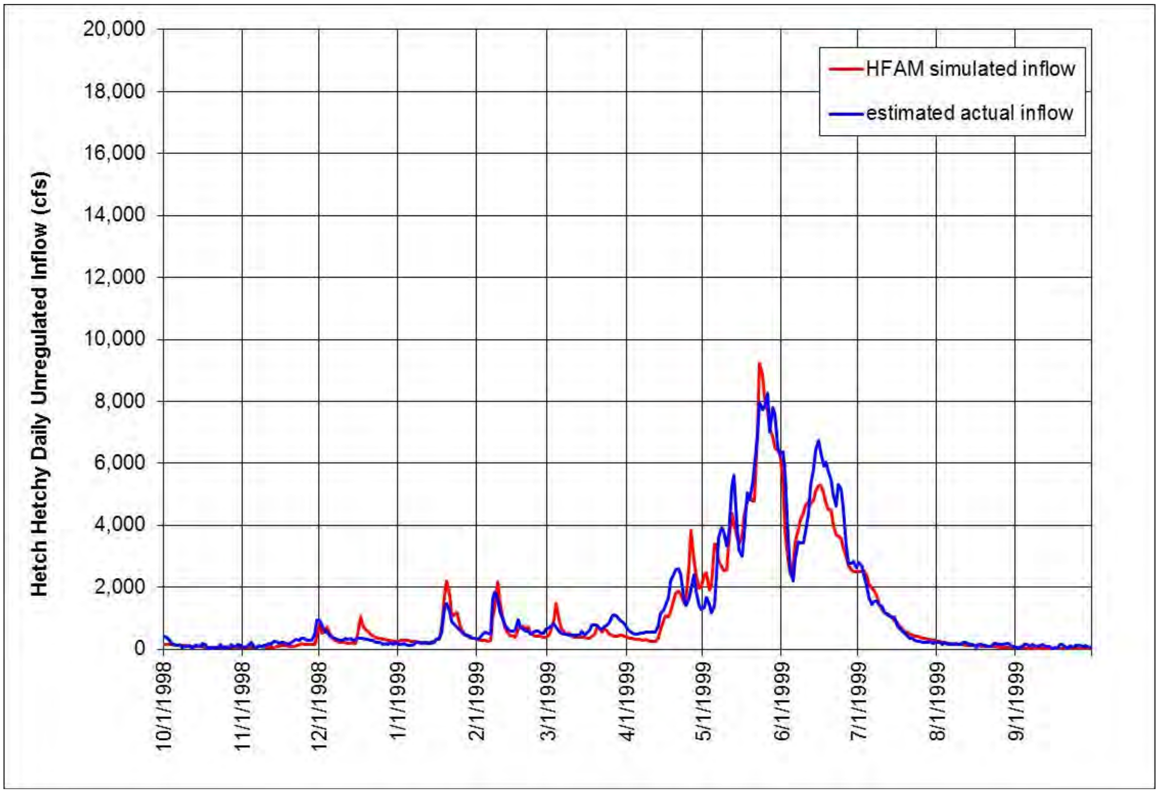


Figure B.25a Hetch Hetchy Daily Unregulated Inflow, water year 1999

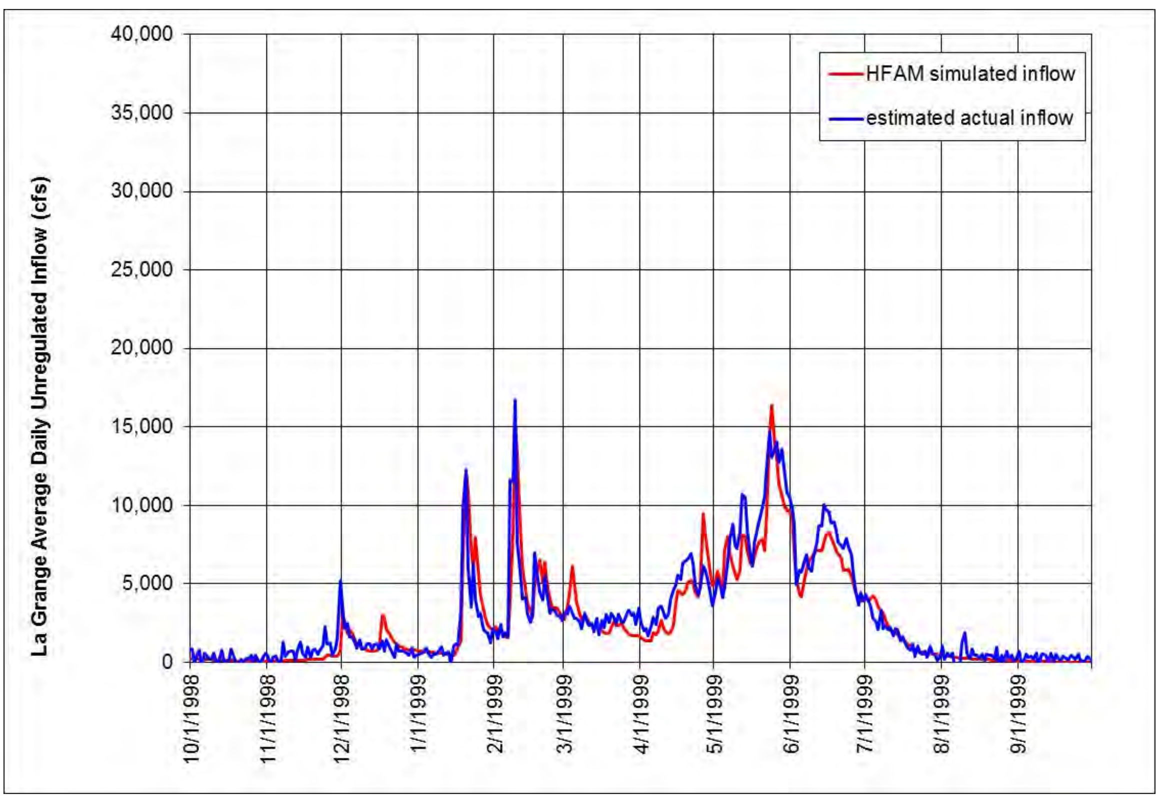


Figure B.25b La Grange Daily Unregulated Inflow, water year 1999

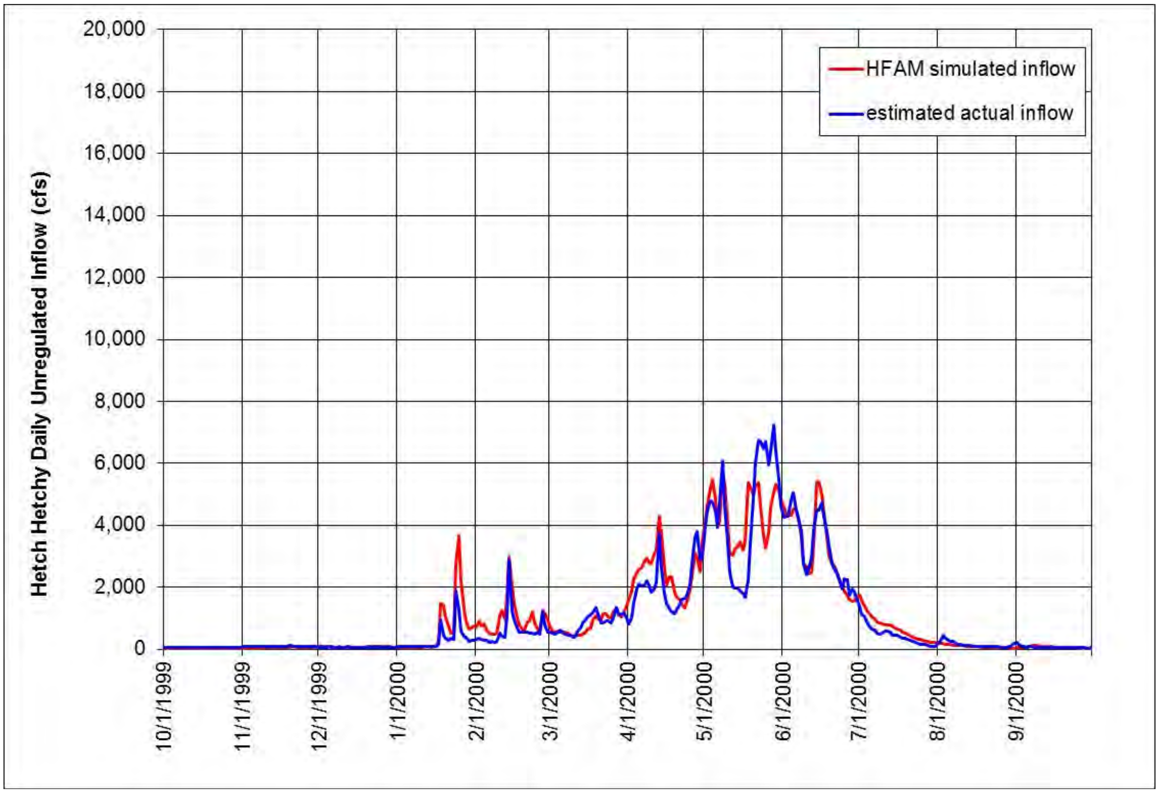


Figure B.26a Hetch Hetchy Daily Unregulated Inflow, water year 2000

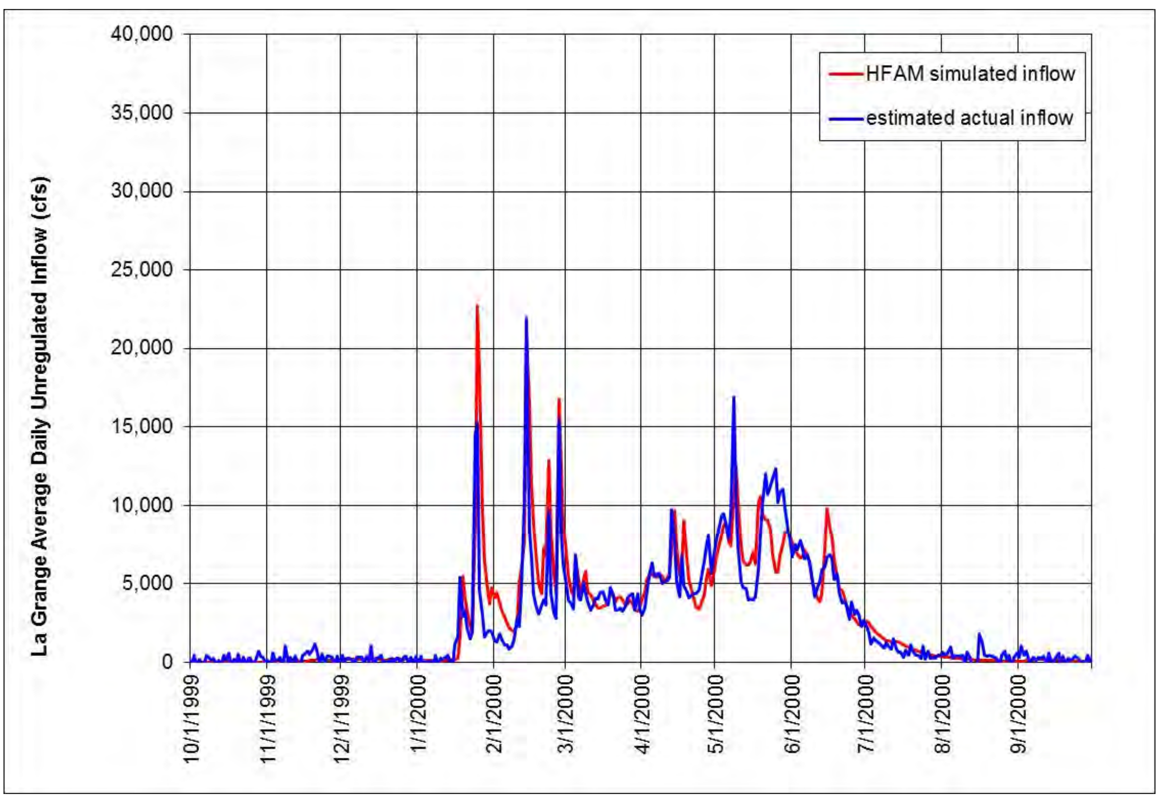


Figure B.26b La Grange Daily Unregulated Inflow, water year 2000

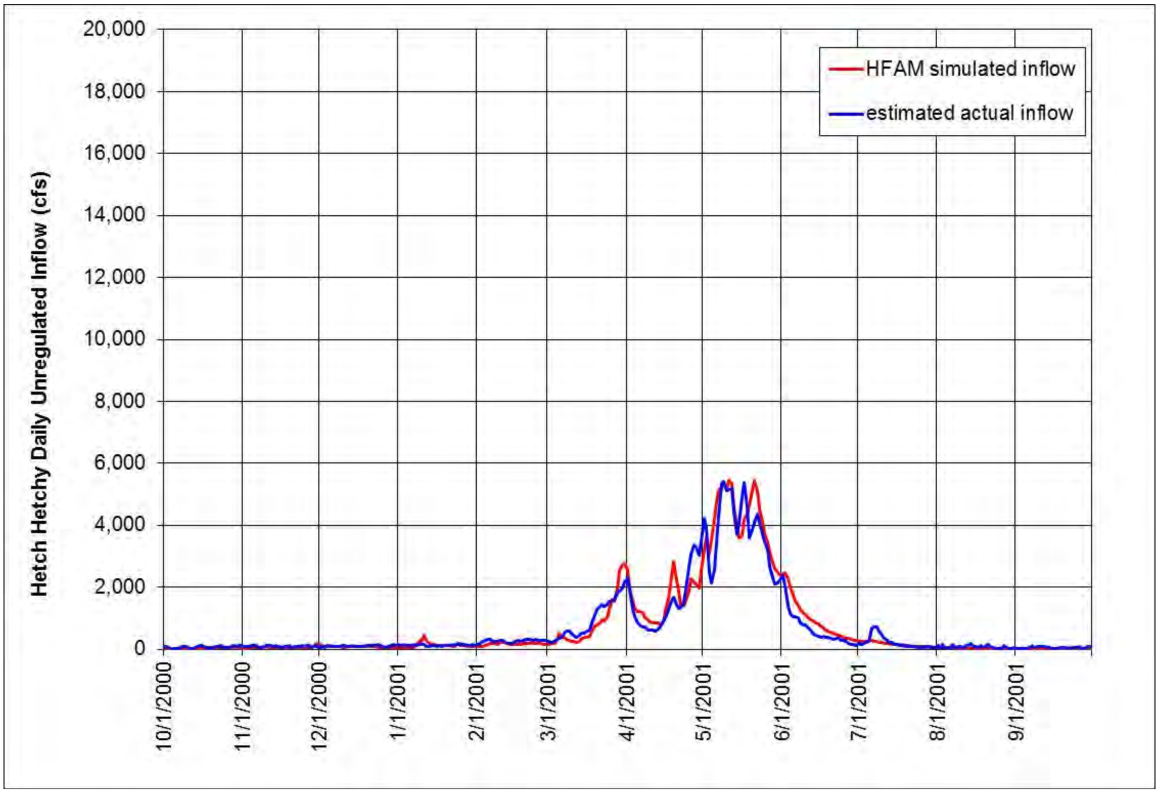


Figure B.27a Hetch Hetchy Daily Unregulated Inflow, water year 2001

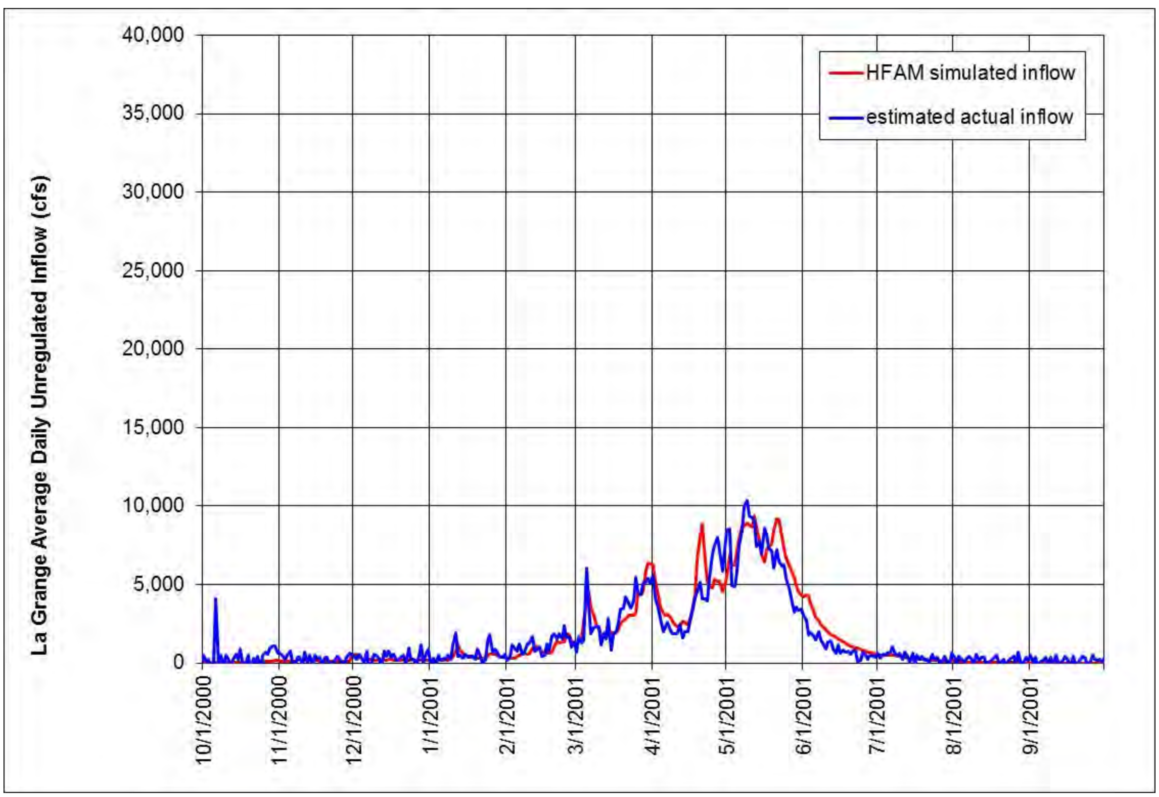


Figure B.27b La Grange Daily Unregulated Inflow, water year 2001

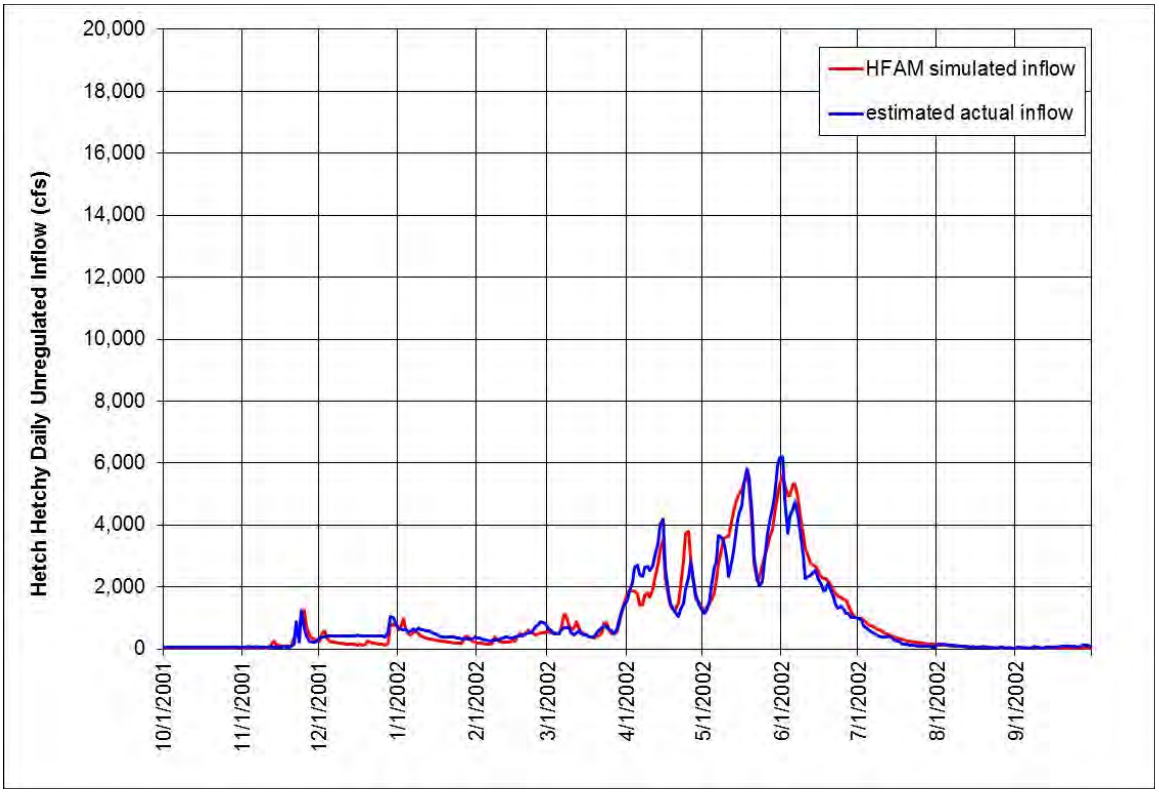


Figure B.28a Hetch Hetchy Daily Unregulated Inflow, water year 2002

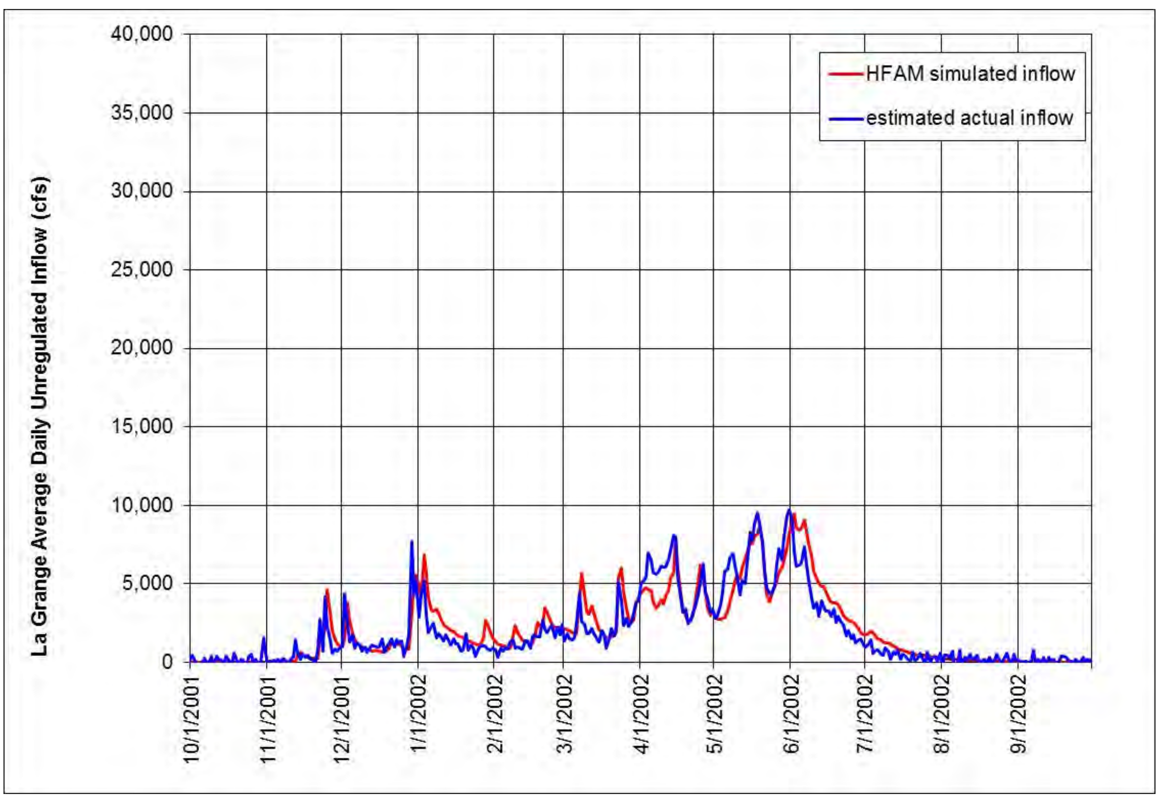


Figure B.28b La Grange Daily Unregulated Inflow, water year 2002

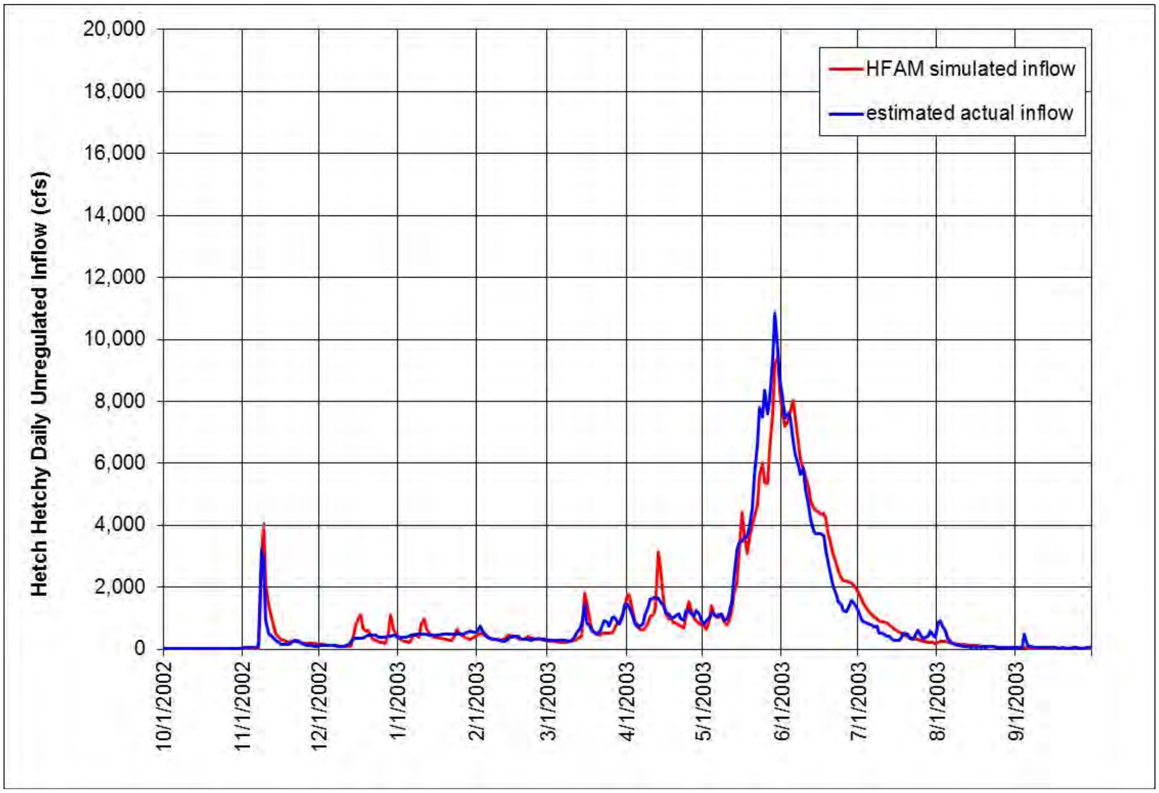


Figure B.29a Hetch Hetchy Daily Unregulated Inflow, water year 2003

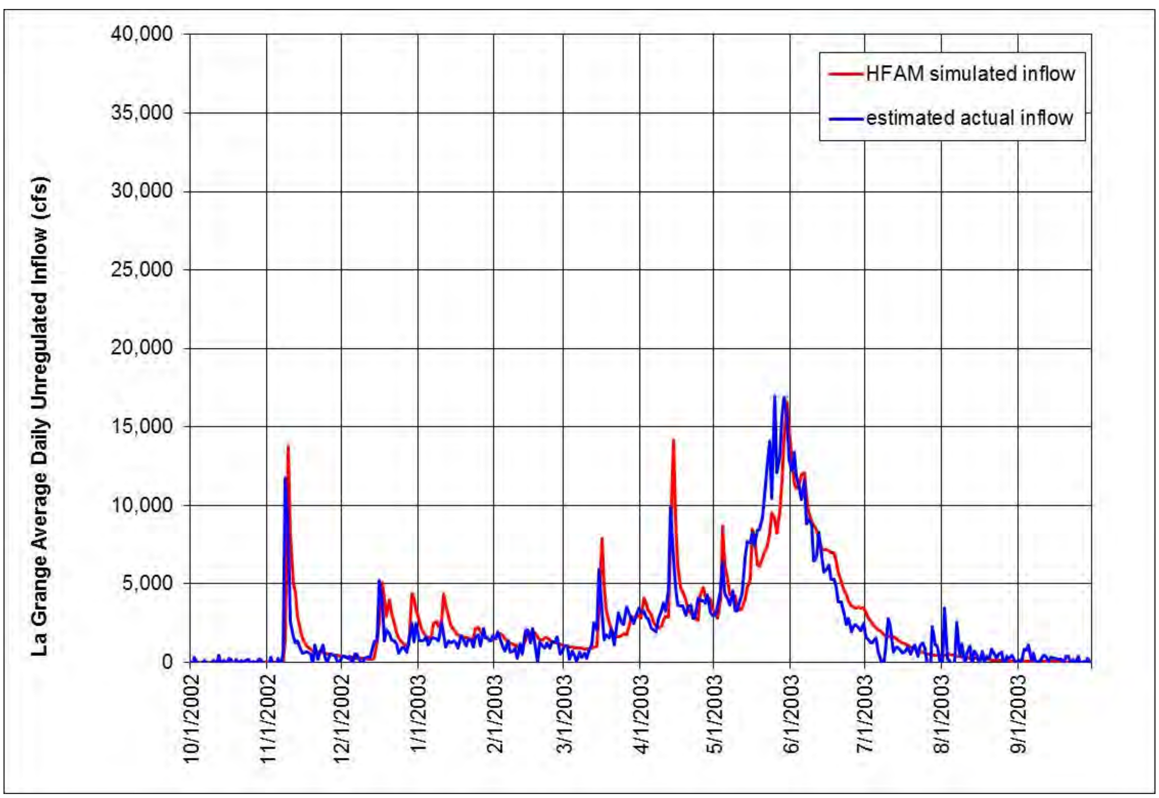


Figure B.29b La Grange Daily Unregulated Inflow, water year 2003

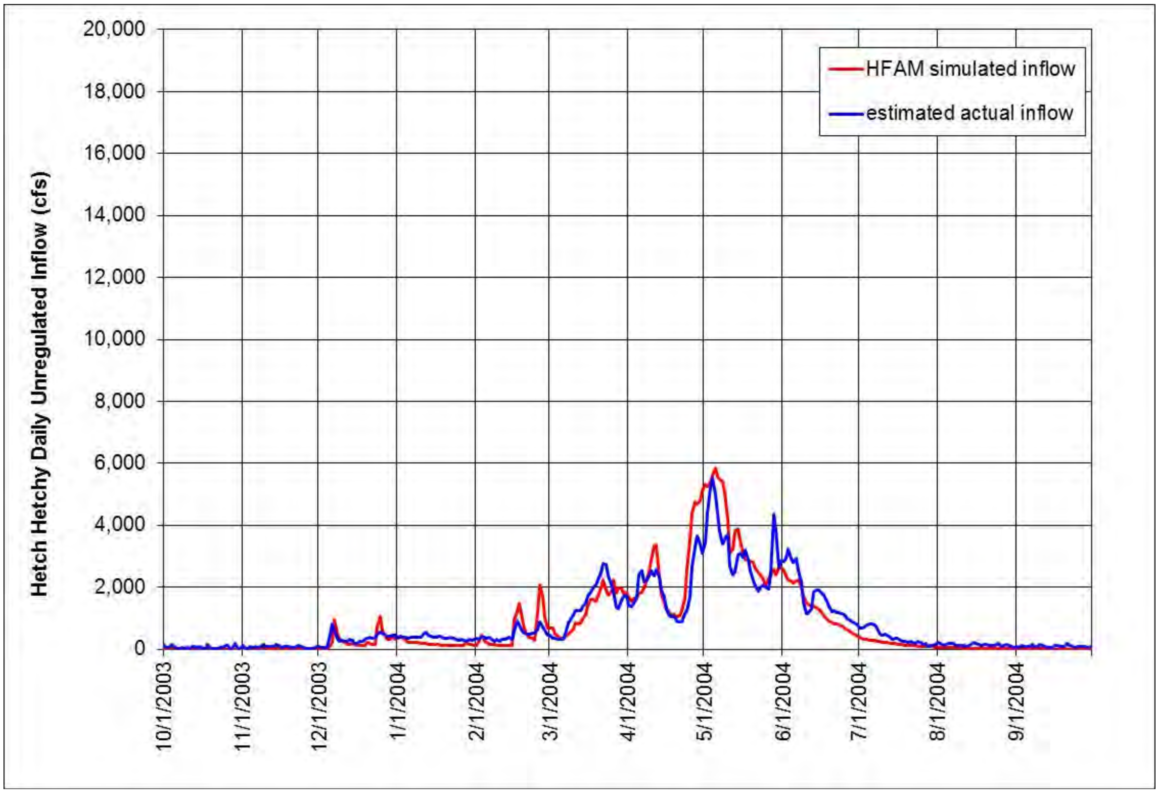


Figure B.30a Hetch Hetchy Daily Unregulated Inflow, water year 2004

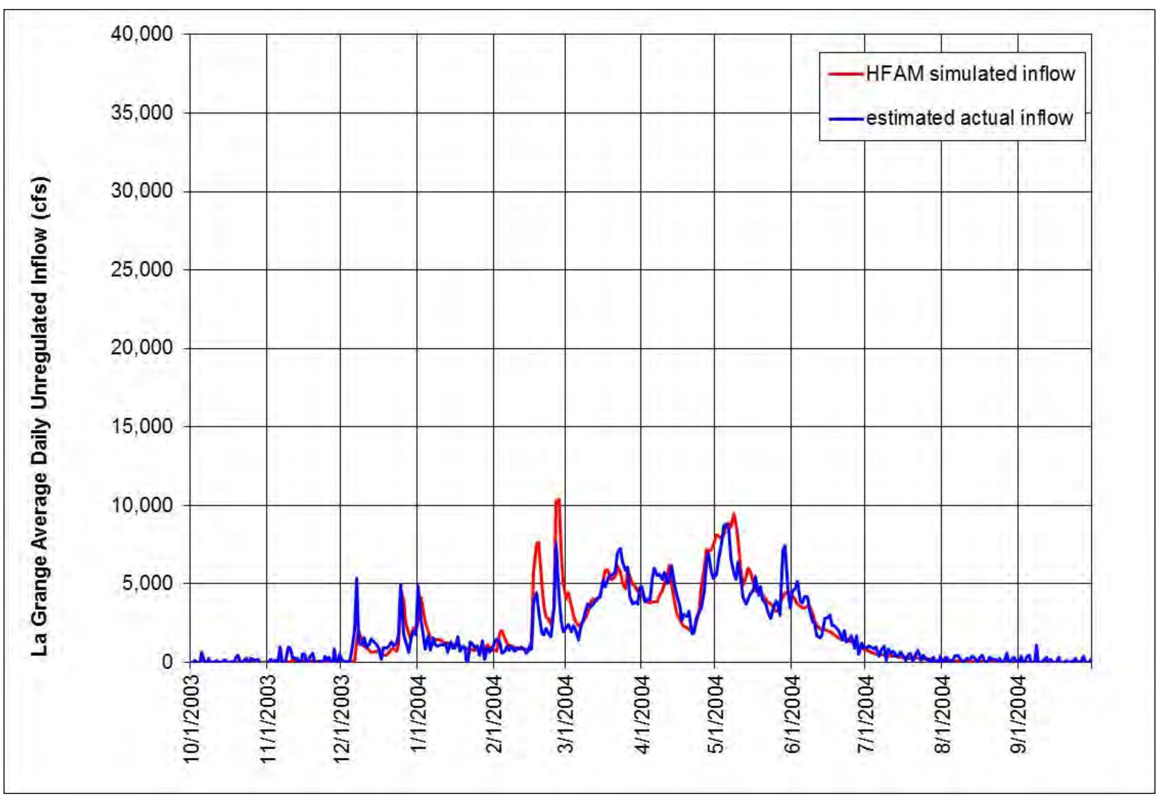


Figure B.30b La Grange Daily Unregulated Inflow, water year 2004

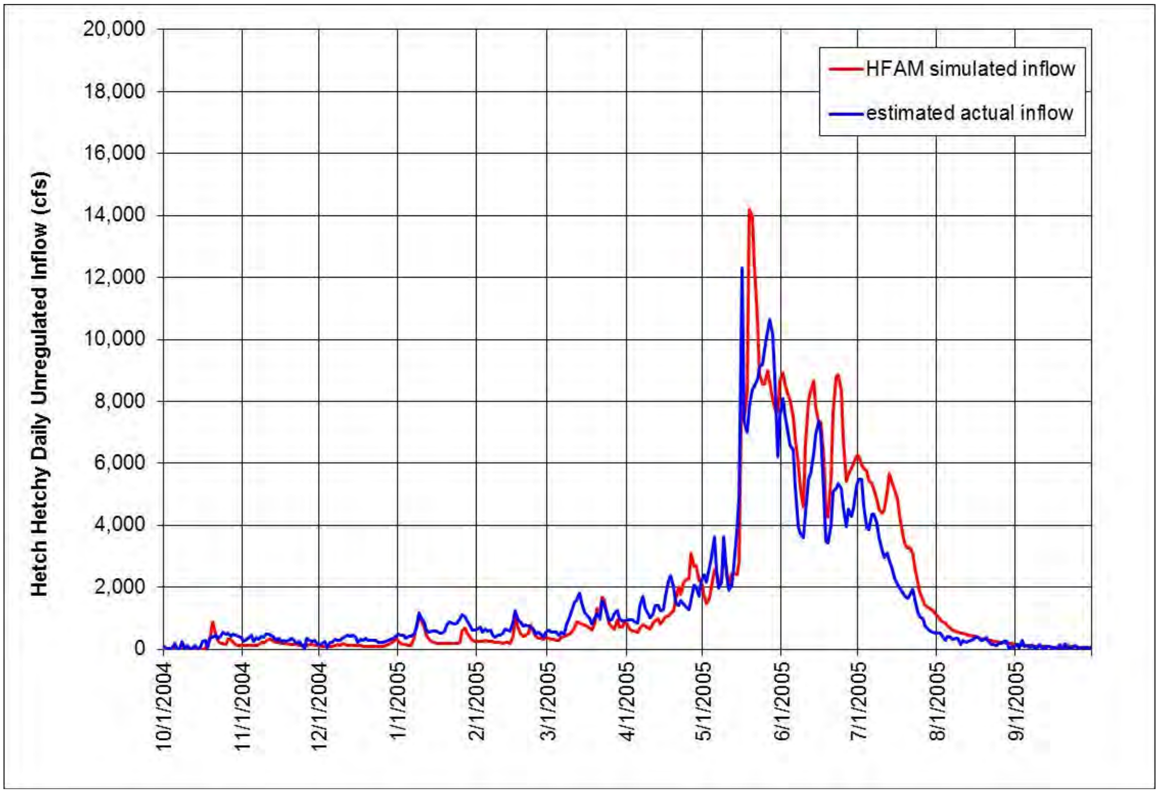


Figure B.31a Hetch Hetchy Daily Unregulated Inflow, water year 2005

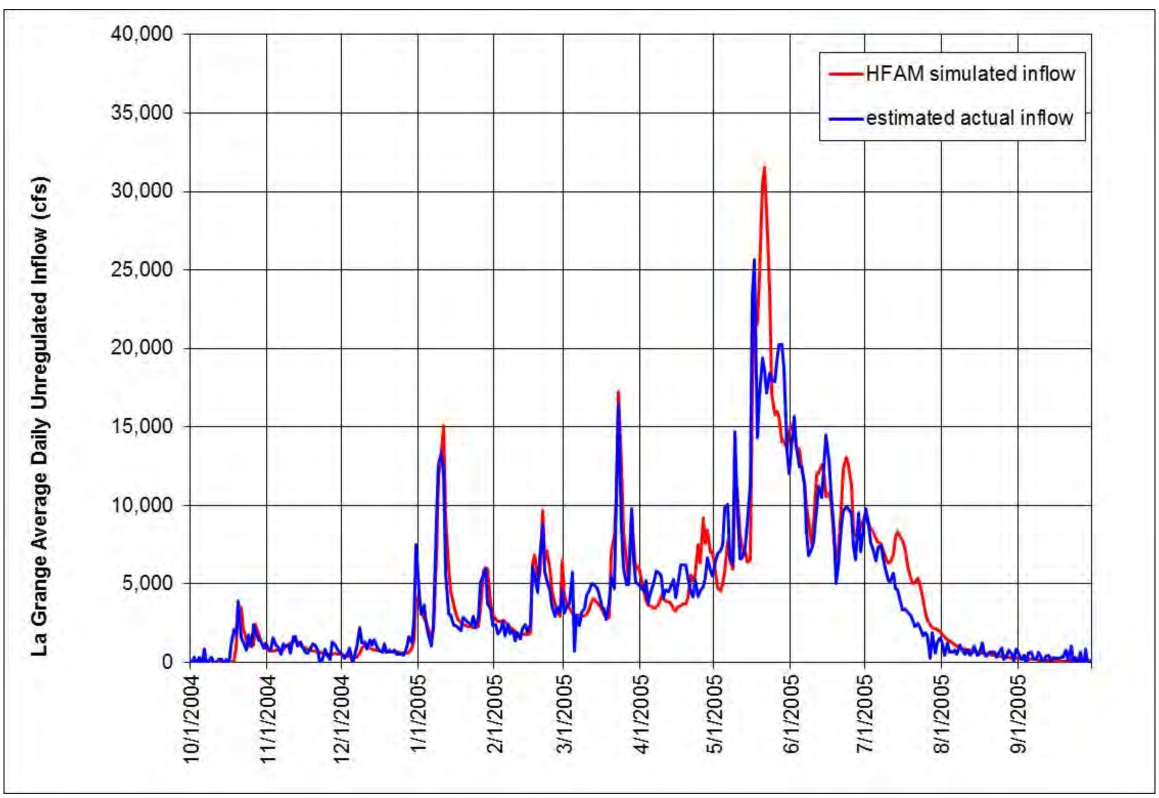


Figure B.31b La Grange Daily Unregulated Inflow, water year 2005

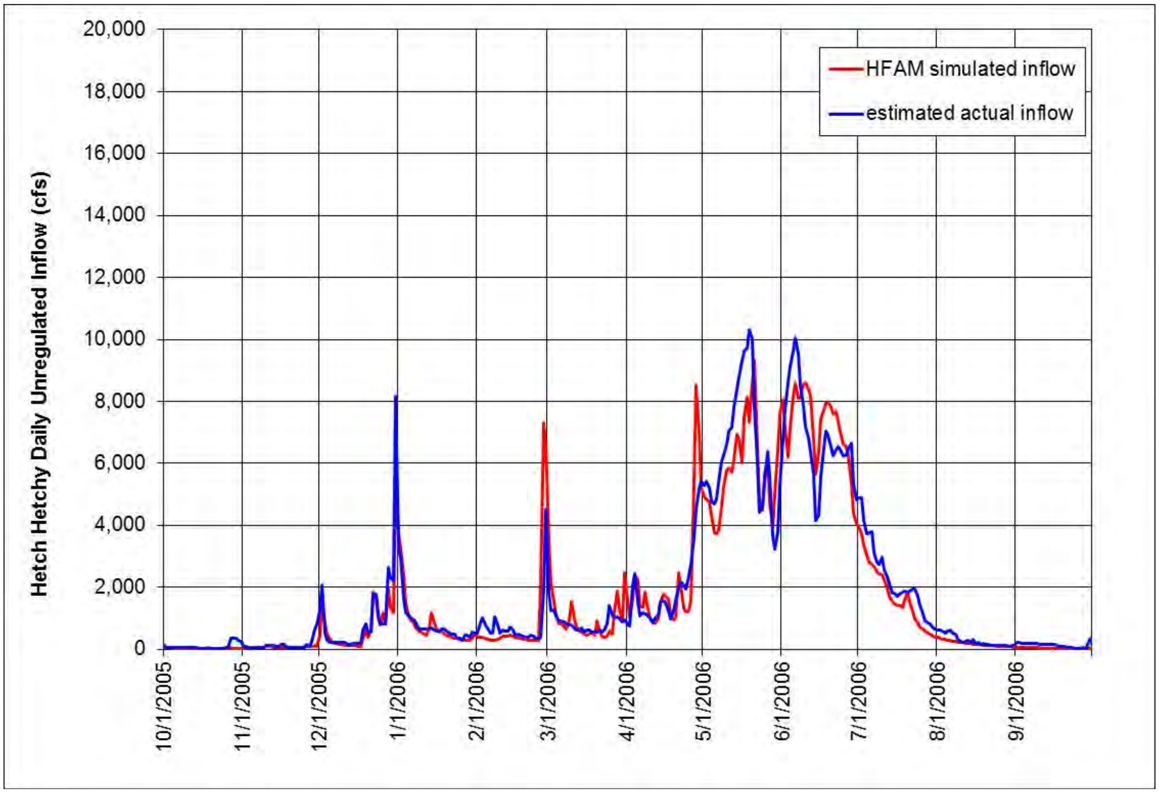


Figure B.32a Hetch Hetchy Daily Unregulated Inflow, water year 2006

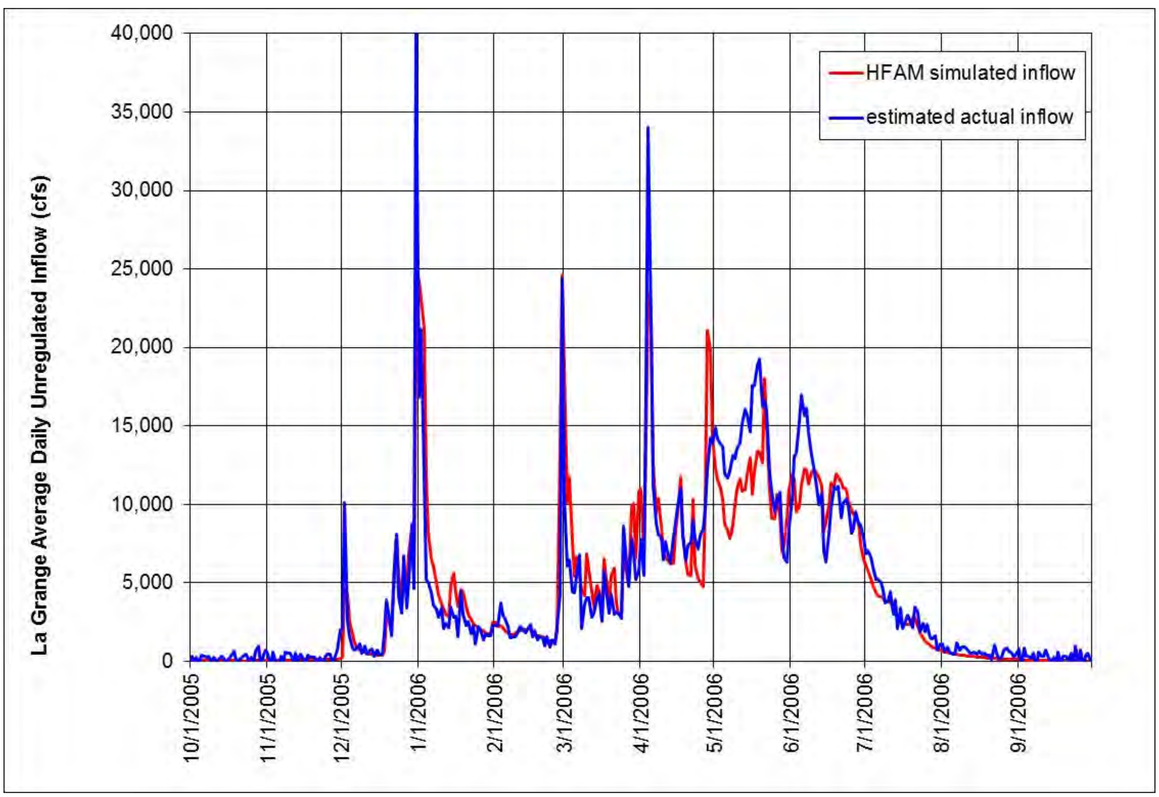


Figure B.32b La Grange Daily Unregulated Inflow, water year 2006

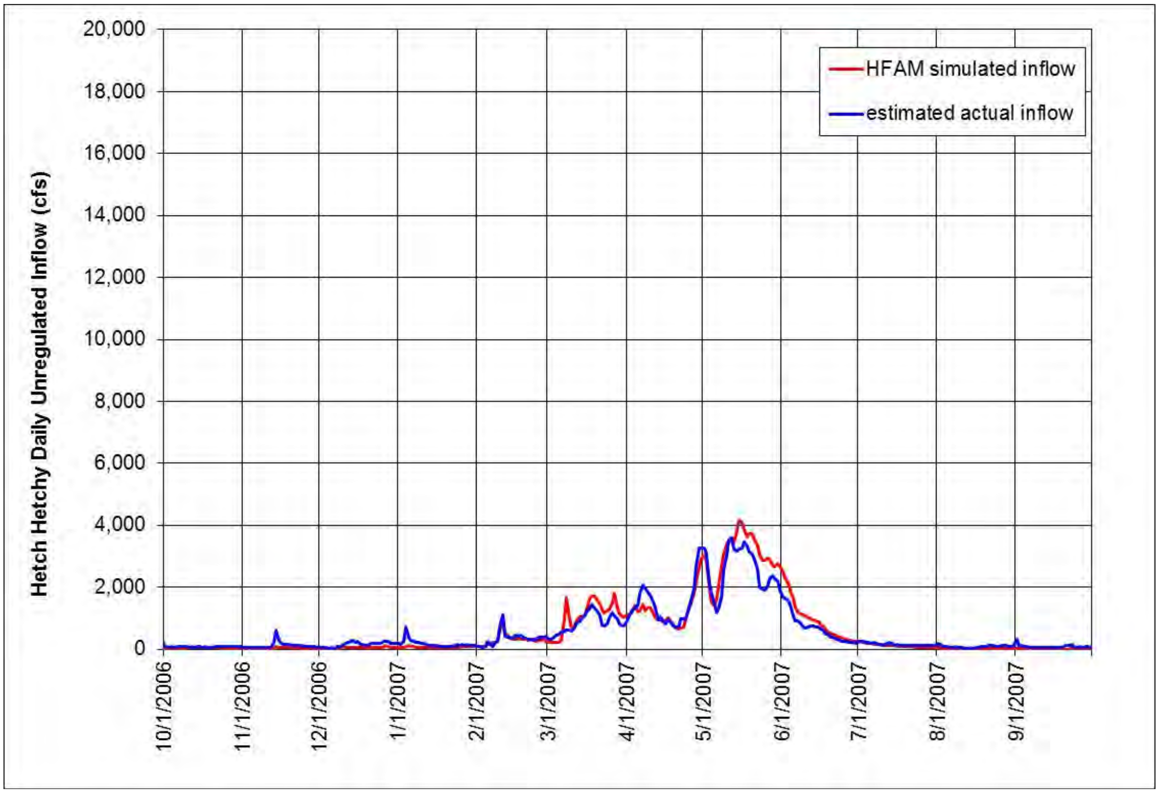


Figure B.33a Hetch Hetchy Daily Unregulated Inflow, water year 2007

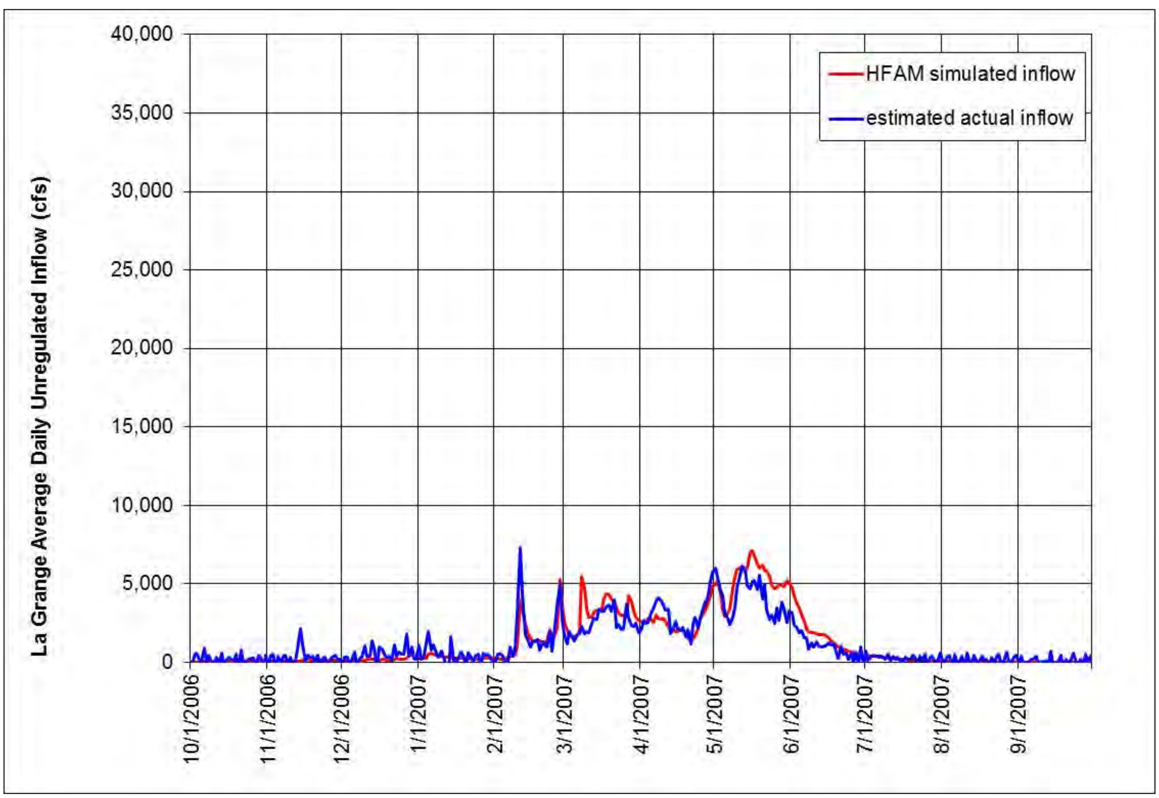


Figure B.33b La Grange Daily Unregulated Inflow, water year 2007

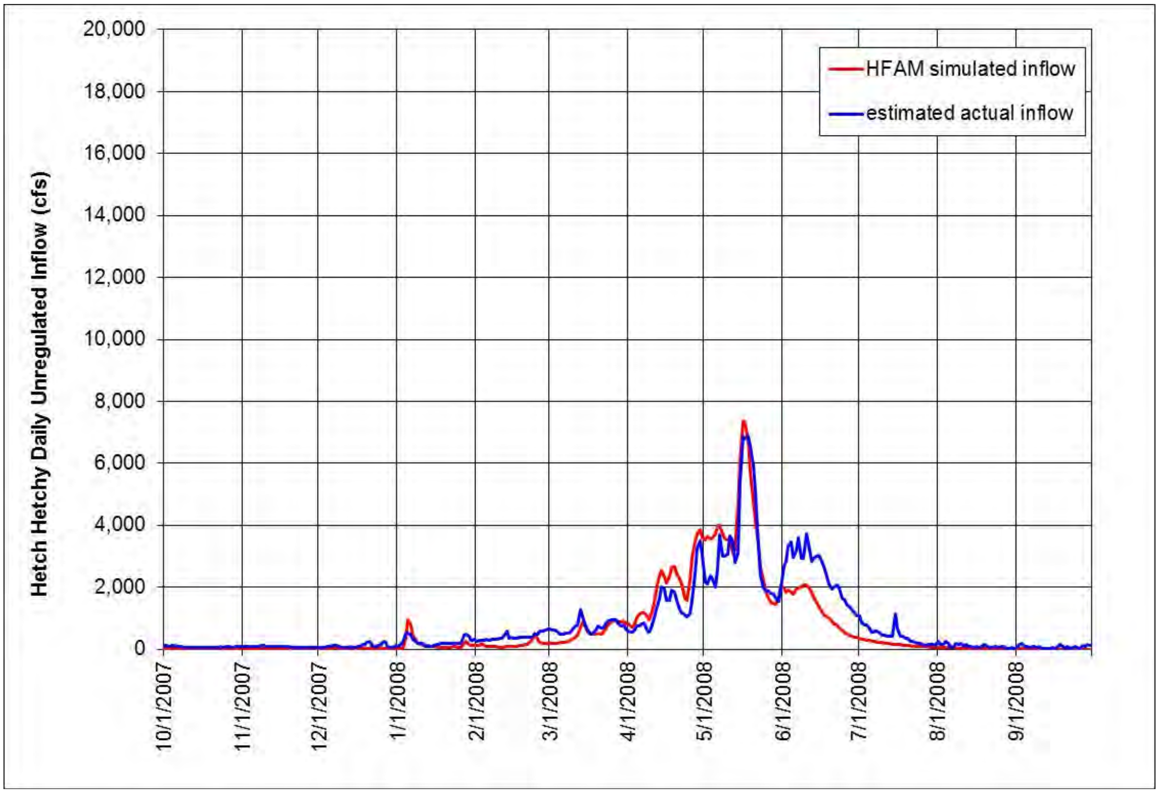


Figure B.34a Hetch Hetchy Daily Unregulated Inflow, water year 2008

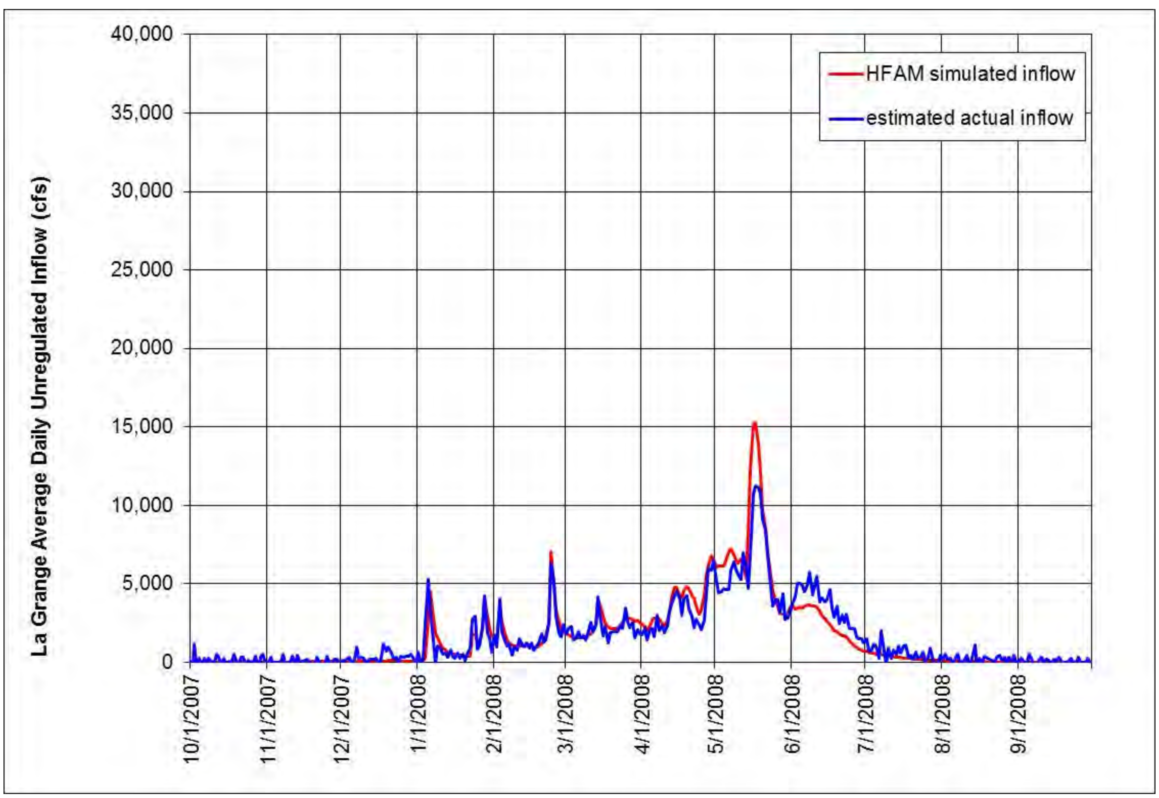


Figure B.34b La Grange Daily Unregulated Inflow, water year 2008

APPENDIX C

Long Term Meteorological Records at Hetch Hetchy and Cherry Valley

APPENDIX C

Long Term Meteorological Records at Hetch Hetchy and Cherry Valley

C.1 NOAA Substation History and Data Base Notes

