RE-ASSEMBLING HETCH HETCHY:
Water Supply Implications of Removing O'Shaughnessy Dam

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Abstract

The Hetch Hetchy System provides San Francisco with much of its water supply. O'Shaughnessy Dam is one component of this system, providing approximately 25% of water storage for the Hetch Hetchy System and none of its conveyance. Removing O'Shaughnessy Dam has gained interest for restoring Hetch Hetchy Valley. Removal would entail reoperating other existing reservoirs for water storage, but would open the valley to restoration, revenue, and economic development from recreation and tourism. The water supply feasibility of removing O'Shaughnessy Dam is analyzed by examining alternative water storage and delivery operations for San Francisco using an economic-engineering optimization model. The economic benefits of O'Shaughnessy Dam, and its alternatives are measured in terms of the quantity of water supplied to San Francisco, economic costs, and hydropower generation.

CHAPTER ONE
INTRODUCTION

O'Shaughnessy Dam, located in Hetch Hetchy Valley of Yosemite National Park, was built by the city of San Francisco in 1923. O'Shaughnessy Dam is a component of the Hetch Hetchy water system, with ten other reservoirs, numerous water conveyance pipelines, and water treatment facilities. This system provides water to 2.4 million people in the San Francisco Bay Area, including the city and county of San Francisco and 29 wholesale water agencies in San Mateo, Alameda, and Santa Clara Counties (USBR, 1987).

O'Shaughnessy Dam was highly controversial at the time it was proposed and built in the early 1900s. Some people, including John Muir, questioned whether a reservoir for San Francisco belonged in a national park 200 miles from the city. Others, such as San Francisco Mayor James Phelan and city engineer Michael O'Shaughnessy, believed Hetch Hetchy Valley could be used to its greatest potential by damming it to ensure a stable water supply for San Francisco.

Today the idea of removing O'Shaughnessy Dam to restore Hetch Hetchy Valley has been raised again. Some believe the idea is preposterous. However, arguments on both sides of the debate have changed and are more complex than in the early 1900s. Yosemite National Park is now one of the most loved and visited parks in the United States. San Francisco is now a major urban center in California, with millions of residents requiring water delivery, the Tuolumne River now has much more storage capacity with the construction of New Don Pedro Reservoir. For restoration to be considered, it must be determined that the Hetch Hetchy System can supply enough water without O'Shaughnessy Dam, or that alternative sources exist. To answer this question, the importance of O'Shaughnessy Dam must be evaluated in the context of the Hetch Hetchy System as a whole. Current operational policies and projected needs for the future must be examined to shed light on O'Shaughnessy Dam's value to the Hetch Hetchy System.

This study provides quantitative estimates for the water supply feasibility of removing O'Shaughnessy Dam using a spatially refined economic-engineering optimization model. The least costly alternatives for San Francisco's water supply are identified. This project highlights how removal of O'Shaughnessy Dam could be expected to change current operations, water supply, deliveries, hydropower generation, the need for water treatment, and their economic costs. Examining the feasibility of removing O'Shaughnessy Dam raises many institutional, political, and economic questions. However, this study ignores many institutional and political implications to focus on optimization of water supply and economic factors. This analysis indicates whether or not water scarcity would increase substantially without O'Shaughnessy Dam assuming no additional water storage. Primary questions include:

- If O'Shaughnessy Dam were removed, could existing water facilities supply the Hetch Hetchy System's service area with water?
- Would additional scarcity occur in other urban, agricultural, or environmental water demand areas in the region without O'Shaughnessy Dam?
- What hydropower revenues would be lost from removing O'Shaughnessy Dam?
- What water quality costs would be incurred from removing O'Shaughnessy Dam?

Literature Review

Throughout the past century, there has been substantial controversy between water developers and conservationists regarding O'Shaughnessy Dam. Most of the literature pertaining to the controversy about damming Hetch Hetchy Valley pre-dates 1920 (Hundley, 1992). John Muir's writings are, without question, the most famous. For many, Muir's writings alone give Hetch Hetchy Valley the feeling of a majestic and awe-inspiring place (Muir, 1912). Excellent summaries of the debate to dam Hetch Hetchy Valley are posted on the Sierra Club webpage and the Library of Congress, conservation crossroads webpage (Sierra Club, 2003, Library of Congress, 2003). In addition an interesting timeline on the events of the debate can be found at *http://www.lcusd.net/lchs/mewoldsen/HetchHetchyDescription.htm*.

After O'Shaughnessy Dam's completion in 1923, the idea of Hetch Hetchy Valley without a reservoir was largely forgotten. In 1987, Donald P. Hodel, then Secretary of the Interior under Ronald Reagan, renewed interest in Hetch Hetchy Valley by suggesting that restoration of Hetch Hetchy Valley might be possible. The U.S. Bureau of Reclamation produced a report for the National Park Service on possible water replacement scenarios to enable dam removal (USBR, 1987). Soon after the Department of Energy issued a report discrediting the proposed replacement scenarios (DOE, 1988). Argent (1988) concluded that a study authorized by Congress to examine potential restoration of the valley is unlikely. Long (1995) claimed restoration of Hetch Hetchy Valley is unlikely because ballot measures regarding the Hetch Hetchy System have always received voter majority. Since the system has always been popular in the past, it probably will be in the future.

A handful of non-profit organizations are evaluating the support for restoring Hetch Hetchy Valley, searching for water storage alternatives to O'Shaughnessy Dam, and investigating policy concerns relating to possible removal of the reservoir. The most prominent group is Restore Hetch Hetchy (Restore Hetch Hetchy, 2003). Policy analysts, engineers, environmental activists, and legal advisors from this organization have been researching the possibility of removing O'Shaughnessy Dam, and meeting with politicians, the public, and Hetch Hetchy System managers to discuss alternatives to the dam. Sierra Club and Environmental Defense are additional non-profit organizations that have publicly endorsed restoration of Hetch Hetchy Valley or studies to evaluate restoration potential of the valley (Sierra Club, 2003; Environmental Defense, 2003).

At this time, the idea of removing O'Shaughnessy Dam is not in the forefront of issues before the public or politicians. However, a handful of newspaper articles on both coasts of the United States have highlighted alternatives to Hetch Hetchy Reservoir. Such articles have been published in the *New York Times* (Murphy, 2002), *San Francisco Examiner* (Brazil, 2000), *LA Times* (Glionna, 2002), *Sacramento Bee* (Philp, 2002; Sample, 2002), *San Jose Mercury News* (Carroll, 2002), *Fresno Bee* (Grossi, 2000), *Contra Costa Times* (Taugher, 2002). Although they do not provide new data or analysis on the feasibility of removing O'Shaughnessy Dam, newspaper articles focused some attention on the idea that restoring Hetch Hetchy Valley may be possible.

This thesis gives a brief overview of Hetch Hetchy Valley and the events that led to the construction of the dam. It then examines current thought on dam removal, as it pertains to O'Shaughnessy Dam. O'Shaughnessy Dam and the Hetch Hetchy System are described, noting characteristics such as reservoir size and primary use, which could affect potential removal decisions. CALVIN, the computer model used to evaluate alternatives to O'Shaughnessy Dam, is then explained. A discussion of parameters in the model, infrastructure modifications, and benefits and limitations of CALVIN follow. Model runs used for this study are described, with important assumptions noted. Discussion then moves to model results. Attention is given to changes that occur when O'Shaughnessy Dam is removed in the model, including surface storage in the Hetch Hetchy System, water deliveries, scarcity, conveyance, hydropower, and water treatment. A short section on the economic value of additional capacity at select facilities follows to highlight possible changes to the Hetch Hetchy System, along with a discussion of possible effects of removing O'Shaughnessy Dam with projected year 2100 urban and agricultural demands. Discussion highlights the extent of water scarcity, changes in water storage in the Hetch Hetchy System, groundwater basins, and changes in hydropower generation with increased demand. The paper concludes with a short discussion on the implications of removing O'Shaughnessy Dam, and the primary institutional and economic factors affecting the feasibility of removing O'Shaughnessy Dam.

CHAPTER TWO
BACKGROUND

Hetch Hetchy Valley

Prior to construction of O'Shaughnessy Dam, Hetch Hetchy Valley looked nearly identical to Yosemite Valley (Figure 1). The same forces and processes formed and shaped the two valleys. Only eighteen miles apart, they had similar waterfalls, rock formations, and vegetation; as well as similar elevation and orientation along the flank of the Sierra Nevada Mountains (DeLorme, 2000). Both valleys were formed from jointed granite bedrock. The valleys were initially cut by the Tuolumne and Merced Rivers respectively; then glaciers scoured them, widening and polishing the surrounding granite. Both valleys once had natural lakes that filled with sediment, forming the flat meadows eventually found there (Huber, 2002). Hetch Hetchy Valley is about three miles long and half a mile wide, smaller than Yosemite Valley.