A NOAA Substation History, published in 1958, shows installation of maximum-minimum temperature gages and a storage rain gage in 1910. No significant changes in location of the gages are listed from 1910 to 1958.The instruments appear to have remained in place to the present, except for the changes noted by Bruce McGurk.

In 1942, a recording rain gage was added at Hetch Hetchy. When the Tuolumne River modeling database was first established in 1998, hourly data were obtained from NCDC for Hetch Hetchy from 1948 to 1996. Overall, the hourly data were only 91 percent complete and the storage rain gage data were more reliable.

When only daily total precipitation data are available, patterns of hourly precipitation distributions for similar daily total precipitation are used. An hourly distribution, randomly selected from a collection of distributions, is used to create hourly data for the day. Hourly distributions are seasonally dependent.

The NOAA Substation History in 1958 includes the Cherry Valley station, installed in October 1955, and states that the instruments are “on the ground, well shaded by surrounding trees”.

C.2 Summary of notes and photographs provided by Bruce McGurk, Operations Manager & Hydrologist, Hetch Hetchy Water & Power - Moccasin in May 2009

The Hetch Hetchy station (HTH) has been at the same site since 1930. The glass maximum and minimum thermometers and standard 8 inch NWS manual brass rain gauge were serviced about 8 am, 7 days per week through 9/13/86 by Hetch Hetchy Water and Power (HHWP) watershed keepers. A retired watershed keeper, who spent 6 months at O’Shaughnessy when he joined HHWP in 1975, described the station as it was in 1975 in a recent phone conversation. His description matches what is there now, with one important change. The thermometers were then in the cotton-belt shelter across the road, about 25 ft. from the rain gauge (Photo 1).

Photo 1. Hetch Hetchy rain gauge and road

The temperature shelter now is on the north side of a cluster of live oak trees, and the shelter is now on the north side rather than the south side of a 12 ft. wide blacktop road. The shelter is about 10 ft. from the road and has shading during a lot of the day, as it did prior to 1986; the view east is occluded by a deciduous and a conifer, and the view west is also mostly shaded but might get late afternoon sunshine in summer.

The rain gauge is on the south side of a 6 ft. patch of evergreen shrubs (Photo 2), the road and conifers to the east, and is fairly open to the west and south. The gauge has no windscreen, which is the normal setup for a NOAA gauge.

Photo 2. Hetch Hetchy rain gauge and evergreen shrubs

The manual rain gauge and the cotton belt shelter have not moved, but on 9/13/1986, a Fisher-Porter 8 inch recording gauge was installed next to the manual can and a new temperature system was installed that was far from optimal. NOAA decided at that time to change from glass thermometers (breakage issues, mercury, etc.) to electronic systems through their system, and installed a thermistor network sensor. NOAA also changed to a naturally aspirated sensor shelter and abandoned the cotton-belt shelter at that time. The new temperature shelter was apparently fastened to the railing of the watershed keeper's house for several years – in February 2006 (Photo 3) you can just see the white blob in front of the blue truck on a railing below the porch roof. Last year it was put on a pole 10 ft. away in the yard, and that is a better site. Being next to the building and only about 3 ft. off the ground was not the NOAA standard. However, there is still a lot of shade there, especially afternoon in the summer, but there is an oak that sheds its leaves and probably leaves the shelter exposed to the sun in the winter time.

Photo 3. Hetch Hetchy temperature gauge

The climate station near Cherry Dam (CHV) has had less change. It is behind the bunkhouse that was built in the 1950's when Cherry Dam was built (see Photo 4). I tracked the station back to 1975, and it is still using the same gage and glass thermometers, and has been consistently serviced by watershed keepers. I do not believe it is an official NOAA site, so it never got the automatic rain gauge or the electronic thermistor setup. The shelter and temperature sensors are shown in Photo 5. A paved parking area is closer than optimal and the access road is near as well.

The Hetch Hetchy and Cherry climate stations may have had vegetation and shading changes over this long time period. I have not researched photos of the Hetch Hetchy site back when the road was a train

Photo 4. Cherry Valley climate station

Photo 5. Cherry Valley shelter and temperature sensors

APPENDIX D

Snow Accumulation and Melt with Climate Change

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Snow Accumulation and Melt with Climate Change