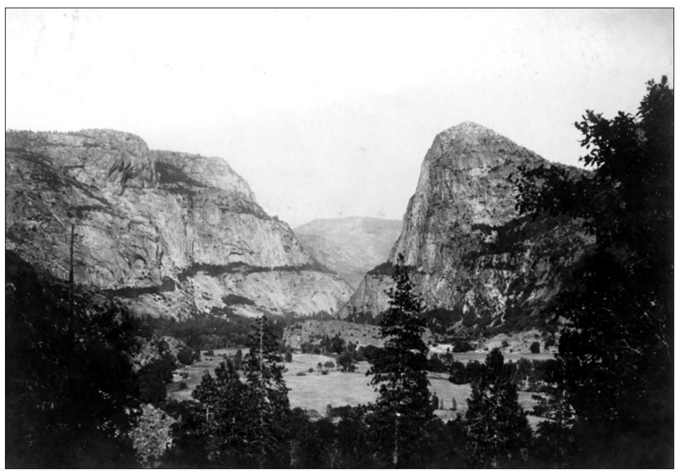

Figure 1. Hetch Hetchy Valley prior to construction of O'Shaughnessy Dam (USGS ID: Topography A107, 1906)

In 1906, following the San Francisco earthquake, the shortcomings of San Francisco's water supply became obvious. At that time, a private water company, Spring Valley Water Works, delivered the city's water (Hundley, 1992). A shortage of water contributed to fires burning out of control after the earthquake. While city water planners had already targeted Hetch Hetchy as the potential site of a large dam to ensure San Francisco's water supply, the fires acted as a catalyst for the public to realize the city's water supply problems (Hundley, 1992).

San Francisco's proposal to dam Hetch Hetchy Valley was met with considerable opposition. Muir formed the Sierra Club and spearheaded the battle to stop the valley from being dammed. In The Yosemite, he wrote, "Dam Hetch Hetchy! As well dam for water-tanks the people's cathedrals and churches, for no holier temple has ever been consecrated by the heart of man." (Muir, 1912). San Joaquin Valley farmers also opposed the dam, fearing their water would be taken even though they had senior water rights (Hundley, 1992). On the other side of the controversy, leading the water developers and city planners was San Francisco mayor, James D. Phelan, Secretary of the Interior, James R. Garfield, and chief forester for the U.S. Forest Service, Gifford

Pinchot. Although a previous Secretary of the Interior had denied San Francisco's request to dam Hetch Hetchy Valley for aesthetic reasons, Garfield believed "Domestic use, … especially for a municipal water supply, is the highest use to which water and available storage basins … can be put" (Reports on the Water Supply, cited in Hundley, 1992). Pinchot used a utilitarian mentality, seeing benefits from multiple-uses of US Forest Service land to argue the need for damming Hetch Hetchy Valley. "The delight of the few men and women who would yearly go into the Hetch Hetchy Valley should not outweigh the conservation policy, [which is] to take every part of the land and its resources and put it to that use in which it will be serve the most people." (USFS, 2002).

Ultimately, San Francisco's voters approved the construction of a dam in Hetch Hetchy Valley by an 86% majority vote in 1908 (Restore Hetch Hetchy, 2002). Despite this, the Taft administration suspended the decision. It wasn't until 1913, under the new administration of Woodrow Wilson, that the Raker Act was passed in Congress. The Raker Act enabled a large reservoir to be built in a national park (Hundley, 1992). O'Shaughnessy Dam was completed in 1923, raised in 1938, and has been in use for the past eighty years (Sierra Club, 2002) (Figure 2).

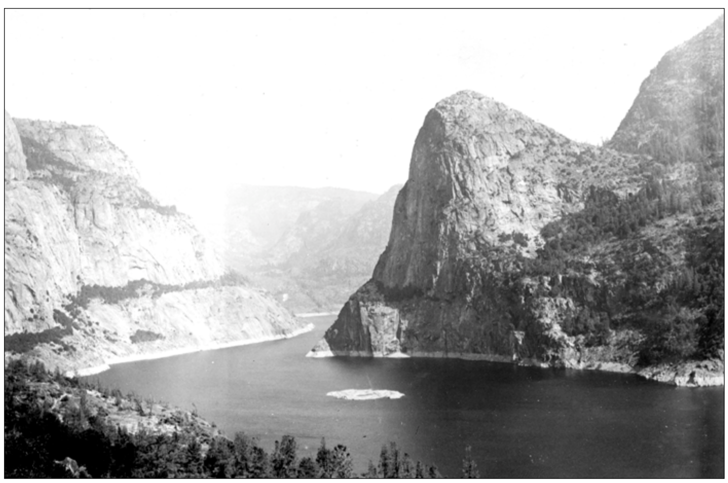

Figure 2. Hetch Hetchy Valley after construction of O'Shaughnessy Dam (USGS ID: Matthes, F. E. 986, 1936)

O'Shaughnessy Dam

O'Shaughnessy Dam has a storage capacity of 360,360 acre-feet (af). The dam itself is a 430 foot concrete gravity arch (USBR, 1987). It is considered a multipurpose reservoir. Its current uses include water storage, hydropower generation, and to a lesser extent flood reduction (USBR, 1987). Primary flood control benefits are provided downstream of O'Shaughnessy Dam, by New Don Pedro Reservoir. If O'Shaughnessy Dam were to be removed, New Don Pedro Reservoir would have to be operated differently to account for uncontrolled inflow (USBR, 1987). The reservoir behind O'Shaughnessy Dam is not used for recreation.

In terms of total water storage in the Hetch Hetchy System, O'Shaughnessy Dam is not an exceptionally large reservoir. It provides 360 thousand acre-feet (taf) of surface water storage, approximately 25% of surface storage in the Hetch Hetchy System. For this study, removal of O'Shaughnessy Dam applies only to the dam and resulting reservoir. No pipelines, diversion capacity, or conveyance facilities would be removed.

The Hetch Hetchy System

Downstream of O'Shaughnessy Dam, the Kirkwood Power Plant and Moccasin Power Plant generate hydropower. Nearby, Cherry Reservoir and Eleanor Reservoir are currently operated primarily for hydropower at Holm Powerhouse. Adequate storage for water supply is usually provided by O'Shaughnessy Dam (CDEC, 2002). The water from O'Shaughnessy Dam, Cherry Reservoir and Eleanor Reservoir all merge into the main stem Tuolumne River or the Hetch Hetchy Aqueduct. Another much larger dam, New Don Pedro Reservoir, is downstream of O'Shaughnessy Dam, Cherry, and Eleanor Reservoirs (SFPUC, 2002).

These four reservoirs, together with numerous Bay Area reservoirs and the connecting pipelines make up the Hetch Hetchy water system operated by the San Francisco Public Utilities Commission (SFPUC). Total surface storage in the Hetch Hetchy System is 2,000 taf (Table 1). In addition to the Hetch Hetchy System total, an additional 1,500 taf of storage is owned by Modesto Irrigation District and Turlock Irrigation District in New Don Pedro Reservoir. The Hetch Hetchy System supplies water to 77% of the urban and industrial uses of the city and county of San Francisco, as well as parts of San Mateo, Santa Clara, and Alameda Counties. In total, over 2 million urban users are supplied with water from the Hetch Hetchy System (DOE, 1988). The three powerhouses on the upper Tuolumne River together provide approximately 2 billion KW hrs/yr of hydropower (USBR, 1987). This is a clean source of energy for residents of San Francisco, and an important source of revenue for the SFPUC.

Table 1. Storage in the Hetch Hetchy System

Reservoir	Capacity (TAF)
O'Shaughnessy	360
Eleanor	28
Cherry	268
New Don Pedro	570*
San Antonio	50
Calaveras	97
Lower Crystal Springs	58
Pilarcitos	3
San Andreas	19
Total Storage	**1,454**
*Space owned by the city and county of San Francisco	
Total Storage in New Don Pedro Reservoir = 2,030	

SFPUC's Capital Improvement Program

Proposition A was the bond initiative for SFPUC's Capital Improvement Program (CIP) passed in November 2002 by San Francisco voters. The CIP slates $3.6 billion over 13 years to "improve the reliability of the SFPUC system and reduce its risk of failure" (SFPUC, 2002). Specifically, main goals are: repair aging infrastructure, provide seismic retrofits (near Calaveras, Hayward, and San Andreas Faults), provide for increasing future demands, and remain in compliance with changing regulations.

Although water storage remains a priority for SFPUC and the Hetch Hetchy System, it is not the 360 taf of water storage that makes O'Shaughnessy Dam valuable; rather, it is because water from O'Shaughnessy Dam has filtration avoidance status (SFPUC, 2002). Typically, filtration of water supplies is an integral step in the multiple drinking water treatment processes used to meet water quality and public health standards. Filtration avoidance means O'Shaughnessy Dam impounds extremely high quality water that meets water quality standards under the federal Surface Water Treatment Rule (SWTR). Only minimal water treatment is currently necessary, such as addition of lime for corrosion control and chlorine or chloramine as a disinfectant (Redwood City PWSD, 2003, SFPUC, 2003). The watershed above O'Shaughnessy Dam is pristine, lying within Yosemite National Park. O'Shaughnessy Dam is the only reservoir in the Hetch Hetchy System to have filtration avoidance. Even Cherry and Eleanor Lakes, less than ten miles from O'Shaughnessy Dam do not qualify for filtration avoidance.