The Tuolumne River watershed's range in elevation and its diverse topography, soils, forests and vegetation is amenable to large-scale snow accumulation and melt process analysis, rather than small-scale analysis that might be done on an experimental watershed. The observed runoff at gages comes from multiple land segments. These land segments are at different elevations, and will have different aspect and shading from solar radiation. Snowpack water yield on a given day may occur only in a limited elevation range.

Real-time stations with snow pillow measurements of snow water equivalent do allow process analysis and comparisons between historic conditions and climate change scenarios. In the following figures, simulated Slide Canyon (SLI) snowpack conditions are compared to historic snow measurements for water year 1992. Slide Canyon is at 9200 feet elevation. Figure D-1 shows Slide Canyon observed and simulated snow water equivalent and liquid water in water year 1992. Figure D-2 shows the same model results for late March, April and May of water year 1992.

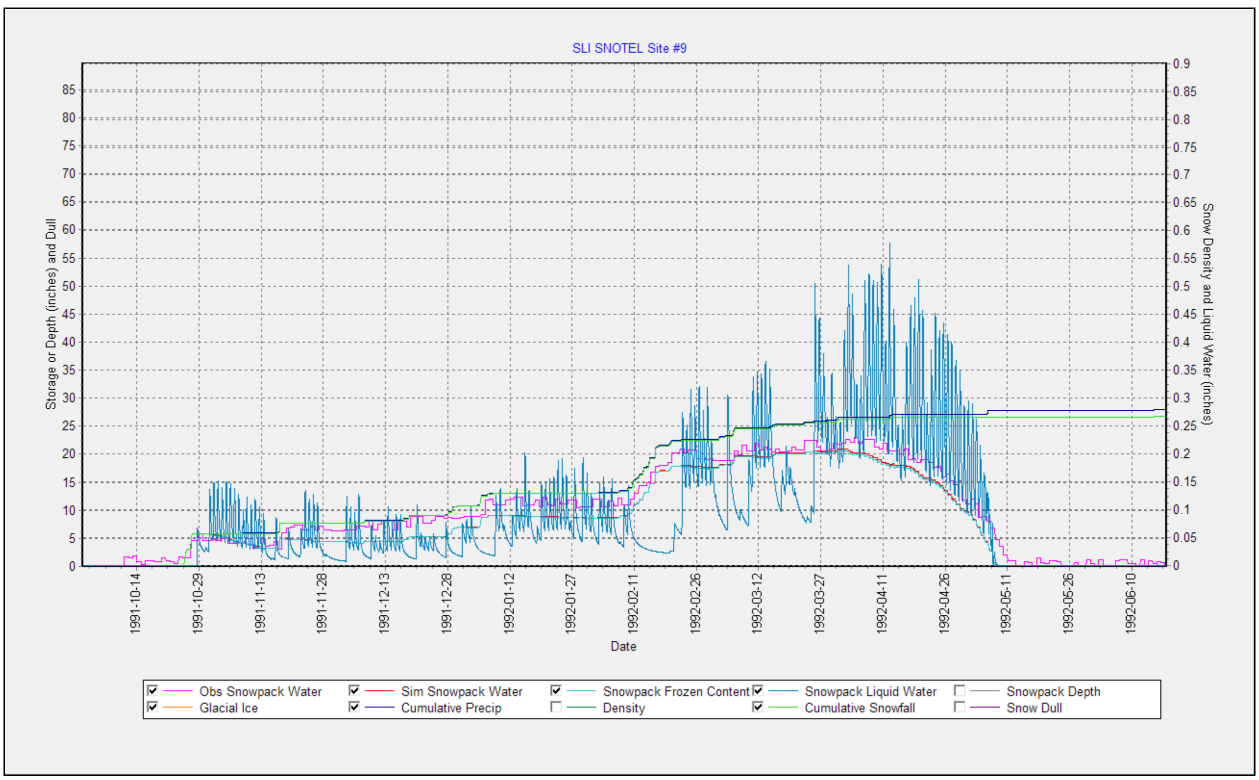

Figure D-1. Slide Canyon observed (pink) and simulated snow water equivalent (red) and liquid water content of the snowpack (blue), water year 1992

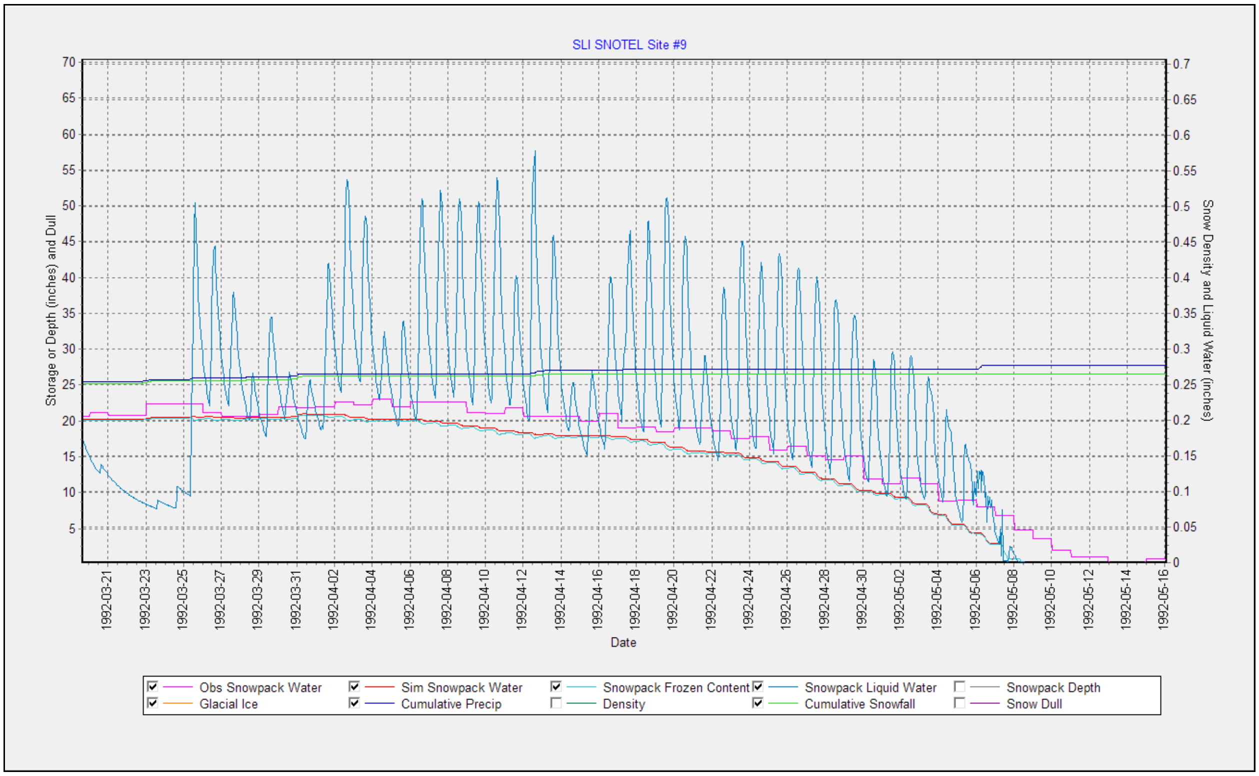

Figure D-2. Slide Canyon observed (pink) and simulated snow water equivalent (red) and liquid water content of the snowpack (blue), March to May, water year 1992.

For each of the climate change scenarios, hourly temperature adjustments were made based on the expected average daily temperature increase and the corresponding change in the maximum and minimum daily temperatures. The simulated snowpack depth is reduced due to these higher temperatures.

Figure D-3 shows Slide Canyon observed historic and simulated climate change scenario 2A in 2100 snow water equivalent and liquid water content in the snowpack. For climate change scenario 2A in 2100 (moderate temperature increase of 3.4 degrees C/6.12 degrees F with no change in precipitation), less snow accumulates than under current conditions because some precipitation that historically fell as snow was simulated as rainfall. Simulated snow depth reaches only 10 inches water equivalent compared to 21 inches water equivalent for historic conditions. The simulated climate change scenario 2A in 2100 results are based on water year 1992 meteorological conditions with the temperature adjustments for climate change scenario 2A in 2100.

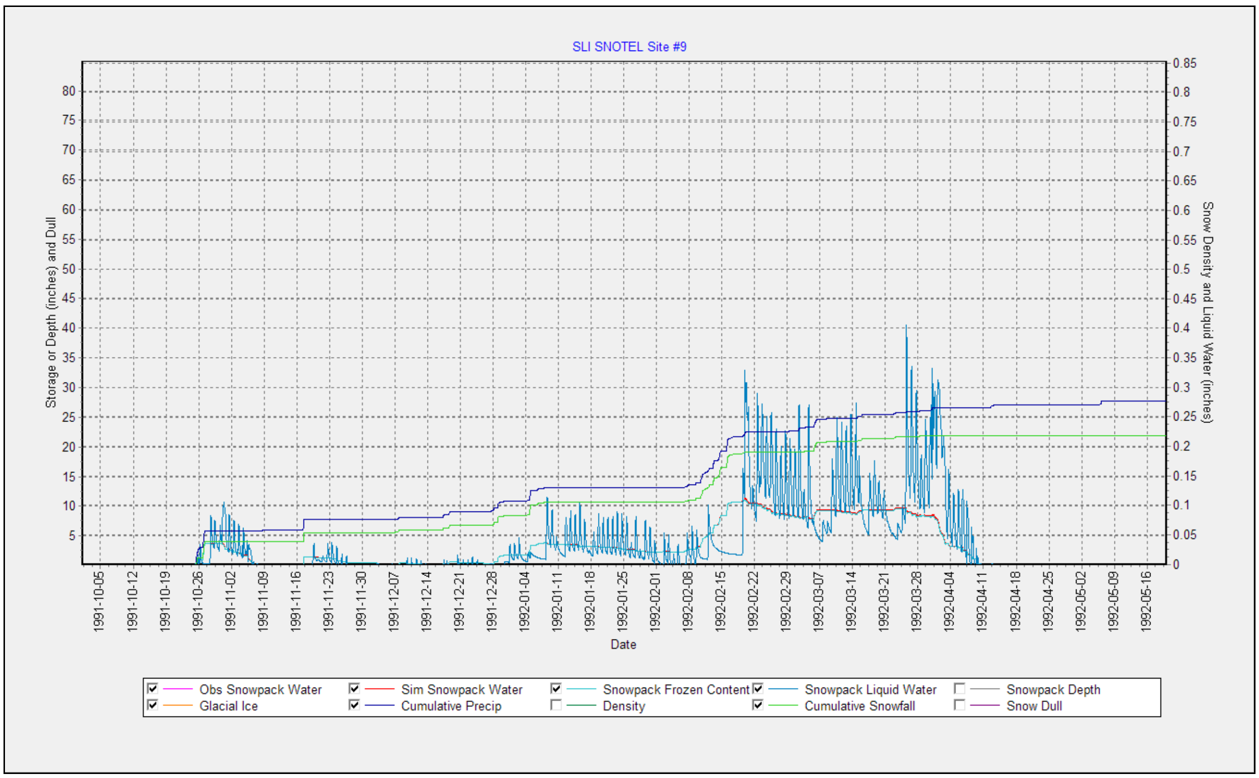

Figure D-3. Slide Canyon observed (pink) and scenario 2A in 2100 snow water equivalent (red) and liquid water content (blue) of the snowpack, water year 1992

Figure D-4 shows details of the snowpack melt out for climate change scenario 2A in 2100. The period of significant melt under the future climate conditions, April 1st to 10th, did not experience significant melt out historically – the historic 'obs snowpack water' in Figure D-4 show only minor melt in March and early April.

The snowpack melts out by April 10, 1992 for climate change scenario 2A in 2100, compared to May 8, 1992 for historic conditions.

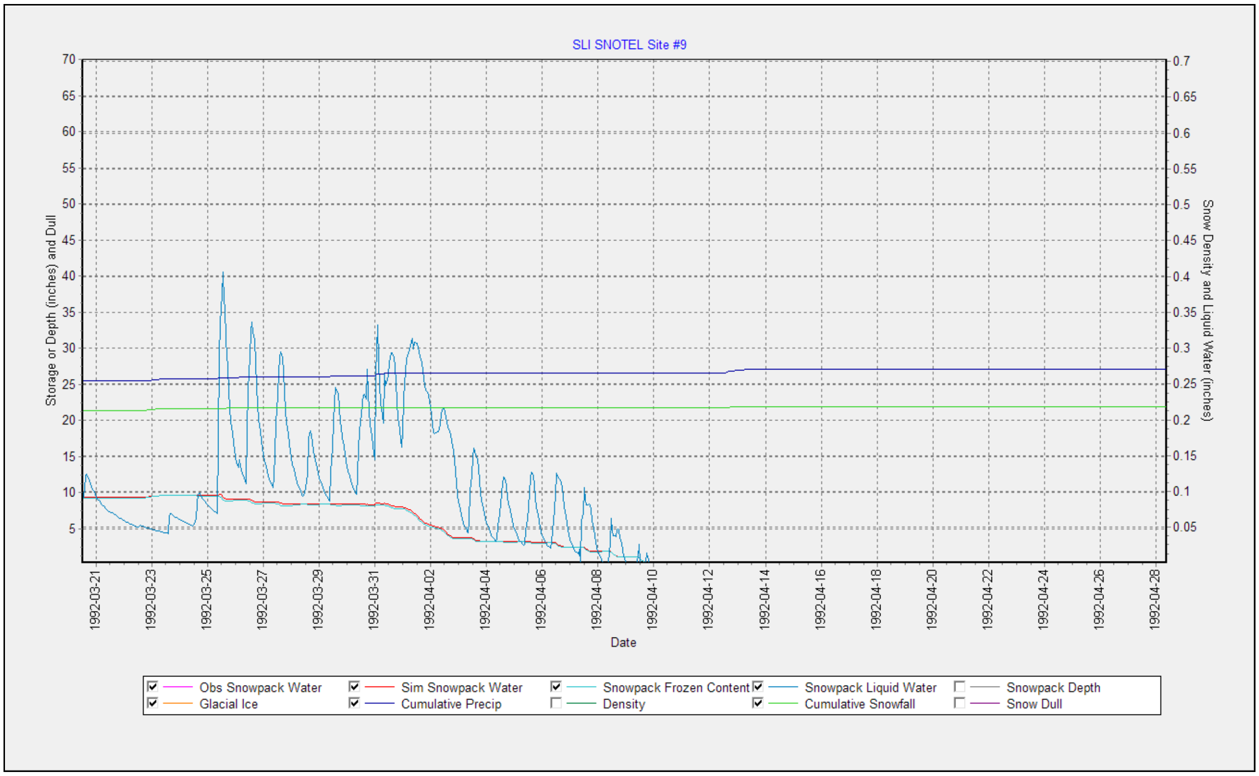

Figure D-4. Details of the Slide Canyon snowpack melt out for scenario 2A in 2100

Figure D-5 shows Slide Canyon simulated historic snowpack albedo, air temperature and solar radiation, solar radiation, negative heat, snow melt and snow yield (water leaving the snowpack) in water year 1992. Figure D-6 shows the same information during only the melt out period of water year 1992.

During the fall and winter with historic conditions, there is little or no water yield from the snowpack. Negative heat builds during the night whenever the snowpack cools below 0 degrees C. The snow must warm to 0 degrees C before melt can occur. Figure D-5 shows that melt does occur in fall and winter, but melt that enters liquid water storage will often re-freeze at night when the net heat exchange between the atmosphere and the snowpack becomes negative and the snowpack cools.

In Figure D-6, it can be seen that warmer night time temperatures reduce or prevent the increase of negative heat during the night time and the snowpack remains at 0 degrees C. The liquid water holding capacity of the snowpack is exceeded, melt occurs, and water leaves the snowpack.

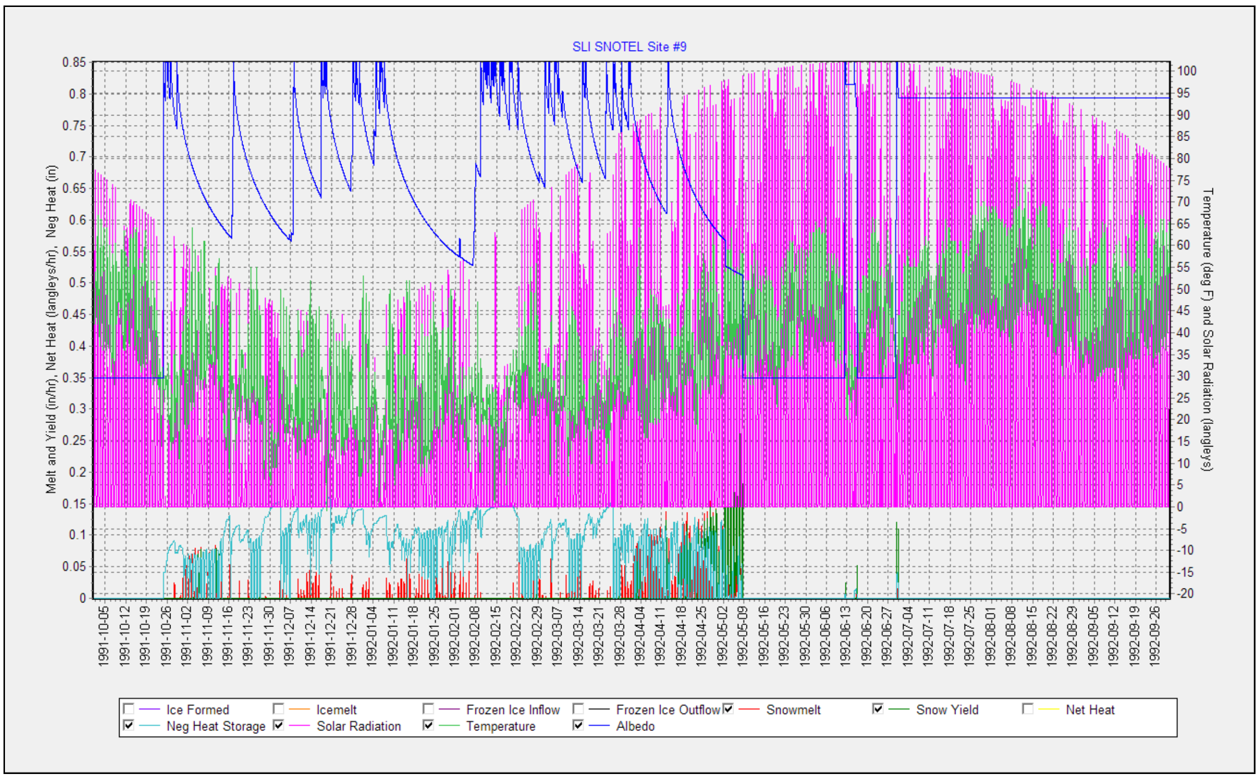

Figure D-5. Slide Canyon simulated historic snowpack albedo, air temperature, solar radiation, negative heat, snow melt and snow yield, water year 1992

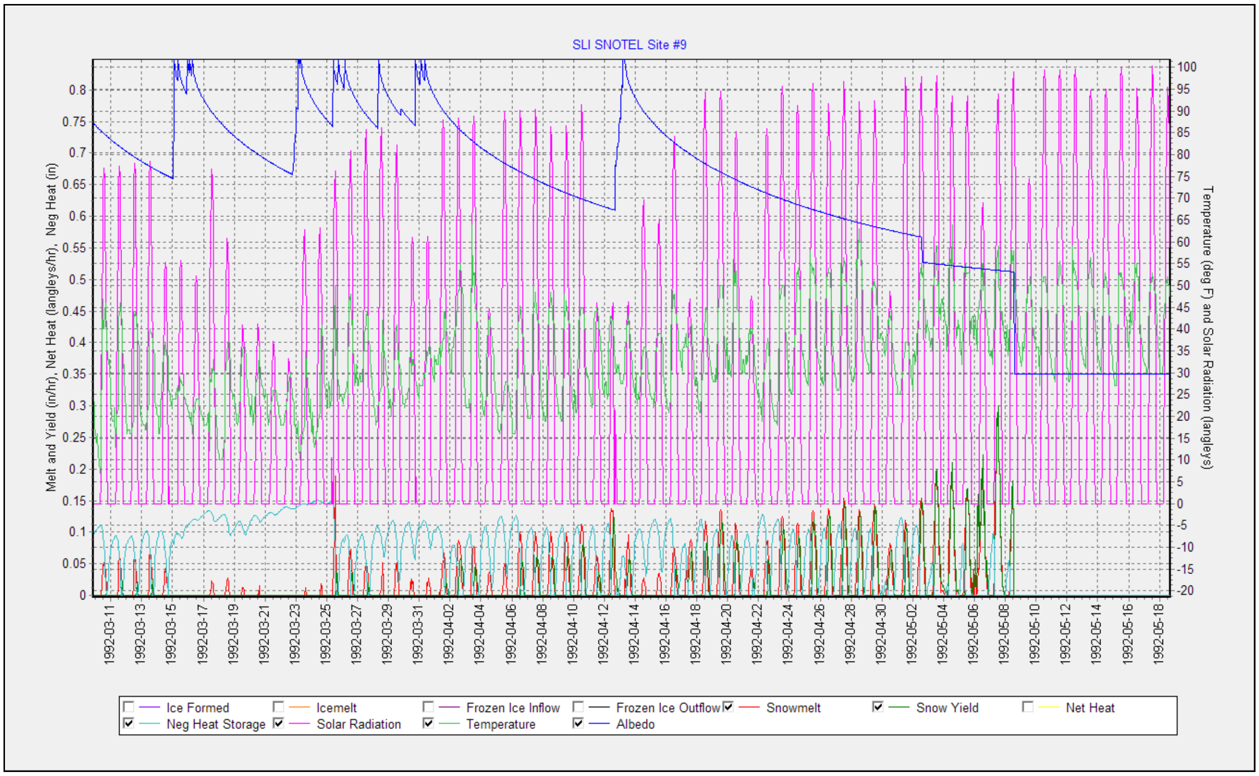

Figure D-6. Slide Canyon simulated historic snowpack albedo, air temperature, solar radiation, negative heat, snow melt and snow yield, May and June of water year 1992

Figure D-7 shows Slide Canyon simulated snowpack albedo, air temperature, solar radiation, negative heat, snow melt and snow yield for climate change scenario 2A in 2100 based on adjusted meteorological data from water year 1992. With higher temperatures, snowpack does not build until late December. Negative heat in Figure D-7 is much less consistent than the historical conditions shown in D-5. Figure D-8 shows the melt out of the snowpack. As in Figure D-6, warmer night time temperatures in Figure D-8 tend to reduce or prevent night time negative heat and the snowpack remains at 0 degrees C. The liquid water holding capacity of the snowpack is exceeded and water leaves the snowpack. In Figure D-8 for climate change scenario 2A in 2100, melt out ends by April 10, 1992 compared to May 8, 1992 for the historical conditions shown in Figure D-6.

With climate change and warmer temperatures and earlier spring melt, physical processes appear to cause melt out to be more episodic. Negative heat appears more likely to interrupt melt when the Slide Canyon snowpack begins melting in March.

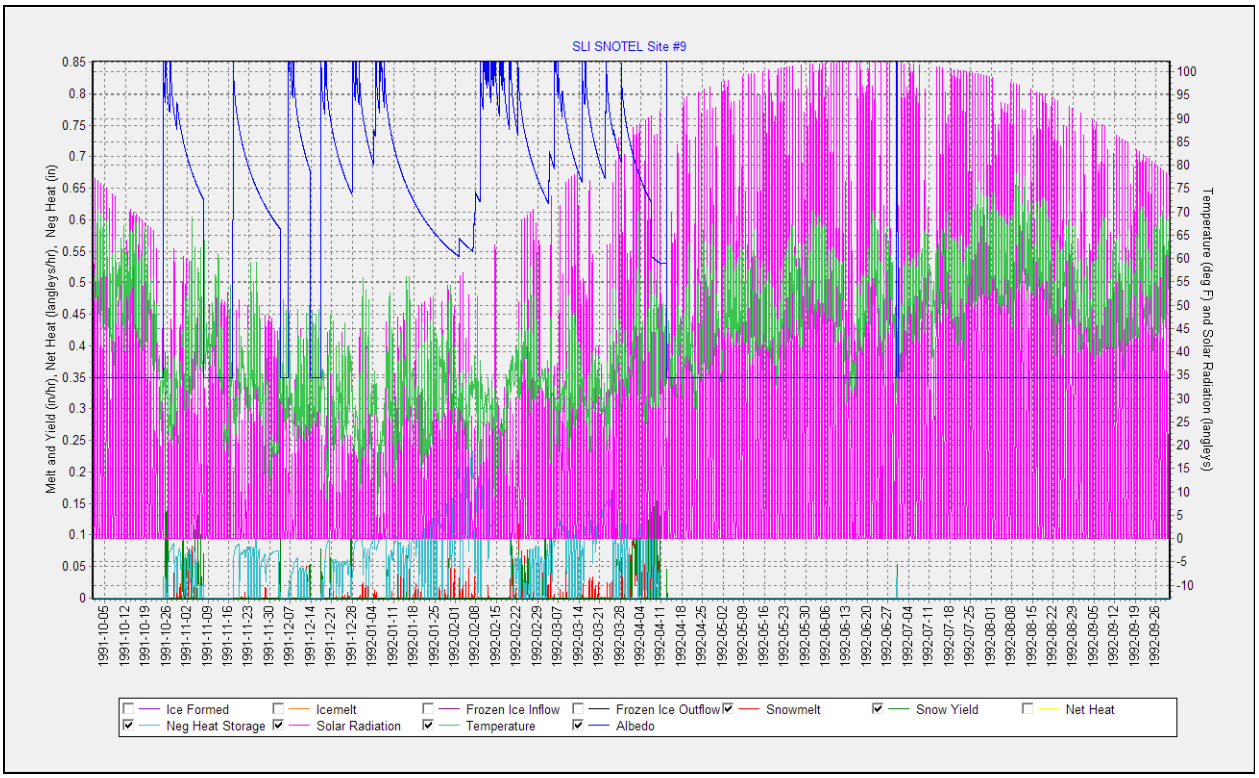

Figure D-7. Slide Canyon simulated snowpack albedo, air temperature, solar radiation, negative heat, snow melt and snow yield for scenario 2A in 2100, water year 1992

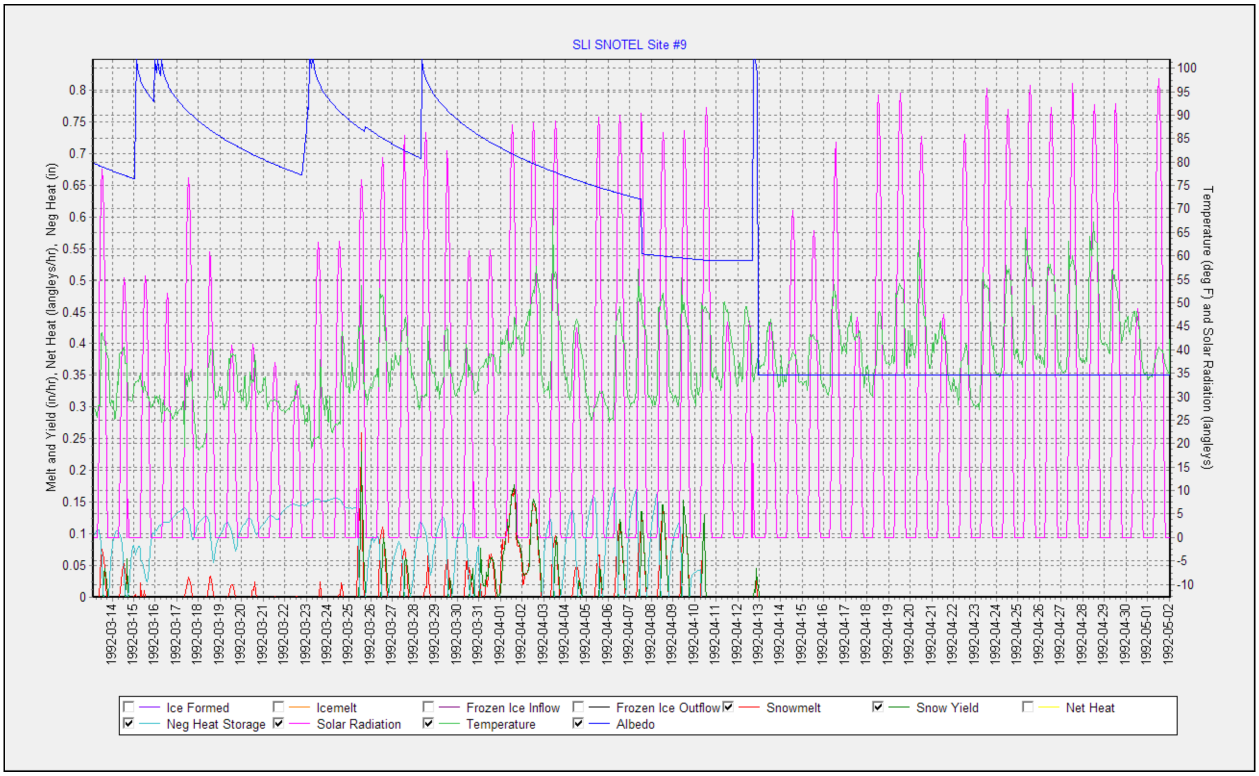

Figure D-8. Slide Canyon simulated snowpack albedo, air temperature, solar radiation, negative heat, snow melt and snow yield for scenario 2A in 2100, May and June of water year 1992

APPENDIX E

Tuolumne Meteorological Data

APPENDIX E

Tuolumne Meteorological Data

HFAM requires hourly input data for precipitation, temperature, evaporation, wind speed and solar radiation.