Filtration avoidance status is rare in large supply systems, but does exist occasionally. The Catskill/Delaware System for New York City just received a renewed filtration avoidance determination in 2002. It was first granted filtration exemption in 1991, and has struggled to maintain the exemption over the past decade (US EPA, 2002). In 1998, the filtration avoidance determination was lost for the Croton System, also serving New York City. The water supply systems for Seattle, Washington and Portland, Oregon also remain unfiltered, although extra filtration equipment has been added in Seattle for at least part of the system (Water Industry, 2003).

Potential for Removing O'Shaughnessy Dam

There are valid arguments for both keeping and removing O'Shaughnessy Dam. Arguments on both sides are primarily economic. Hydropower is generated when water is released from O'Shaughnessy Dam. In addition, loss of filtration avoidance determination would incur considerable costs to the Hetch Hetchy System, and thus to water users. Furthermore, the existence of O'Shaughnessy Dam provides security in the water supply, whether real or imagined, to operators of the Hetch Hetchy System and its customers. Finally, some environmentalists believe that O'Shaughnessy Dam is a poor choice for removal because there is relatively little ecological improvement to be gained from removal of this dam. Its removal would benefit no threatened or endangered species, and would make only minor improvements to the ecological connectivity of the Tuolumne River system. The land under the reservoir could be restored, but this is a small land area to justify removal on environmental grounds.

The arguments for removing O'Shaughnessy Dam deal primarily with increasing open space in Yosemite National Park for tourism and recreation. Yosemite National Park is one of the most heavily visited national parks in the nation. Within the park, Yosemite Valley is grossly impacted. Restoring Hetch Hetchy Valley could open a valley nearly identical to Yosemite Valley in terms of beauty and size to wildlife and the public (Figure 3). Revenue from tourism could offset some or all of the lost revenues from removal of O'Shaughnessy Dam. However, SFPUC would lose revenue from removal of O'Shaughnessy Dam, though they would not receive economic benefit through increased tourism to Hetch Hetchy Valley. Still, this problem can be thought of as weighing two scarce resources, water and space, in Yosemite National Park. There are also ethical questions regarding the existence of O'Shaughnessy Dam. It has been argued that a reservoir for San Francisco residents simply does not belong in Yosemite National Park, land that in theory belongs to all Americans (Muir, 1912).

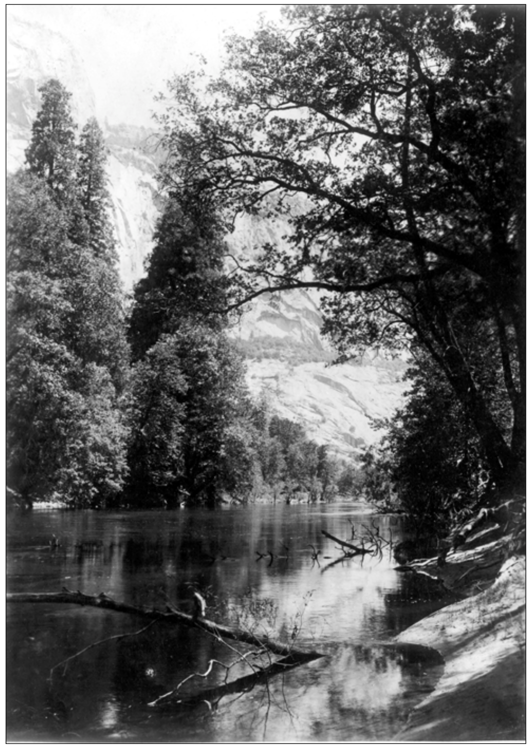

Figure 3. The Tuolumne River in Hetch Hetchy Valley (USGS ID: Topography A112, 1906)

If O'Shaughnessy Dam were to be removed, restoration efforts would likely be intensive since Hetch Hetchy Valley is in Yosemite National Park. Restoration could include removal of the concrete face of the dam, which would be more thorough for restoration, but also entails operating heavy machinery in a restoration site. Or the reservoir could be drained, but the dam left in place as a historical monument, with restoration focusing on the valley behind it. For either option the lower 118 ft of the dam, the portion that was excavated into bedrock, would most likely be left to make the longitudinal stream profile of the Tuolumne River function normally (Riegelhuth, Botti, and Keay, n.d.).

O'Shaughnessy Dam is unique in the sense that sedimentation is probably negligible. Rates of sedimentation in natural Sierra Nevada lakes typically vary based on size of the lake. The smallest lakes can receive 2 ft/1000yrs of sediment, whereas larger natural lakes such as Tenaya Lake may receive 6 in/1000yrs (Schaffer, 1997). Hence, the reservoir behind O'Shaughnessy Dam probably receives no more than 6 in/1000yrs of sediment. Similarly, dams typically increase nutrient retention in the reservoir (Stanley and Doyle, 2002). This too is most likely low because there is little pollution above the reservoir, the snow fed water in the Tuolumne River is cold, and there are relatively few aquatic organisms in the river. If sedimentation and nutrient retention occur at all, it is at the upper end of the reservoir where the river velocity slows as it enters the reservoir. Were O'Shaughnessy Dam to be removed, little or no dredging or removal of silt would be necessary.

It is assumed the Tuolumne River would return to its natural channel without human assistance. During 1977, a critically dry year, the river was in its original channel in the upper four miles of Hetch Hetchy Valley that were exposed from low reservoir levels (Riegelhuth, Botti, and Keay, n.d.). Herbaceous vegetation could return to Hetch Hetchy Valley within a year or two. Woody shrubs and tree saplings could follow over the next decade. Thus, it would not take long for Hetch Hetchy Valley to become a pleasant recreation site. Very large trees could take 50-100 years. The bathtub ring left by the reservoir would be noticeable long into the future. The bathtub ring occurs from the absence of lichen, as well as the bleaching of natural water stains from submersion of the granite walls. Lichen could grow within 75-120 years (Riegelhuth, Botti, and Keay, n.d.). The staining of the granite from moisture would not return on a human timescale.

Trends in Dam Removal

The majority of the 20th century was marked by immense popularity for dam and water infrastructure projects. Dams have been instrumental in providing the safety and standard of living that we take for granted today. They supply energy from hydropower, provide flood control benefits, supply water for irrigation, open water recreation opportunities, allow humans to farm on productive floodplain soils, and provide a reliable water supply for urban areas, especially for arid or drought-prone regions (Poff and Hart, 2002). Over the past few decades, substantial research has been devoted to the impacts of dams on river processes, aquatic organisms and vegetation. While negative effects of dams vary with the type of dam, the age of the dam, its operation and maintenance, and the type of pre-existing ecosystem, the negative effects of dams are now well documented (Poff and Hart, 2002; Bednarek, 2001; Graf, 2001).

This knowledge has led to the idea of a “water ethic” of increasing water efficiency without new infrastructure (Poff and Hart 2002). The options for increasing the efficiency of our water supply are wide reaching, including: coordinated use of existing water infrastructure, conjunctive use between surface water and groundwater, conservation technologies, and water transfers (Lund and Israel, 1995; Howe et al, 1986; DWR, 1998). In some of these scenarios, improved water conveyance facilities become more important than water storage facilities. A reservoir could be replaced by pipelines to improve flexibility in the supply system. Today, increasing numbers of people look at the unforeseen costs of damming America’s rivers and wonder if there might be better methods of supplying water. With this apparent shift of ideology, the popularity of dam removal has risen dramatically. At least 467 dams were removed in the latter part of the 20th century, with an additional 30 dams removed in 2001 alone (Poff and Hart, 2002; American Rivers, 2002). However, some of these dam removals are for reasons other than ecological or aesthetic, such as improper maintenance of facilities or safety concerns.

While there is a noticeable lack of scientific framework for dam removal, research regarding dam removal is becoming more common. Major research and synthesis on dam removal has recently been undertaken by such groups as: the Heinz Center (Heinz Center, 2002), the Patrick Center, and the Aspen Institute (Aspen Institute, 2002). Additionally, the majority of the August 2002 edition of *Bioscience* was devoted to the subject (Bioscience, 2002). These groups have taken a multi-disciplinary approach to dam removal, enlisting physical scientists, economists, engineers, social scientists, lawyers, and public policy analysts.

CHAPTER THREE
METHODS

This chapter begins with a quick introduction to various computer modeling approaches, and why optimization was used for this study. CALVIN, the model used for this study is described, and its objective function and constraints are presented. The physical parameters and economic data used to create the model are given. An outline of the model area and its facility components follows. All assumptions of the model are addressed, including simplification of water systems, possible future capacity expansions, and omission of institutional and legal constraints. Next, the changes that were made to the model for projected year 2100 model runs are outlined. The year 2020 and year 2100 model runs that are compared for this study are presented. This chapter concludes with a discussion of the limitations of the model and the modeling approach.

Modeling Approach

Simulation is the most common modeling approach for exploring solutions to water resource problems. They answer 'what if' type questions and are useful for fine-tuning results once promising scenarios have been identified. Optimization models are another approach. They can suggest promising solutions when flexibility exists in a system and implicitly evaluate many alternatives without numerous simulation model runs. Optimization models must include explicit objectives to be maximized or minimized within system constraints. Until recently, optimization models were too computationally burdensome to be practical for large systems or problems. Now, more powerful computers make optimization of large systems feasible (Labadie, 1997; Yeh, 1985).