For the current project, the HFAM meteorological database for the Tuolumne watershed was improved by correcting obvious errors in the data and updating the database to Sept 30, 2008. The current database includes data for all stations for water years 1931-2008. Data sources and adjustments are described in detail in section E.1.

In addition to the historic database, a static database was created for water years 1931-2008 which represents the climatic conditions in 2010, as described in section E.2.

Future climate scenarios are developed from the 2010 current conditions static database. The method for addressing the different trends in minimum and maximum temperatures is described in section E.3.

It is important to distinguish between climate change and climate variability when predicting future meteorological conditions. A short analysis of historical temperature data and climate variability is presented in section E.4.

E.1 Tuolumne Meteorological Data Sources

E.1.1 Precipitation Data

Table E.1 summarizes the station names and data sources for Tuolumne hourly precipitation data compiled for the HFAM meteorological database.

Table E.1 Precipitation data in HFAM database

HFAM PRECIPITATION DATA						
HFAM Station #	**CODE**	**Station Name**	**Station Elev. (ft)**	**Station for Estimation of Earlier Record**	**Extended Data Starts**	**Extended Data Ends**
218	HTH	Hetch Hetchy	3858	(none)		
220	BKM	Buck Meadows	3200	Groveland 2	1930	June 1999
235	TUM	Tuolumne Meadows	8600	HTH	1930	Sept. 1997
260	CHV	Cherry Valley Dam	4764	HTH	1930	approx. 1955
265	MCN	Moccasin	938	HTH	1930	approx. 1950

E.1.2 Temperature Data

Table E.2 summarizes the station names and data sources for Tuolumne hourly temperature data compiled for the HFAM meteorological database.

Table E.2 Temperature data in HFAM database

HFAM TEMPERATURE DATA							
HFAM Station #	**CODE**	**Station Name**	**Station Elev. (ft)**	**Observation Interval**	**Station for Estimation of Earlier Record**	**Extended Data Starts**	**Extended Data Ends**
218	HTH	Hetch Hetchy	3858	Daily	none		
265	MCN	Moccasin	938	Daily	none		
260	CHV	Cherry Valley Dam	4764	Daily	HTH	Oct. 1930	Dec. 1952
230	PDS	Paradise Meadow	7650	Hourly	CHV	Oct. 1930	Sept. 1991
235	TUM	Tuolumne Meadows	8600	Hourly	HTH	Oct. 1930	Oct. 1992
220	BKM	Buck Meadows	3200	Hourly	CHV	Oct. 1930	Sept. 1991
245	HRS	Horse Meadow	8400	Hourly	CHV	Oct. 1930	April 1988
255	SLI	Slide Canyon	9200	Hourly	CHV	Oct. 1930	Oct. 1990

Estimation of Hourly Temperature Data

Temperature data are recorded and published in two observation intervals, either daily maximum and minimum temperatures or hourly temperatures. Daily stations are Cherry Valley Dam, Hetch Hetchy, and Moccasin. These records are available for a longer period than the hourly records and are more complete.

To disaggregate daily temperatures to hourly values required by HFAM, the daily maximum is assigned to 4 PM and the daily minimum is assigned to 4 AM. Temperatures at other hours are calculated using a symmetrical diurnal variation between maximum and minimum temperatures.

Hourly temperature records acquired from telemetry stations operated by the US Forest Service and the California Dept. of Water Resources are listed in Table E.3.

Table E.3 Real-time stations in the Tuolumne watershed

ID	Name	Latitude	Longitude	Elevation (ft)	Operator
BKM	BUCK MEADOWS	120.10	37.823	3200	US Forest Service
HRS	HORSE MEADOW	119.66	38.158	8400	CA Dept of Water Resources
PDS	PARADISE MEADOW	119.67	38.047	7650	CA Dept of Water Resources
SLI	SLIDE CANYON	119.43	38.092	9200	CA Dept of Water Resources
TUM	TUOLUMNE MEADOWS	119.35	37.873	8600	CA Dept of Water Resources

Some of these stations were installed in the 1980's but data are less reliable in the early years. Hourly data in the HFAM database begin the month after the end of extended (i.e. estimated from long-term stations) data, as indicated in the last column of Table E.2.

For years prior to the start of hourly telemetry records, data are estimated from nearby stations. HFAM's Horse Meadow, Buck Meadows, Paradise Meadow, and Slide Canyon temperature records are estimated from Cherry Valley Dam temperatures. Tuolumne Meadows temperatures are estimated from Hetch Hetchy. Estimated temperature is a function of lapse rates and the difference between elevations of the stations:

Estimated Temperature = Temperature at Nearby Station + (Lapse Rate * Elevation Difference)

Temperature lapse rates are given in Table E.4. Lapse rates were calculated from concurrent record at the two stations and were re-calculated for the current study. Hence the current HFAM database has been revised for the early (extended) data period.

Table E.4 Lapse Rates for estimation of early records in the HFAM database (deg F/1000ft)

	Record Based on Cherry Valley Data				Record Based on Hetch Hetchy Data
Month	PDS-CHV	SLI-CHV	HRS-CHV	BKM-CHV	TUM -HTH
JAN	4.30	3.68	4.58	1.19	3.55
FEB	4.46	4.01	4.91	0.98	3.88
MAR	4.54	4.18	5.10	1.03	3.94
APR	4.82	4.28	5.14	0.93	3.92
MAY	5.01	4.41	5.38	1.74	3.78
JUN	4.81	4.48	5.18	1.14	3.62
JUL	5.00	4.60	5.19	0.51	3.81
AUG	5.26	4.63	5.35	0.00	3.99
SEP	4.91	4.55	5.16	0.00	4.24
OCT	4.87	3.98	4.95	0.00	3.86
NOV	4.42	3.97	4.70	0.00	3.65
DEC	4.29	3.63	4.48	0.56	3.38
MEAN	**4.72**	**4.20**	**5.01**	**0.67**	**3.80**

E.1.3 Evaporation Data

The evaporation data station is Hetch Hetchy (HFAM station HTH 218). For years when no evaporation data are available, average values are adequate. It was not necessary to revise the evaporation data for the current study.

E.1.4 Wind Data

The wind data in prior versions of the HFAM database were measured at Buck Meadows. In the current database, wind data are based on NCEP-NCAR Reanalysis (Kalnay et al. 1996) 700 millibar wind data for Yosemite (latitude 37.5 N, longitude 120 W).

For the period October 2005 to September 2008, reanalysis wind data were not available. For those years, HFAM's wind data are a function of surface wind measurements at Buck Meadows modified to increase consistency with the reanalysis data.

During the final calibration, selected periods of wind data were modified to improve simulation of spring snowmelt.

The current database retains the station name Buck Meadows. A summary of data sources is shown in Table E.5.

Table E.5 Sources of wind data in the current HFAM database

HFAM Wind Data for Station ID BKM 220	Start Date	End Date
Monthly average for years 1948 to 2008	1/1/1930	12/31/1947
Reanalysis wind data, scaled by 1/7	1/1/1948	9/30/2005
A function of hourly Buck Meadows wind, based on a correlation between reanalysis data and Buck Meadows data	10/1/2005	9/30/2008

Reanalysis Wind Data

The NCEP-NCAR Reanalysis Project provides simulated historical meteorological data, including upper atmosphere wind speeds.[7] The website states that "reanalysis datasets are created by assimilating ("inputting") climate observations using the same climate model throughout the entire reanalysis period in order to reduce the effects of modeling changes on climate statistics. Observations are from many different sources including ships, satellites, ground stations, RAOBS, and radar." Reanalysis wind data were provided to Hydrocomp for the period 1948-2005.

The format of the reanalysis data is a pair of velocities for each day, which are components of velocity on the north-south coordinate and the east-west coordinate. The N-S (or zonal) velocity is called Vwind and the E-W (or meridianal) component is called Uwind.

Zonal Components	Value (+ or -)	Direction
Vwind	+	towards North (southerly wind)
Vwind	-	towards South (northerly wind)

Meridianal Components	Value (+ or -)	Direction
Uwind	+	towards East (westerly wind)
Uwind	-	towards West (easterly wind)

[7] Reanalysis data are provided by the NOAA-ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.esrl.noaa.gov/psd/

To create a data series for HFAM, the resultant magnitude of the wind speed was calculated from Uwind and Vwind. The wind direction information is not used in HFAM. The units were converted to miles per hour and the time step was converted from daily to hourly assuming the same wind speed for all hours in each day.

HFAM requires data for wind speeds at the land surface. The upper-atmosphere (700 millibar) reanalysis wind speeds were divided by seven to estimate wind speed at the land surface. It is not necessary to define this scaling factor precisely because HFAM parameters are adjusted during model calibration.

Correlation between Buck Meadows Surface Wind and Reanalysis Data

Prior versions of the HFAM database included wind speeds measured at the Buck Meadows weather station. The reanalysis data differ statistically from surface measurements of wind. The surface measurements are much less variable than the reanalysis wind data. To increase the consistency of the HFAM database Buck Meadows wind data for October 2005 – September 2008 was modified:

- For Buck Meadows wind speeds less than 1.5 MPH, the HFAM wind is 0.2 MPH
- For Buck Meadows wind speeds between 1.5 and 3.4, the HFAM wind was computed as:
  HFAM wind = $0.8104x^2 - 1.3762x + 0.4681$ (where x is wind speed at Buck Meadows)
- For Buck Meadows wind speeds greater than 3.7, the HFAM wind was computed as
  HFAM wind = $0.6x + 3.7$ (where x is wind speed at Buck Meadows)

These modifications to the wind data improved the simulation of snowmelt for 2005-2008.

Wind Data Modifications for the Final Calibration

Adjustments to wind were made in 1980, 1985, 1988, 1993, 1995, 1997, 2005 and 2008. Adjustments were for periods of two to four weeks during April, May or June and wind velocities were typically scaled by 0.5 to 2 during these periods.

E.1.5 Solar Radiation Data

The solar radiation data in prior versions of the HFAM database are data from the weather station at Buck Meadows. In the current database, solar radiation data for water years 1975-2008 were estimated from theoretical maximum solar radiation at the land surface and sky cover descriptions at Cherry Valley Dam and Moccasin. This method improved the model calibration because it is more consistent from year to year. The solar radiation data prior to 1975 are the original HFAM data scaled by a factor of 1.07 to increase consistency and remove trends.

The current database retains the station name Buck Meadows. A summary of data sources is shown in Table E.6

Table E.6 Sources of solar radiation data in the current HFAM database

HFAM Solar Radiation Data for Station ID BKM 220	Start Date	End Date
Prior HFAM data scaled by 1.07	1/1/1930	9/30/1974
Cherry Valley Dam and Moccasin Sky cover description,	10/1/1974	9/30/2008
and theoretical clear sky solar radiation		

Theoretical Clear Sky Solar Radiation

Maximum (clear sky) solar radiation at the land surface was obtained from an Excel spreadsheet application called ***solrad.xls (version 1.2)*** developed by Greg Pelletier of the Washington State Department of Ecology, Olympia, WA. Solar radiation was calculated for the latitude and longitude coordinates of Buck Meadows and an elevation of 1000 m. The *solrad.xls* spreadsheet provided hourly values of solar radiation for one year. Figure E.1 shows the seasonal variation of solar radiation at noon.

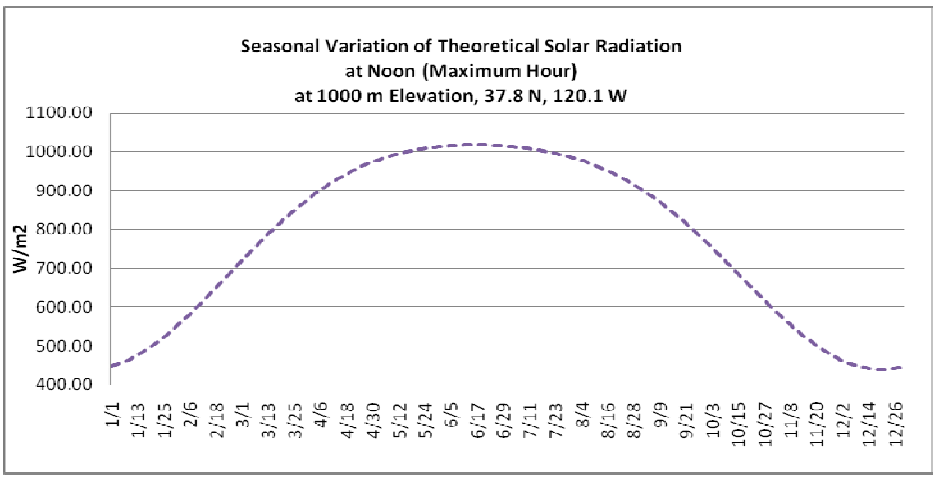

Figure E.1 Seasonal variation of solar radiation at noon

The HFAM data series of solar radiation was estimated by multiplying clear sky solar radiation by percent possible sunshine:

Solar Radiation = Theoretical Clear Sky Solar Radiation (hourly) * % Possible Sunshine (daily)

Percent possible sunshine was estimated from sky cover descriptions. For the study period, water years 1975-2008, the most useful data available are sky cover descriptions at Cherry Valley Dam and Moccasin. By comparing a short record (Oct 2006 to April 2007) of solar radiation measurements at Buck Meadow (BKM), as well as the average of measurements at Tuolumne Meadows (TUM), Dana Meadows (DAN) and Tioga Entrance Station (TES) correlations between sky cover and percent possible sunshine were developed, shown in Table E.7.

Table E.7 Daily sky cover descriptions and corresponding values of percent possible sunshine

Sky Cover Description	% Possible Sunshine
Rain or Snow	40
Cloudy	50
Fog or Smoke	90
Part Cloudy	90
Clear	100

Figure E.2 shows the comparison of percent possible sunshine based on solar radiation measured at weather stations with percent possible sunshine estimated from sky cover descriptions, for October 2006 to January 2007.

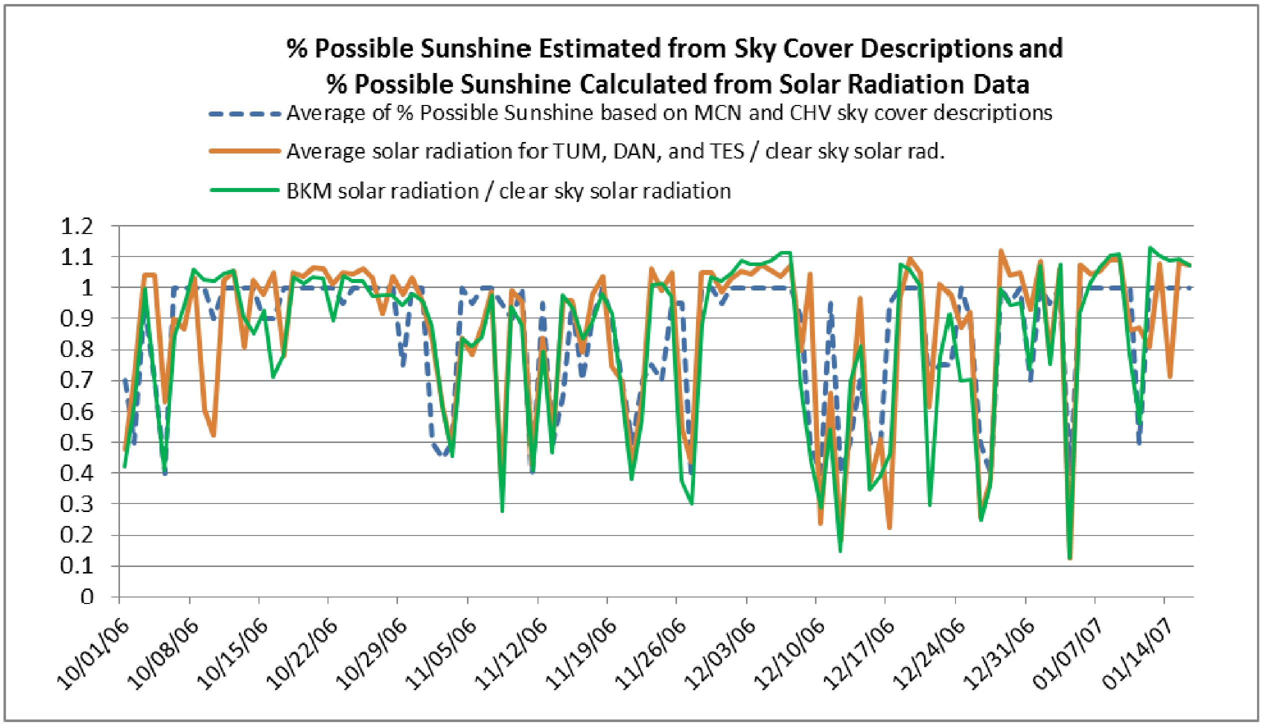

Figure E.2 Percent possible sunshine estimated from solar radiation data

E.2 Trends in Historic Meteorological Database and HFAM Static Data

Hydrocomp evaluated trends in historical temperature data using the revised database which includes data added for recent years and corrections made to erroneous temperature data.