There are many types of optimization models. Each has benefits and limitations. Linear programming (LP) is the most common. It ensures a global optimal solution and shadow values for sensitivity analysis. All equations for the objective function and constraints must be linear. A special case of LP optimization is network flow models, where a system is represented with interconnecting arcs and nodes. This is a simple and intuitive method. These models can be deterministic or stochastic, dynamic or static, and have lumped or distributed parameters.

CALVIN

CALVIN (CALifornia Value Integrated Network) is an implicitly stochastic, network flow economic-engineering optimization model of California's inter-tied water management system. It was developed by Jenkins et al. at the University of California, Davis (2001 and appendices, Draper et al., 2003). Reports on CALVIN are online (*http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/*). Only main points of CALVIN fundamental to understanding this study of O'Shaughnessy Dam are included in this paper.

The objective function for CALVIN is to minimize total economic costs. Mathematically it is represented as

$$\text{Minimize } Z = \sum_{i}\sum_{j} c_{ij} X_{ij}$$

where Z is total cost, c_{ij} is the cost coefficient on arc ij, and X_{ij} is flow from node i to node j. CALVIN also has constraints representing physical or operational bounds. These include constraints for conservation of mass, upper bounds, and lower bounds. Mathematically, these are written as

Subject to: $\sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j$ for all nodes j

$X_{ij} \le u_{ij}$ for all arcs

$X_{ij} \ge l_{ij}$ for all arcs

where X_{ij} is the flow from node i to node j, a_{ij} is gains or losses on flows in arc, b_j is external inflows to node j, u_{ij} is upper bound on arc, and l_{ij} is lower bound on arc (Jenkins et al., 2001). The HEC-PRM (Hydrological Engineering Center Prescriptive Reservoir Model) code within CALVIN solves for the least cost solution.

CALVIN uses 72 years of monthly unimpaired historical data to represent future hydrology, from water year 1922 to water year 1993. The three worst droughts on record, 1929-1934, 1976-1977, and 1987-1992, occurred during this period. This span is used to represent the variability of California’s hydrology.

As stated above, California’s entire inter-connected water system has been modeled with CALVIN. The statewide model has been used to identify promising water supply options, assess user willingness to pay for water, integrate facility operations, identify promising facility changes, and examine climate changes (Jenkins et al, 2001; Lund et al., 2003; Draper et al., 2003). Additionally, regional CALVIN models of California have been used to study water markets in Southern California, water management strategies for the San Joaquin Valley and San Francisco Bay Area, and the effects of increased Delta exports on Sacramento Valley's economy and water management (Newlin et al., 2002; Ritzema, 2002; Tanaka 2001).

Parameters and data

Physical and economic parameters are used to represent California’s water supply system in CALVIN (Figure 6). Physical parameters include infrastructure capacities, environmental requirements, and hydrology. Surface reservoirs and groundwater basins each have an upper and a lower bound. For surface reservoirs, the maximum capacity is the bottom of the flood storage level and minimum capacity is the top of dead storage. For groundwater basins, the maximum capacity is the total amount of water that can be stored in the aquifer. The lower bound is the lowest level that groundwater has historically been pumped. There are also upper bounds on pumping and conveyance facilities, corresponding to the maximum capacity of a pump or pipeline.

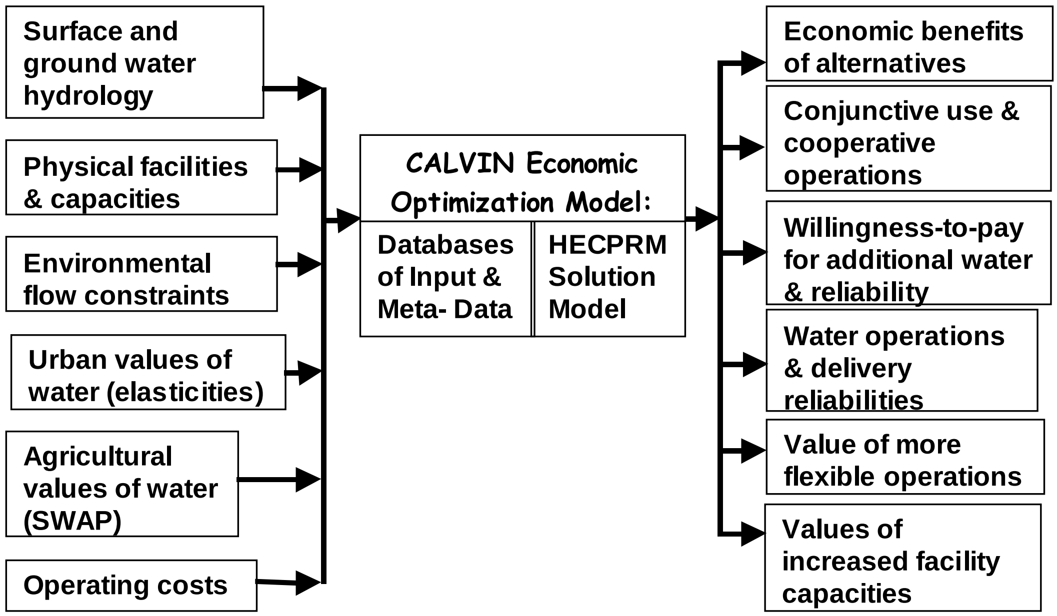

Figure 6. Data Flow Schematic for CALVIN

Environmental requirements include minimum instream flows and flows to refuges. Due to the controversy inherent in applying prices to environmental uses of water, environmental water requirements are modeled as constraints. This ensures that environmental uses, such as minimum instream flows, receive all their water before urban and agricultural demand areas.

Economic parameters include penalty / demand functions and operating costs. CALVIN uses projected demands for the year 2020 for agricultural and urban demand areas. Since the objective function of CALVIN is to minimize cost, economic penalties are imposed if agricultural and urban demands are not met. If all demand for water is met, penalties are zero. Operating costs correspond to variable costs, primarily for groundwater pumping, surface pumping, water treatment, and urban salinity damage.

Major hydropower facilities are included in this modeling study because they provide economic returns. Hydropower penalty curves are non-linear, and are thus difficult to model. Hydropower can be generated from fixed head facilities, where reservoir storage head is a minor part of total head. These facilities can be represented fairly easily with piece-wise linear algorithms in which penalty curves are broken down into many linear sections. However, many facilities have variable storage head, where higher reservoir storage levels produce higher head, which in turn generates more power. The storage and release penalties (SQ) method was chosen to represent variable head facilities. It estimates a non-linear hydropower penalty function by summing many independent linear storage and release penalties. This results in a penalty surface bounded by minimum flows needed for hydropower generation and maximum capacity of the facility; and by minimum and maximum storage of the reservoir. The penalty surface is then fit to a piece-wise linear surface using a Least Squares approach (Ritzema, 2002). Although it is also possible to model these facilities using an iterative variable head (IVH) method, this method is computationally burdensome and thus impractical when numerous hydropower facilities are included.

Model Area and Assumptions

The statewide CALVIN model can be separated into regional models. To examine the effects of removing O'Shaughnessy Dam, this study focuses on Region 3, the San Joaquin and South Bay Area. The southern boundary is the San Joaquin River; the northern boundary is the north fork of the Stanislaus River and the South Bay Aqueduct. The model spans the western Sierra Nevada to the Pacific coast (Figure 7).

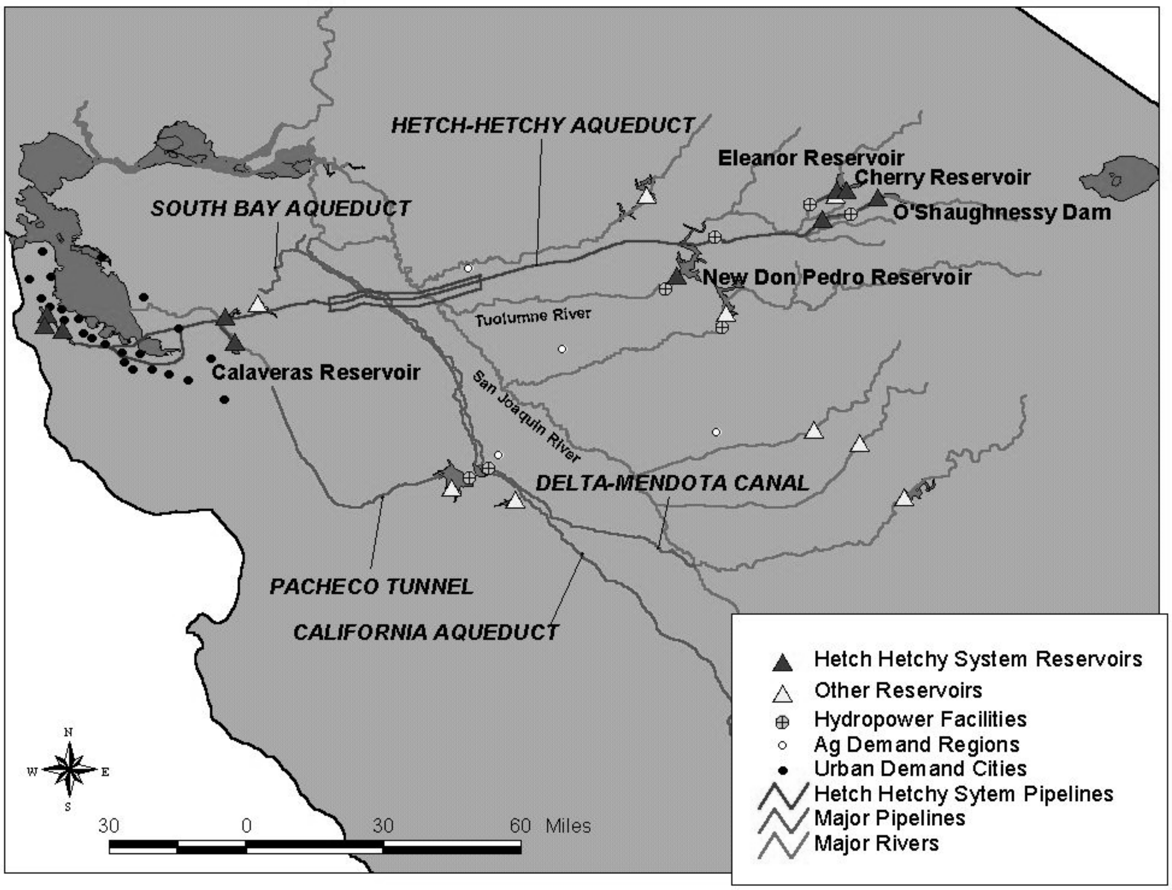

Figure 7. Map of region 3

The model area includes 13 surface reservoirs, excluding O'Shaughnessy Dam, and five groundwater basins (Figure 8). Major conveyance facilities include: the Hetch Hetchy Aqueduct, the California Aqueduct, the Delta Mendota Canal, the South Bay Aqueduct, and the Pacheco Tunnel (San Felipe Unit). Seven hydropower plants have been included, all use variable head algorithms, except San Luis Reservoir, which used a fixed head algorithm. Minimum instream flows have been imposed on a river reach on the Tuolumne River below New Don Pedro Reservoir, on the San Joaquin River below the confluence with the Stanislaus River at Vernalis, and on the Stanislaus River below

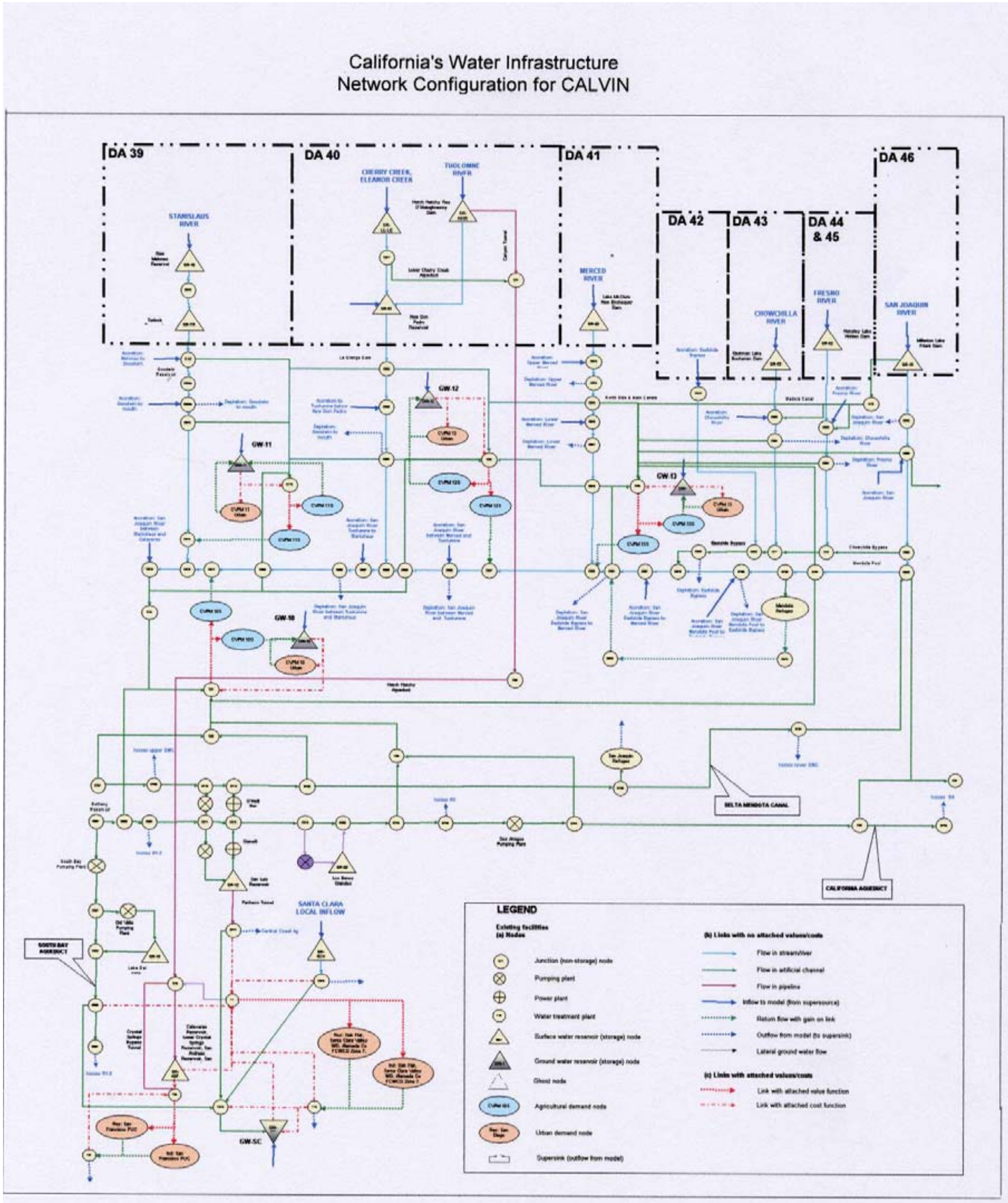

Figure 8. Schematic of the San Joaquin and South Bay Area of CALVIN

Goodwin Reservoir. For details of the CALVIN Region 3 model, see (Ritzema, 2002; Ritzema and Jenkins, 2001).

Six urban demand regions and four agricultural demand areas are included in the model area. Projected year 2020 demand data was obtained from DWR's Bulletin 160-98 data on per capita urban water use by county and detailed analysis unit (DAU) (Jenkins, 2000). Four urban demand areas in the Central Valley are not economically modeled because data was not available and because these areas are primarily groundwater users. They have relatively small demands that are represented as fixed diversions. Demand for cities such as Modesto, Turlock, Merced, Manteca, and Madera are modeled in this manner (Jenkins, 2000; Ritzema and Jenkins, 2001).

The remaining two urban demand areas for Bay area users aggregate numerous communities. The San Francisco Public Utilities Commission demand area combines the city and county of San Francisco with most of San Mateo County. The Santa Clara Valley demand area includes Santa Clara Valley Water District, Alameda County Water District, and Alameda County Zone 7. Both the SFPUC and SCV water demand areas are represented using economic value functions. In both these areas, residential and industrial water users are separated into two different value functions (Jenkins, 2000; Ritzema and Jenkins, 2001).

Agricultural demands are modeled using economic value functions for water derived from the Statewide Water and Agricultural Production Model, or SWAP (Howitt et al., 2001).

Although the regional model is large enough to allow for coordinated use between different storage and conveyance facilities, the focus of this study is the Hetch Hetchy System (Table 2). The Hetch Hetchy System includes eleven reservoirs. In CALVIN, the local San Francisco area reservoirs (Calaveras, Lower Crystal Springs, San Andreas, and San Antonio) have been represented as a single, aggregated service area reservoir. Pilarcitos Reservoir was not included because it has negligible storage (3 taf). Cherry and Eleanor Reservoirs are represented as a single reservoir in the model because of the inability to disaggregate inflows into these reservoirs and the existence of a connecting tunnel between them (Figure 9). Due to aggregated reservoirs, some conveyance facilities have been simplified or eliminated from the model. Non-storage reservoirs in the Hetch Hetchy System, such as Early Intake and Moccasin Reservoir are represented as non-storage nodes instead of reservoirs. Hydropower is included in the model for Kirkwood, Holm, Moccasin, and New Don Pedro power plants. Minimum instream flows of 50-125 cfs are imposed on the Tuolumne River downstream of New Don Pedro Reservoir (USBR, 1987).