Trends in the current solar and wind data were also calculated. As shown in Figures E.3 and E.4, the final wind and solar data do not have significant long-term trends over the water years 1931-2008

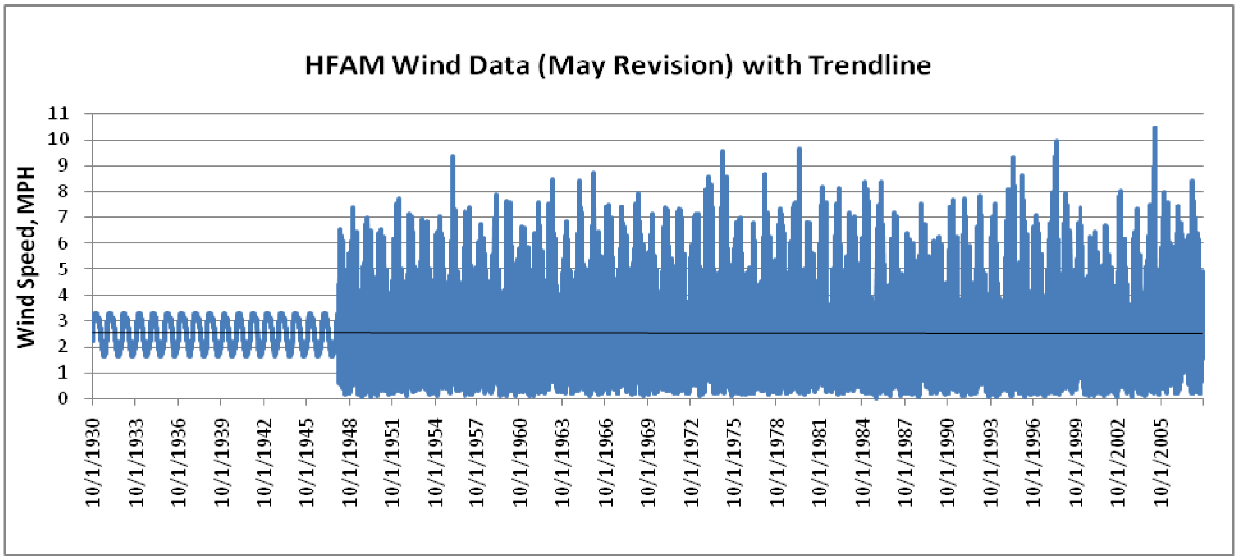

Figure E.3 Trends in wind data for 1931-2008

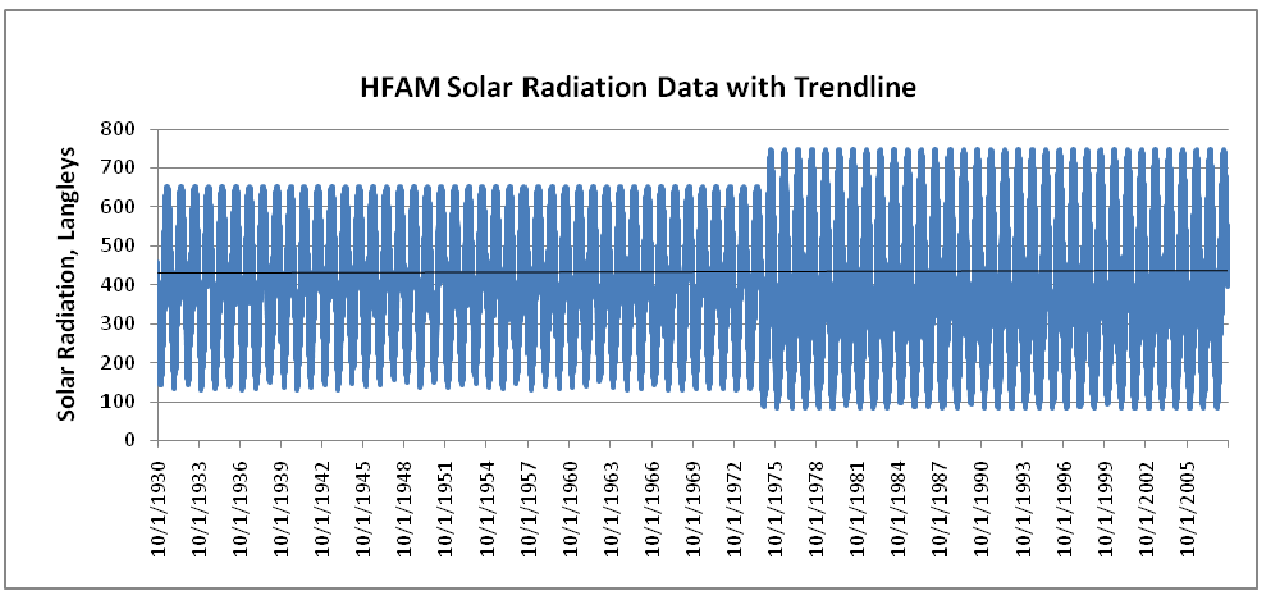

Figure E.4 Trends in solar radiation data for 1931-2008

Trends in Temperature Data

Trends in the HFAM temperature data were quantified from linear regression equations calculated by MS Excel. The average annual temperature change for the long-term records for Cherry Valley Dam, Hetch Hetchy and Moccasin are given in Table E.8 for the 34-year climate change study period, water years 1975-2008.

Table E.8 Average annual change in temperature over the 34-year period 1975-2008 (deg F/year)

	CHV	HTH	MCN
Daily Maximums	0.0756	0.0703	0.0926
Daily Minimums	0.1118	0.1285	0.0262

The annual rates in Table E.8 multiplied by 34 give temperature change over the 34-year climate change study period (1975-2008), as shown in Table E.9. Average daily temperature changes in HFAM are equivalent to the average of the change in daily maximum and daily minimum temperature because HFAM uses a constant symmetrical pattern to disaggregate daily maximum and minimum temperatures to hourly temperatures.

Table E.9 Change in temperature based on trend for 1975-2008 (deg F)

	CHV	HTH	MCN
Daily Maximums	2.57	2.39	3.15
Daily Minimums	3.79	4.37	0.89
Average	3.18	3.38	2.02

Trends were also calculated for the 49-year period 1960-2008 because preliminary analysis indicated that 1960 was the beginning of the warming trend. A longer record may give more reliable information. The 49-year trends are shown in Table E.10.

Table E.10 Average annual change in temperature over the 49-year period water year 1960-2008 (deg F/year)

	CHV	HTH	MCN
Daily Maximums	0.0103	0.0175	0.1052
Daily Minimums	0.1138	0.1031	0.0268

Multiplying the annual rates in Table E.10 which were calculated over the 49-year period by 34 gives another estimate of the temperature change over the 34-year climate change study period (1975-2008), shown in Table E.11. Moccasin trends are similar for both 34-year and 49-year calculations. However, Cherry Valley Dam and Hetch Hetchy temperature changes are larger for the 34-year records than the 49-year record, especially for maximum temperatures.

Table E.11 Change in temperature based on trend for 1960-2008 (deg F)

	CHV	HTH	MCN
Daily Maximums	0.35	0.60	3.58
Daily Minimums	3.87	3.51	0.91
Average	2.11	2.05	2.24

Trends were also calculated for the hourly telemetry stations. These shorter records are more subject to short-term weather fluctuations. Table E.12 shows the trends calculated for these stations.

Table E.12 Trends for telemetry stations with hourly temperature data average annual change for analysis period (deg F/year)

Station	Trend Analysis Starts	# of years	Change in Daily Average Temperature	Change in Daily Maximum Temperature	Change in Daily Minimum Temperature
Horse Meadow	Oct 1989	19	0.23 deg F/year	0.23 deg F/year	0.20 deg F/year
Paradise Meadow	OCT. 1991	17	0.16 deg F/year	0.15 deg F/year	0.15 deg F/year
Tuolumne Meadows	Oct. 1993	15	0.19 deg F/year	0.25 deg F/year	0.13 deg F/year
Buck Meadows	Oct. 1991	17	0.07 deg F/year	0.11 deg F/year	0.07 deg F/year
Slide Canyon	Oct. 1990	18	0.12 deg F/year	0.14 deg F/year	0.08 deg F/year

Corrections to Historic Temperature Data to Develop Static Records

The steps followed to develop static temperatures are:

1) Generate static temperature records for the long-term daily maximum and minimum temperatures stations: Cherry Valley Dam, Hetch Hetchy, and Moccasin
2) Confirm that there are no trends in the static data for the period 1930-2008 for Cherry Valley Dam, Hetch Hetchy, and Moccasin
3) Extend the short records for hourly telemetry station by applying lapse rates to the static temperature data.
4) Confirm that there are no trends in the static data for hourly telemetry stations for the period 1930-2008

Static Temperatures Records for the Daily Max-Min Temperatures Stations: Cherry Valley Dam, Hetch Hetchy, and Moccasin

Daily maximum-minimum temperature records are disaggregated to hourly data for the HFAM database using the same hourly pattern each day. Minimum temperatures are assigned to 4 AM and maximums are assigned to 4 PM. Because the diurnal pattern never varies, the historical record's mean, maximum and minimum temperatures can be modified by adding hourly temperature increments.

For example, to create a static temperature record for Moccasin, hourly temperature increments in Figure E.5 were added to the historical Moccasin record. The increment to the daily minimum temperature is 0.91 deg F and the increment to the daily maximum temperature is 3.58 deg F; the average daily increment is 2.4 deg F. These increments were determined by trend analysis for the period 1960-2008 (see Table E.11).

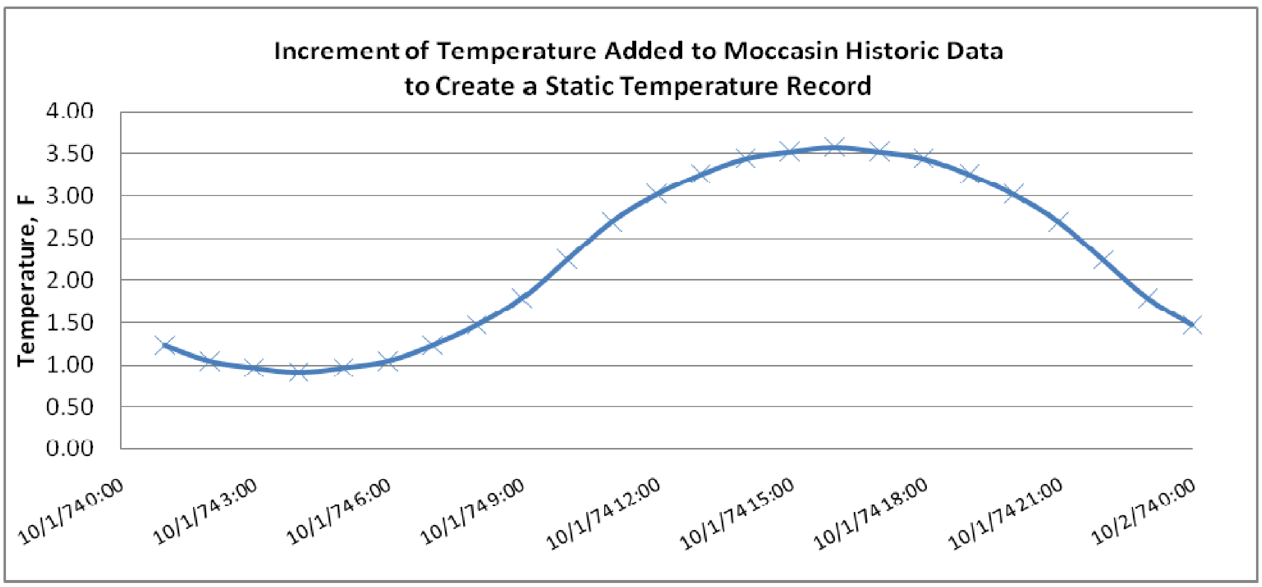

Figure E.5 Increments of temperature added to Moccasin historic data to create a static record

Warming trends for minimum temperatures at Cherry Valley Dam and Hetch Hetchy are greater than the trend in daily maximum temperatures. Only minimum temperatures trends were incorporated in static temperature data. Figure E.6 shows the adjustments used to generate static temperature records for the long-term stations and Table E.13 illustrates the pattern of adjustments for Cherry Valley Dam and Hetch Hetchy.

Table E.13 Cherry Valley Dam, Hetch Hetchy, and Moccasin temperature change applied to the 34 years 1975-2008 to create static record

	CHV	HTH	MCN
Daily Maximums	0	0	3.58
Daily Minimums	3.87	3.51	0.91
Average	1.93	1.76	2.24

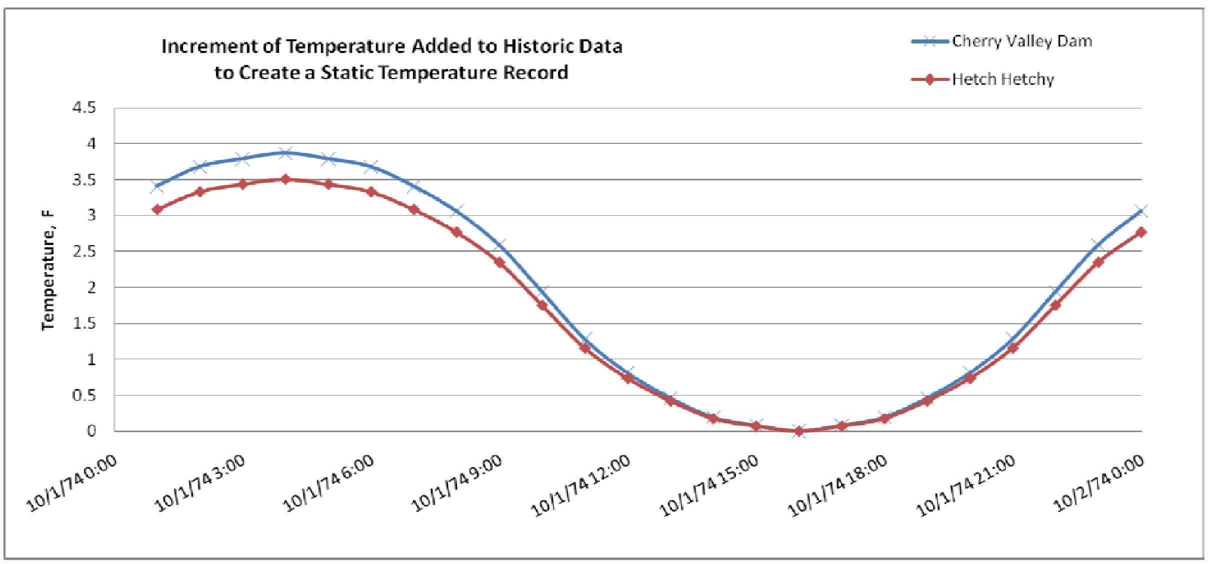

Figure E.6 Increments of temperature added to Cherry Valley and Hetch Hetchy historic data to create a static record

The static adjustments to Moccasin, Hetch Hetchy and Cherry Valley temperatures shown in Figures E.5 and E.6 were decreased linearly for water years 1975-2008. The static temperature is calculated with the following equation using scaling factors illustrated in Figure E.7:

Static Temperature = Historic Temperature + (Static Adjustment * Scaling Factor)

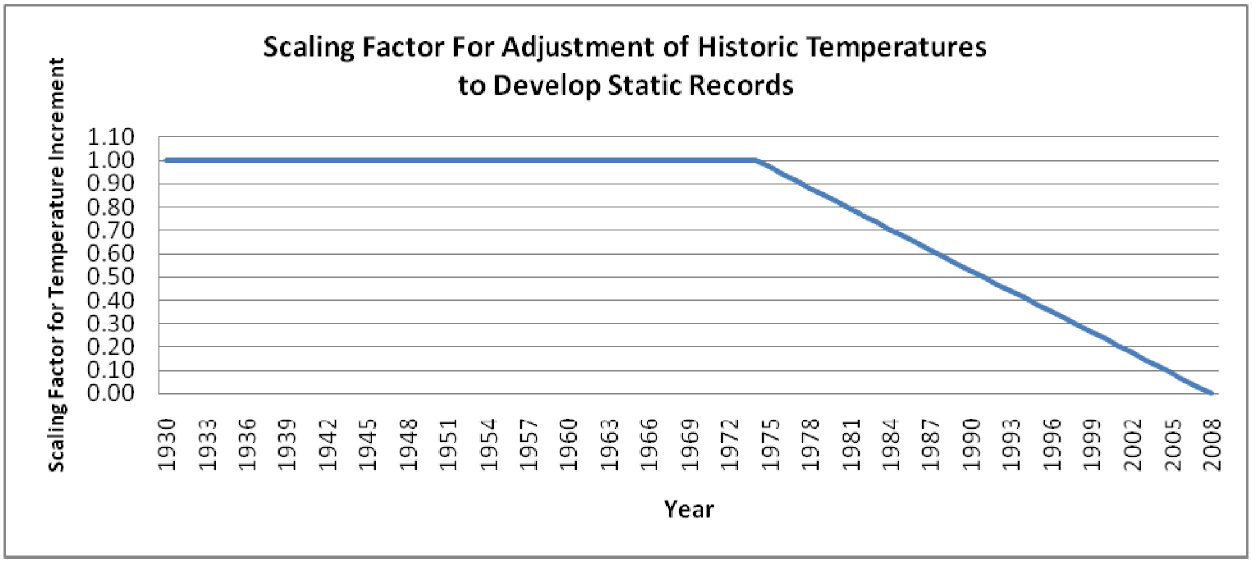

Figure E.7 Scaling factors for static temperature records

Figures E.8 and E.9 are examples of the scaled static temperature increments for Moccasin. The scaling factor for 10/1/1980 is 0.82 and the factor for 10/1/2000 is 0.24.