Table 2. Components of the Hetch Hetchy System

Representation in CALVIN	Component Name	Schematic Name
surface storage node / non-storage node	O'Shaughnessy Dam	SR-HHR
surface storage nodes	Cherry and Eleanor Lakes	SR-LL-LE
	New Don Pedro Reservoir	SR-81
	Calaveras, Lower Crystal Springs, San Andreas, San Antonio Reservoirs	SR-ASF
variable head hydropower plants (SQ)	Kirkwood Hydropower Plant	SR-HHR_C44
	Moccasin Hydropower Plant	C44_C88
	Holm Hydropower Plant	SR-LL-LE_SR-81
	New Don Pedro Hydropower Plant	SR-81_D662
non-storage node	La Grange Dam	D662
diversion links	Mountain Tunnel	SR-HHR_C44
	Lower Cherry Creek Aqueduct	SR-LL-LE_C44
	Hypothetical New Don Pedro Inter-tie	SR-81_C88
	Hetch Hetchy Aqueduct	C44_C88, C88_C79, C79_SR-ASF
	Crystal Springs Bypass Tunnel	C79_T20
minimum instream flow	Tuolumne River below New Don Pedro	SR-81_D662
ground storage nodes	Delta-Mendota Basin	GW-10
	Modesto Basin and south portion of Eastern San Joaquin County Basin	GW-11
	Turlock Basin	GW-12
urban demand nodes	City and County of San Francisco, most of San Mateo County	SFPUC: Residential and Industrial
	Santa Clara Valley WD, Alameda Co. WD, Alameda Co. Zone 7	SCV: Residential and Industrial
	Madera, Merced, San Joaquin, and Stanislaus Counties	CVPM 10 Urban
	San Joaquin and Stanislaus Counties	CVPM 11 Urban
	Merced and Stanislaus Counties	CVPM 12 Urban
agricultural demands	Valley floor west of San Joaquin River	CVPM 10
	Valley floor east of San Joaquin River	CVPM 11
	Eastern Valley Floor between San Joaquin River and Tuolumne River	CVPM 12
water treatment nodes	SFPUC Water Treatment	T20
	Santa Clara Valley Water Treatment	T7
wastewater	SFPUC Water Treatment	T21

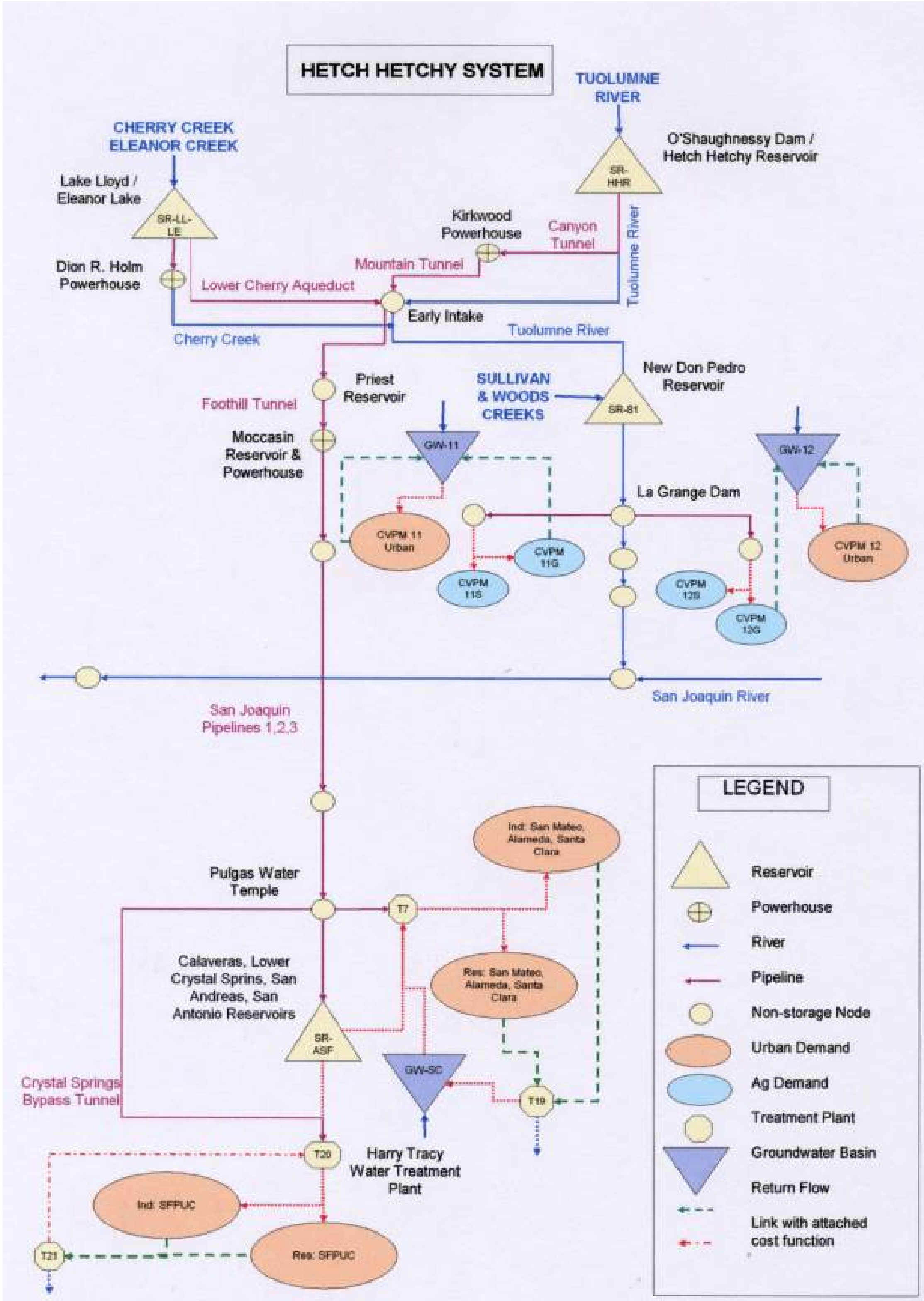

Figure 9. Hetch Hetchy System Model Schematic

Although raising the dam at Calaveras Reservoir is often discussed, in all model runs Calaveras Reservoir is given a maximum capacity of 91 taf. Likewise, storage at this site has not been lowered to the current restriction of 28% of total maximum storage (SFPUC, 2003). Model runs show surplus storage (greater than the amount reduced) already exists at the single aggregated reservoir that represents local San Francisco area storage. An additional model could have been run with more storage, but it should show no changes to storage levels or operations for local San Francisco water storage. While additional water storage is a priority for SFPUC and the Hetch Hetchy System, this study assumes no new storage.

New Don Pedro Reservoir has a maximum capacity of 2,030 taf. Of this, SFPUC and the Hetch Hetchy System own 570 taf. Modesto Irrigation District and Turlock Irrigation District own the remaining storage. In CALVIN, storage space in New Don Pedro Reservoir is not divided between different owners. Rather, the maximum capacity of New Don Pedro Reservoir was set to 2,030 taf and water is allocated to different urban and agricultural demands as needed. Because CALVIN is economically driven, when water scarcity occurs, it occurs in demand areas with lower economic willingness to pay for water, usually agricultural areas. Here, results should be interpreted to indicate the extent of water scarcity. However, actually water scarcity often occurs to demand areas based on water rights and contracts. In this area, agricultural users would be unlikely to face scarcity due to senior water rights.

For model runs in which O'Shaughnessy Dam has been removed, an inter-tie between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct has been added. Physically, the Hetch Hetchy Aqueduct crosses New Don Pedro Reservoir. As stated above, the Hetch Hetchy System owns storage space in New Don Pedro Reservoir; however, there currently is no way to route this water to Bay Area users except by releasing it through the Tuolumne River to the San Joaquin River, pumping from the Delta, then routing it to either the South Bay Aqueduct or the Pacheco Tunnel via the California Aqueduct. This hypothetical New Don Pedro-Hetch Hetchy Aqueduct inter-tie increases flexibility in the conveyance system, and ensures higher quality water to Bay Area customers than water pumped from the Delta. For this study, the New Don Pedro inter-tie is given unlimited capacity, although it connects to the Hetch Hetchy Aqueduct, which has a maximum capacity of 465 cfs, which in essence, also constrains the New Don Pedro inter-tie.

Water treatment costs are typically non-linear with high fixed costs and economies of scale. In CALVIN, they can only be modeled implicitly with unit costs on treatment links. O&M treatment costs from Owens Valley and the LA Aqueduct System were applied to the Hetch Hetchy System to estimate possible increased variable treatment costs from loss of the filtration avoidance determination. The LA Aqueduct System was chosen because, like Hetch Hetchy, water from this area originates in a fairly pristine watershed. Thus, treatment costs should be similar (Newlin et al., 2001). Additional fixed costs for constructing water treatment plants requires a side calculation outside of the model.

Year 2100 Demands

This study includes two model runs with estimated urban and agricultural water demands for the year 2100. The goal of model runs with forecast demands for the year 2100 is to examine the effects of removing O'Shaughnessy Dam when water demand is much, much greater. Whether these demands occur in 2100, 2080, or 2120 is unimportant for these purposes. These "2100" model runs could be interpreted as an extreme scenario when population and urban development are at levels much higher than those the Hetch Hetchy System was designed for.

The estimated population data for these runs was taken from Landis and Reilly's spatially disaggregated projection for the year 2100 (Landis and Reilly, 2002, cited in Pulido-Velazquez and Jenkins, 2002), and input into CALVIN. There are about 32 million people in California today. Population may rise to 45 million by 2020, and 92 million by 2100 (using the high population scenario of Landis and Reilly's study) (Pulido-Velazquez and Jenkins, 2002). Historic hydrology was used for these runs, excluding possible climate change and sea level rise scenarios. For detailed descriptions of year 2100 demand data see the CALVIN climate change report (Lund et al., 2003), and Appendix B (Pulido-Velazquez and Jenkins, 2002). Some network changes were made to represent probable future alterations:

- San Francisco and Santa Clara Valley demand regions were given unlimited access to seawater desalination at a constant unit cost of $1000/acre-foot;
- urban wastewater recycling was made available for up to 50% of return flows, also at a cost of $1000/acre-foot;
- increasing some environmental demands to include Level 4 demands; these changes occurred on the San Joaquin River, Mendota Refuge, and San Joaquin Refuges; there were no environmental demand changes for links on or from the Tuolumne River; and
- O&M water treatment costs were increased to represent the loss of filtration avoidance by the year 2100. (Treatment costs were increased to the same level as 2020 model runs with higher treatment costs.)

Model Runs

Five model runs are compared for this study, three from the year 2020 modeling set, and two model runs with year 2100 demands (Figure 10). Of the year 2020 runs, two runs include O'Shaughnessy Dam. Of these, one run has increased water treatment costs to represent loss of filtration avoidance; the other run has no change to water treatment costs to represent filtration avoidance has been maintained. For all runs where O'Shaughnessy Dam is eliminated from the model, an inter-tie from New Don Pedro Reservoir to Hetch Hetchy Aqueduct has been added. Removing O'Shaughnessy Dam would end filtration avoidance designation, so higher O&M water treatment costs were imposed. An additional model run, without O'Shaughnessy Dam but with filtration avoidance was completed, although it is impossible for regulatory reasons. It was thought it would be useful for comparison with other model runs; however, it produced no new results. The two model runs with year 2100 water demands have increased water treatment costs. In one O'Shaughnessy Dam has been removed and an inter-tie linking New Don Pedro Reservoir with the Hetch Hetchy Aqueduct has been added.

	Keep Filtration Avoidance	Lose Filtration Avoidance
Retain O'Shaughnessy Dam	2020	2020 2100
Remove O'Shaughnessy Dam and add New Don Pedro inter-tie	scenario modeled, produced no new results	2020 2100

Figure 10. Model runs by filtration condition, dam status, and year

Limitations

Consequences of O'Shaughnessy Dam removal could be substantial. O'Shaughnessy Dam, with other reservoirs in the Hetch Hetchy System, provides water for one of California's most populated regions. The complexity of the system and management options for the system require a quantitative approach, for which computer modeling is well suited. There are several limitations to this approach.

As with all such modeling studies, management and river systems are simplified. Economic benefits from recreation are not included in CALVIN at this time. Recreation and tourism in Hetch Hetchy Valley would likely be substantial, providing revenue and benefits to Yosemite National Park and nearby towns. Flood control is also not included in CALVIN, but is not overly important for this study. An important limitation with CALVIN is perfect foresight. This allows the model to prepare for droughts, reducing water scarcity and associated costs. However, this limitation tends to be of lesser importance when large amounts of storage (including groundwater) are available (Draper, 2001). Urban and agricultural demands are assumed to be fixed, and groundwater basins are extremely simplified. For more on the limitations of CALVIN, see Jenkins et al., 2001, Chapter 5 and Appendices 2C (Ritzema and Jenkins, 2001) and 2K (Draper, 2001).

In all model runs, operations are unconstrained by current institutional and legal allocation policies. This severely limits the length and extent of water scarcity. However, it is helpful to unconstrain operations with current policies to show what is possible with existing facilities and infrastructure. In these model runs, operations and water allocation are economically driven. Results from a modeling set of Region 3 which represents 2020 conditions with current operating and allocation policies, based on CVPIA PEIS No Action Alternative and DWRSIM run 514a, are described in the 2001 CALVIN Report (Jenkins et al., 2001). Some of these results are included in the results chapter for comparison. They are referred to as base case results.

Perhaps the greatest limitation is the absence of institutional aspects and implications, and public or political support for the idea. This cannot be part of a model, but are nevertheless driving factors. It is a major omission, as the idea will ultimately succeed or fail in these arenas.

CHAPTER FOUR
RESULTS

This chapter compares year 2020 model runs with and without O'Shaughnessy Dam and presents important results. First, the effects of removing O'Shaughnessy Dam on water storage, water deliveries, and water scarcity are discussed. Next, attention is given to conveyance of water through the Hetch Hetchy System. Then the effects on hydropower generation and water treatment are estimated. Shadow values of selected facilities are evaluated to highlight promising facility changes for the Hetch Hetchy System. Finally, an analysis of possible changes from removing O'Shaughnessy Dam with projected year 2100 urban and agricultural demands concludes this chapter.

Overall, year 2020 model runs show there is little water scarcity when O'Shaughnessy Dam is removed and an inter-tie added between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct. Although storage at the O'Shaughnessy damsite is eliminated, flow in the Tuolumne River does not change. Capture of significant quantities of water into the upper Hetch Hetchy Aqueduct remains possible. The addition of an inter-tie between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct allows capture of flows past the O'Shaughnessy damsite, from downstream New Don Pedro Reservoir. Thus, the lower Hetch Hetchy Aqueduct can remain full at all times regardless of the existence of O'Shaughnessy Dam.

Although water deliveries are not greatly affected by removal of O'Shaughnessy Dam, removal could be costly. Hydropower generation suffers without water storage at O'Shaughnessy Dam. Also, removing this reservoir would end SFPUC's filtration avoidance determination and create the need for additional water treatment facilities. Filtration avoidance determination status is important and expensive enough to drive decisions regarding potential removal of O'Shaughnessy Dam.

Water Storage

Total water storage in the Hetch Hetchy System falls in model runs without O'Shaughnessy Dam (Figure 11). Minimum storage values occur in very dry years, when storage is used to sustain deliveries. Maximum storage values occur in very wet years, when storage nears capacity. As seen in Figure 1, without O'Shaughnessy Dam storage drops by approximately 350,000 af in each type of water year, the approximate capacity of O'Shaughnessy Dam. To assess whether the storage space lost from removal of O'Shaughnessy Dam is critical to meet water deliveries, storage in the other Hetch Hetchy System reservoirs can be evaluated.

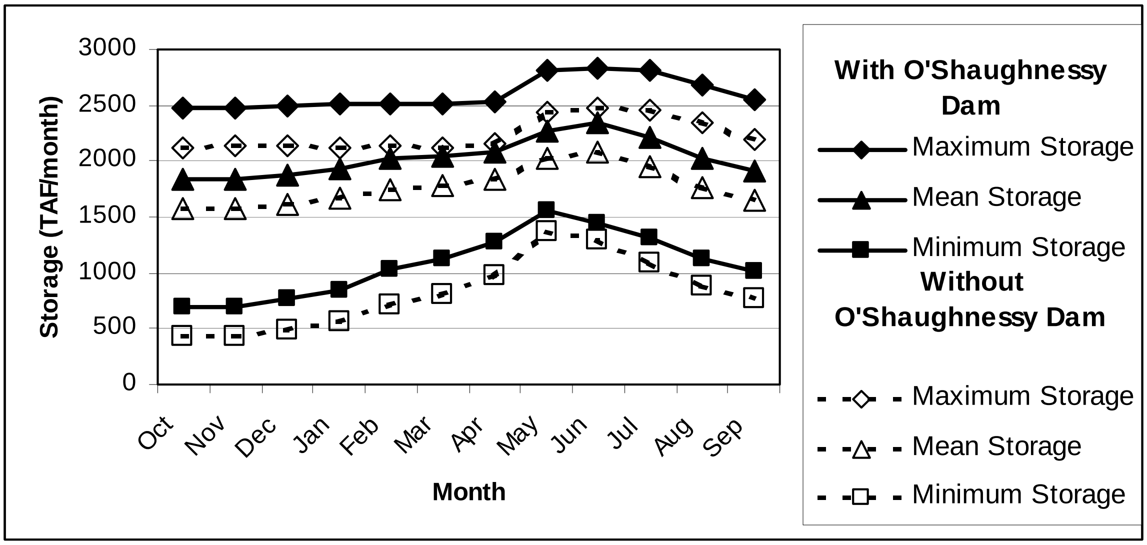

Figure 11. Hetch Hetchy System water storage

Water storage remains about the same in Cherry/Eleanor Reservoir, New Don Pedro Reservoir, and local San Francisco reservoirs when O'Shaughnessy Dam is removed from the model (Figures 12-14). This shows that considerable storage remains without O'Shaughnessy Dam in the Hetch Hetchy System, so reoperation of these reservoirs is not necessary. Reservoir operations remain surprisingly stable without O'Shaughnessy Dam. Special attention should be paid to local San Francisco water storage in Figure 14. Initial and ending storage levels are constrained to approximately one half of available storage (as they are for all surface and groundwater nodes in CALVIN). However, water storage levels drop immediately, implying extra storage space in the Hetch Hetchy System, even without O'Shaughnessy Dam. This additional local storage in the water delivery service area may have considerable value for emergencies, such as earthquake disruption of the Hetch Hetchy System.