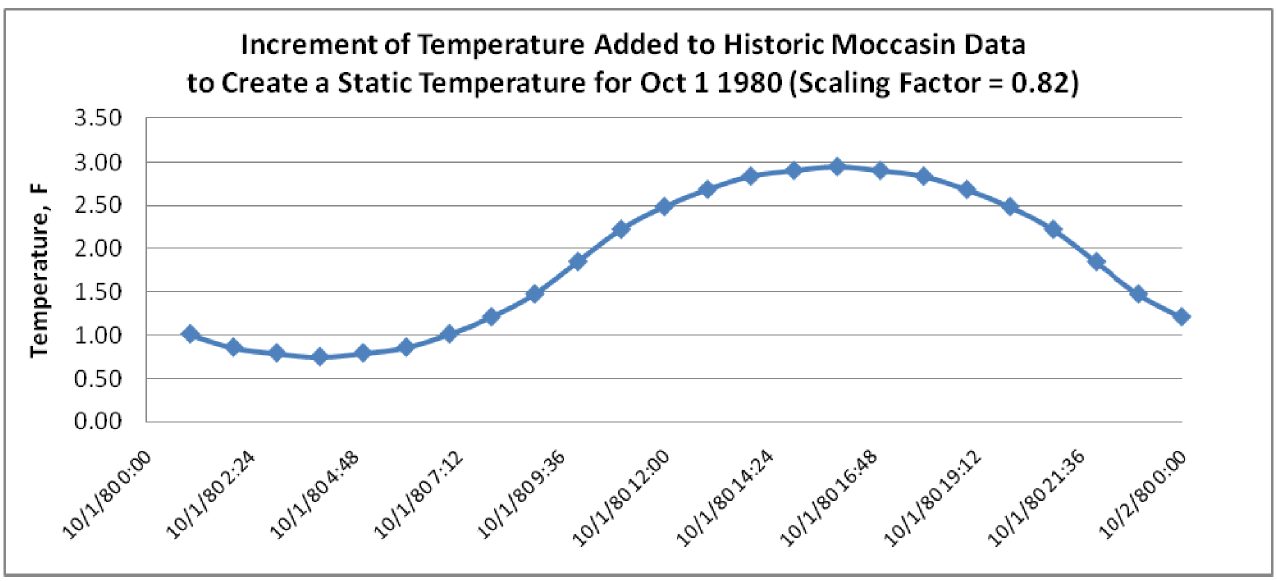

Figure E.8 Scaled static temperature increments for Moccasin, 1980

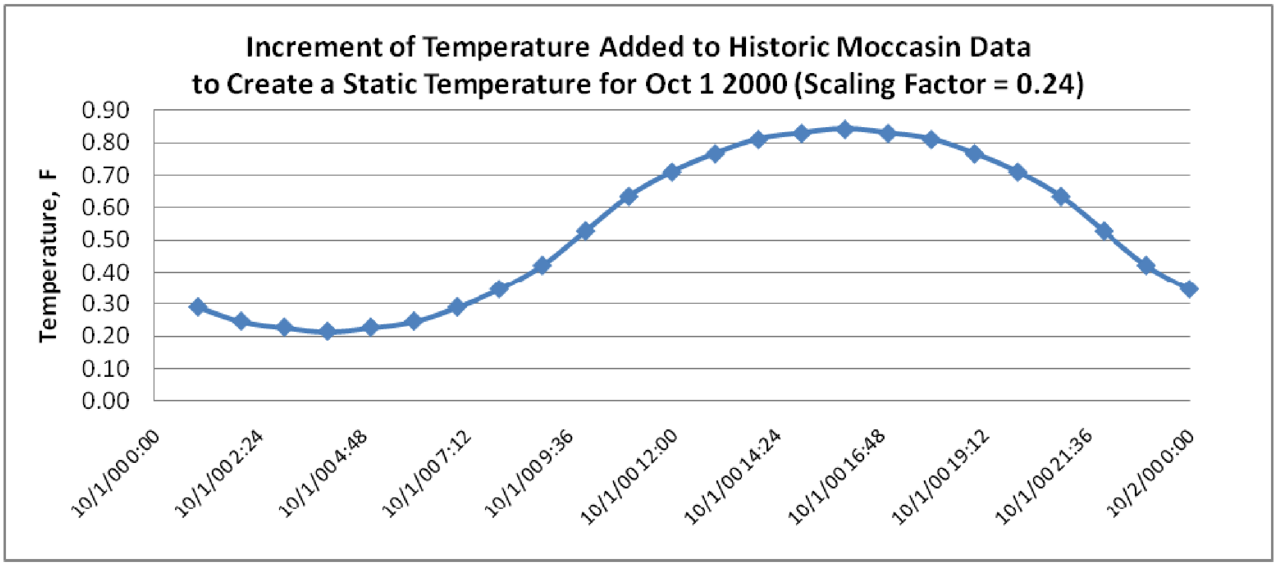

Figure E.9 Scaled static temperature increments for Moccasin, 2000

Static Temperatures Records for the Hourly Telemetry Temperatures Stations: Horse Meadow, Tuolumne Meadows, Paradise Meadow, Buck Meadows and Slide Canyon

Warming trends were calculated for the hourly temperature stations. However, there is less certainty in trends because the records are shorter.

The HFAM database contains estimated data for years prior to the start of hourly telemetry records. HFAM's Horse Meadow, Buck Meadows, Paradise Meadow, and Slide Canyon temperature records are estimated from Cherry Valley Dam temperatures. The HFAM historical data were estimated by applying lapse rate adjustments from Cherry Valley Dam to the telemetry stations. To create the static HFAM data, the same lapse rate adjustments were applied to the static Cherry Valley temperature record. Trend analysis of the resulting records for the period 1930-2008 is acceptable.

Tuolumne Meadows (TUM) is the only hourly record extended with Hetch Hetchy (HTH) temperature data. Lapse rate adjustment of the static Hetch Hetchy temperature to Tuolumne Meadows did not remove trends in temperature data. A different method was used to create a static record for TUM:

1. Adjust the historic TUM data for November 1, 1992- September 30 2008 by +2.9 degrees F multiplied by scaling factor. The scaling factor decreases linearly from 1.0 to 0.0.
2. Extend the TUM record based on HTH data. Both static adjustments and lapse rate adjustments were made. The lapse rate adjustments are the same as were used for the HFAM historic database. The static temperature adjustments are a diurnal pattern shown in Figure E.10. No scaling factor is used.

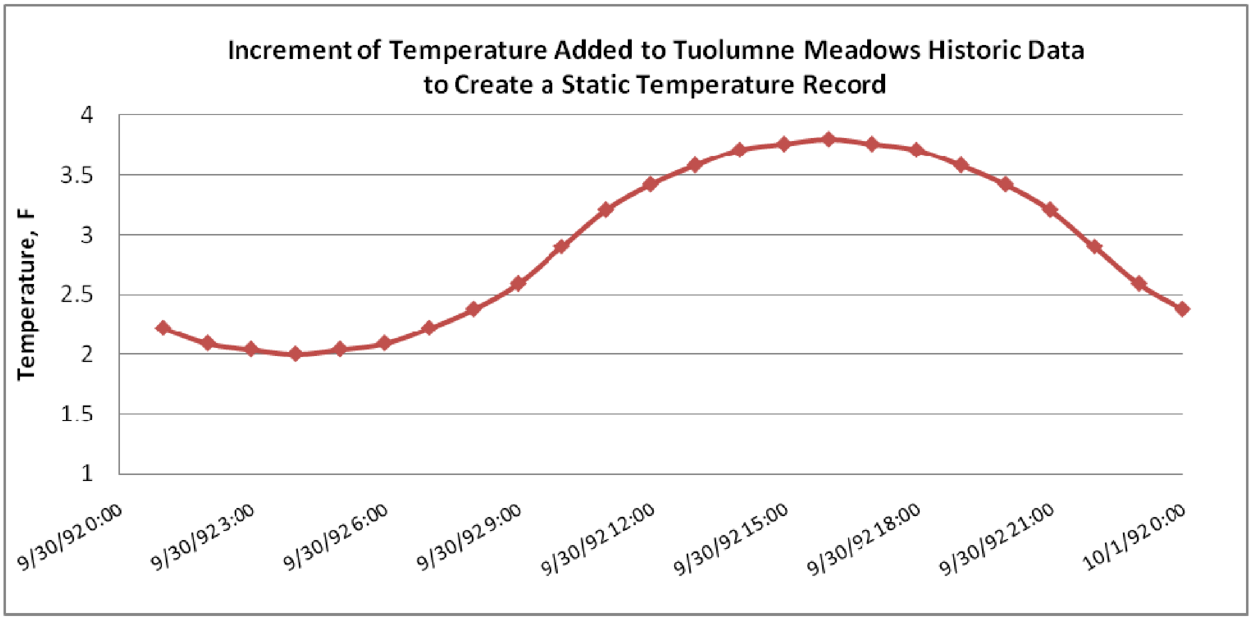

Figure E.10 Static temperature increments for Tuolumne Meadows

Trends in HFAM Static Temperature Data

The HFAM static temperature records were checked to ensure that trends are small. Table E.14 summarizes the trends in daily maximum, minimum and average temperature by the HFAM temperature stations for the 78 years 1930-2008. All changes are less than 2 degrees F. Trends in daily average temperature are all less than 1.1 degrees F over 78 years.

Table E.14 Trends in HFAM Static Temperature Records
Changes in Temperature over 79 years, 1930-2008 (deg F)

Stations With Daily Observations					
	CHV	**HTH**	**MCN**		
Daily Maximums	-1.16	-1.34	0.22		
Daily Minimums	0.07	1.29	-0.21		
Daily Average	**-0.49**	**-0.01**	**0.04**		
Stations With Hourly Observations					
	BKM	**HRS**	**PDS**	**SLI**	**TUM**
Daily Maximums	1.45	-0.19	0.01	0.30	0.39
Daily Minimums	-1.66	-0.84	-0.52	-0.27	0.39
Daily Average	**-1.03**	**-0.99**	**-0.92**	**-1.09**	**-0.13**

E.3 Development of future temperature timeseries

A delta-adjusted future meteorological database was generated from the static meteorological database to represent each of the future climate conditions listed in Table 3-1. The delta method consists of adjusting existing timeseries by a given factor or factors to develop a new set of timeseries (Bader et al. 2008).

Predicted temperature changes are given as average temperature increases in Table 3-1. The historical temperature records in the Tuolumne at Hetch Hetchy and Cherry Valley show that minimum daily temperatures have increased much more than maximum daily temperatures. This tendency is assumed to continue, with the daily temperature cycle becoming gradually more moderate.

Hydrocomp developed a method to calculate the increases to daily minimum and daily maximum temperatures, given a specified increase to daily average temperatures. Figure E.11 shows the relationship used to determine the daily minimum and daily maximum temperature increases from the average daily temperatures increase in degrees F. Use of this relationship when calculating the hourly temperature increase ensures that the daily range in temperature (i.e. the daily maximum minus the daily minimum temperature) remains within reason for all climate change scenarios.

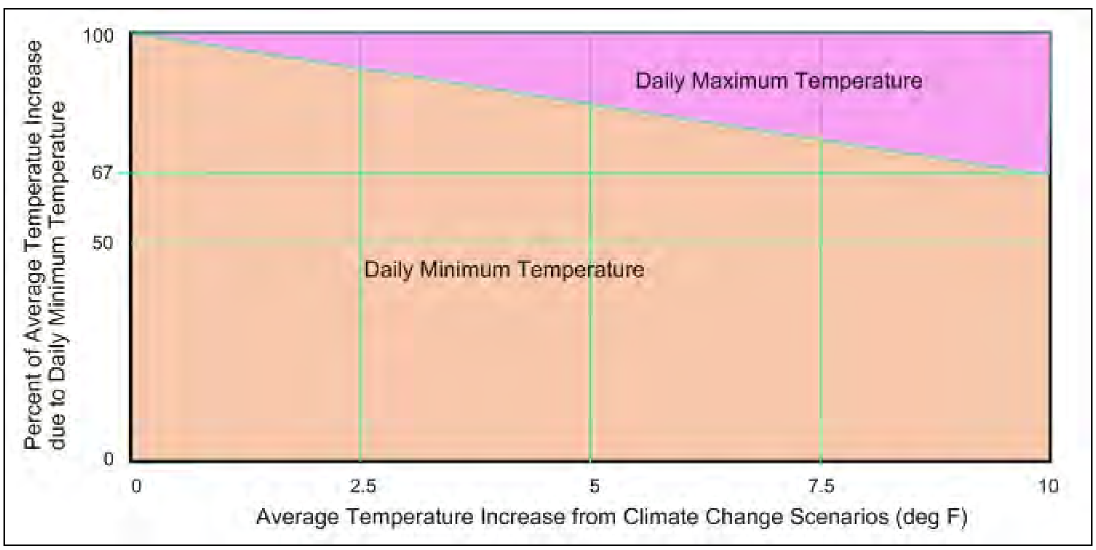

Figure E.11. Percentage of average temperature increase due to daily minimum and daily maximum temperature increases

E.4 Climate variability and trends in temperature data

The potential climate change scenarios were developed based on statistical analysis of historical meteorological data. It is important to distinguish between climate change and climate variability in such an analysis. Weather in the Sierras is driven by climate patterns over the Pacific Ocean, which are affected by El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Mantua N. 2002). The overall warming trend in the Western United States between 1950 and 1999 is smaller when the PDO is accounted for (Bonfils et al. 2008).

The impact of the PDO on weather in the Upper Tuolumne Basin was studied by correlating the Pacific Decadal Oscillation Index (PDOI) with the daily minimum and maximum temperatures (T_{min} and T_{max}) at Hetch Hetchy Dam from 1930-2009 and at Cherry Valley Dam from 1953-2010. There is a small correlation between the PDOI and T_{min} that is seen at both sites when data are averaged monthly, seasonally, or annually. There is no consistent relationship between the PDOI and T_{max}). Figure E.12 shows the correlation between the annual average value of T_{min} and the PDOI at Hetch Hetchy.

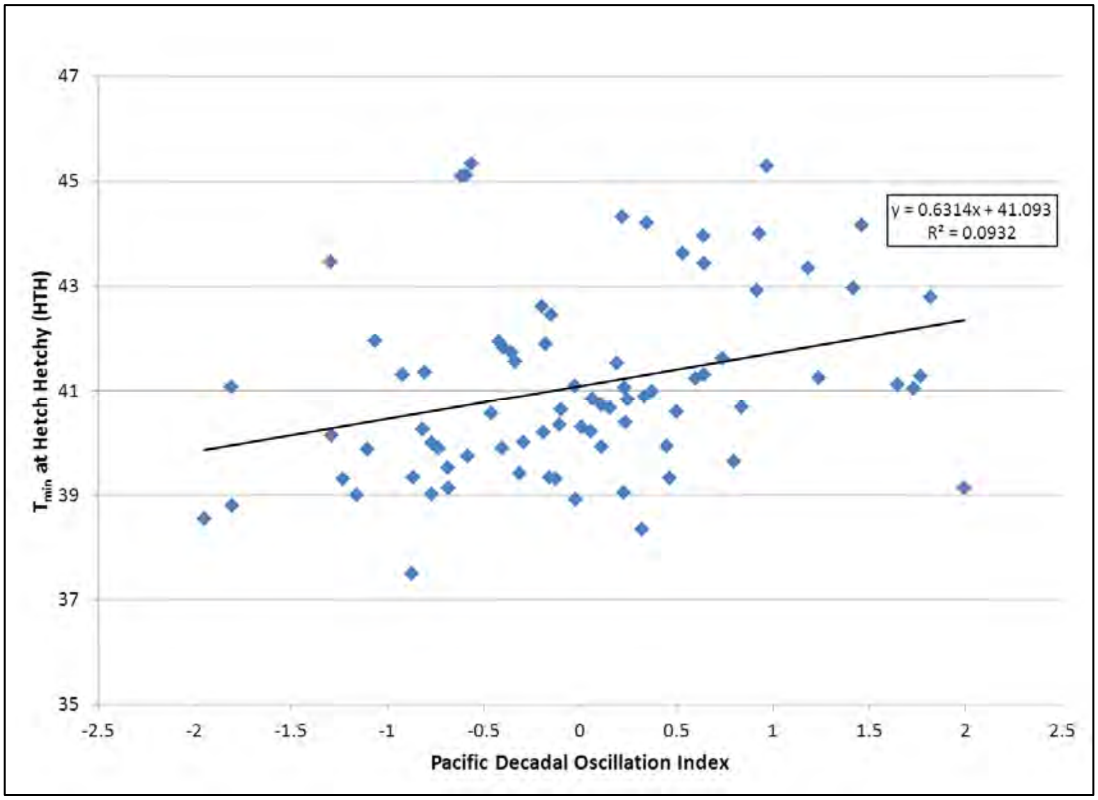

Figure E.12. Correlation between PDOI and annual average Tmin at HTH

The annual average daily minimum temperature at Hetch Hetchy with the PDOI correlation removed is presented in Figure E.13. The timeseries that excludes the PDO is slightly different than the raw timeseries, and the warming trend after 1960 is not significantly altered. The raw timeseries is used to develop inputs for the HFAM model so that the input includes all climate variability.

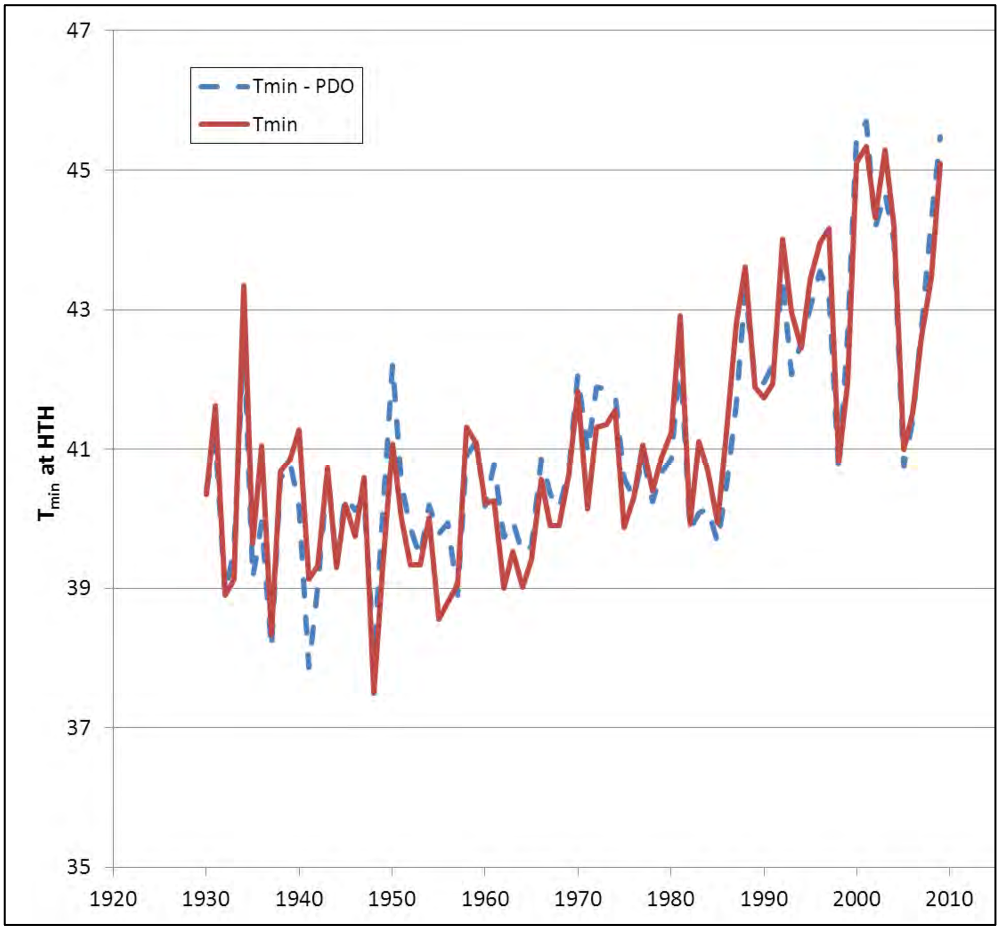

Figure E.13. Annual average Tmin without the PDOI correlation

There was no significant relationship found between Tmin and Tmax and the ENSO index.