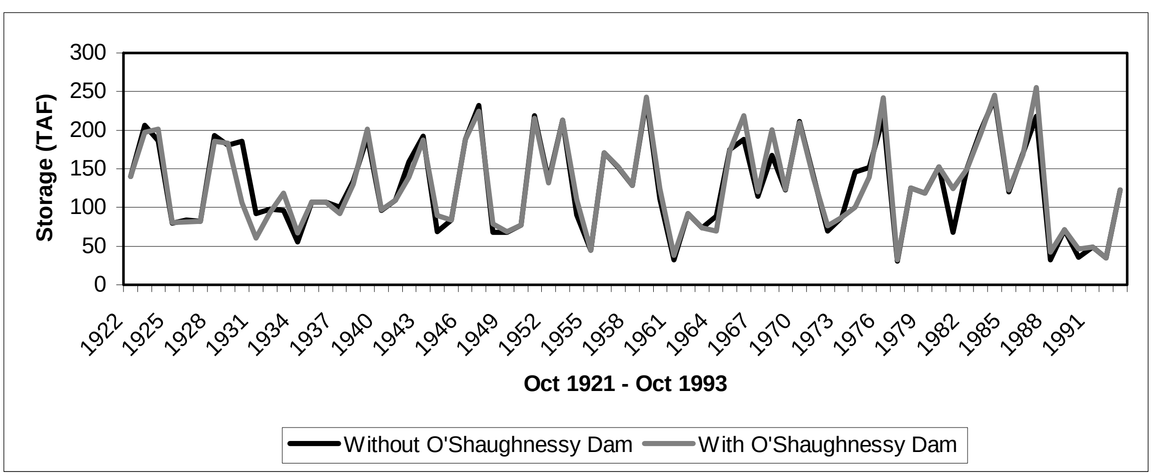

Figure 12. Annual average water storage at Cherry and Eleanor Reservoirs

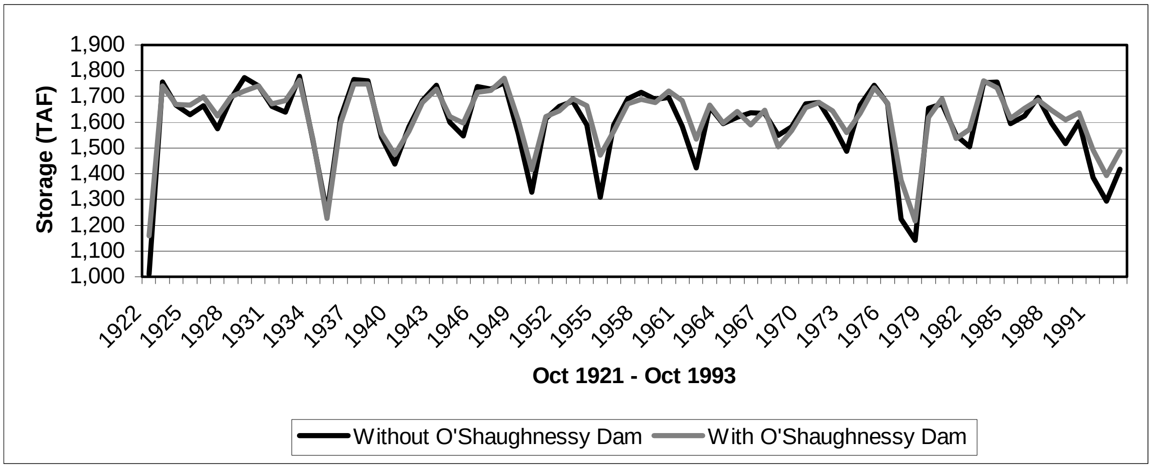

Figure 13. Annual average water storage at New Don Pedro Reservoir

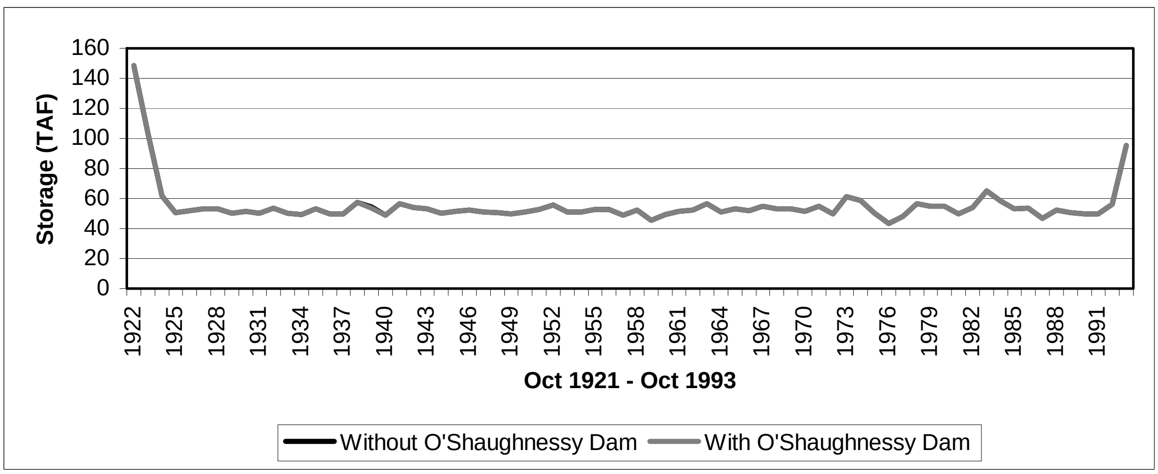

Figure 14. Annual average local San Francisco and Calaveras water storage

Water Deliveries and Scarcity

Without O'Shaughnessy Dam, full deliveries are made to urban demand areas. There is no water scarcity (Table 3). There are six urban demand areas in the model. The two demand areas in the San Francisco Bay Area and Santa Clara Valley make up the majority of urban demand. Four smaller urban demand regions are in the Central Valley. Although it is possible to deliver water to the San Francisco and Santa Clara Valley urban demand areas via the Hetch Hetchy Aqueduct, the Pacheco Tunnel, or the South Bay Aqueduct, deliveries remain routed via the Hetch Hetchy Aqueduct. This is an important finding, because model runs indicate that removing O'Shaughnessy Dam would change operation of the Hetch Hetchy System somewhat, but need not affect surrounding water resources. When model runs are constrained to current operational constraints, as they are in the base case results from another study, a small amount of scarcity occurs to urban water users (Jenkins et al., 2001; Ritzema, 2001).

Table 3. Average urban deliveries, scarcity, and scarcity cost

Demand Area	Location	Base Case with O'Shaughnessy*	With O'Shaughnessy	Without O'Shaughnessy **
	Annual Average Urban Deliveries (taf/yr)	**1,424**	**1440**	**1440**
SFPUC	City and County of San Francisco, San Mateo County	232	238	238
SCV	Santa Clara Valley, Alameda County and Alameda Zone 7 Water Districts	646	656	656
CVPM 10 Urban	Madera, Merced, San Joaquin, and Stanislaus Counties	42	42	42
CVPM 11 Urban	San Joaquin and Stanislaus Counties	232	232	232
CVPM 12 Urban	Merced and Stanislaus Counties	109	109	109
CVPM 13 Urban	Madera and Merced Counties	162	162	162
	Total Urban Scarcity (taf/yr)	**16**	**0**	**0**
	Total Urban Scarcity Cost ($1,000/yr)	**15,290**	**0**	**0**

* Constrained to current operating policies
** Results do not change with loss of filtration avoidance

In all model runs, full deliveries are made for environmental uses. This includes minimum instream flows on the lower Tuolumne River and flows to wildlife refuges such as the San Joaquin and Mendota Refuges.

There is a slight decrease in deliveries to agricultural demand areas in model runs without O'Shaughnessy Dam (Table 4). Total annual average deliveries to agricultural regions is 5,257,983 af/yr with O'Shaughnessy Dam, but are 575 af/yr less without O'Shaughnessy Dam. Out of four agricultural demand areas, two –the valley floor west of the San Joaquin River (CVPM 10) and the eastern valley floor between the San Joaquin River and the Merced River (CVPM 13), experience no change in scarcity regardless of whether O'Shaughnessy Dam is included or removed from the model. However, the eastern San Joaquin Valley above the Tuolumne River (CVPM 11) and the Eastern San Joaquin Valley floor between the Merced River and the Tuolumne River agricultural area (CVPM 12) have a small decrease in water delivered during dry years. In the model run without O'Shaughnessy Dam, inclusion of a New Don Pedro inter-tie routes some water away from the Tuolumne River into the Hetch Hetchy Aqueduct. Some water is diverted to CVPM 11 and CVPM 12 from the Tuolumne River in CALVIN, so there is a transfer of water from agricultural uses to urban uses during very dry years. This transfer is small, it never amounts to more than 13 taf/month, or 41 taf/year. When current operating constraints are included, as they are in the base case results, scarcity to agricultural regions is extensive despite the existence of O'Shaughnessy Dam in the system (Jenkins et al., 2001; Ritzema, 2001).

Table 4. Average agricultural deliveries, scarcity, and scarcity cost

Demand Area	Location	Base Case with O'Shaughnessy*	With O'Shaughnessy	Without O'Shaughnessy**
	Annual Average Ag. Deliveries (taf/yr)	**5259**	**5258**	**5257**
CVPM 10	Valley Floor west of San Joaquin R.	1698	1698	1698
CVPM 11	Eastern San Joaquin Valley above Tuolumne R.	867	866	866
CVPM 12	Eastern Valley Floor between San Joaquin R. and Tuolumne R.	803	803	802
CVPM 13	Eastern Valley Floor between San Joaquin R. and Merced R.	1891	1891	1891
	Annual Average Ag. Scarcity (taf/yr)	**0**	**1**	**1.5**
CVPM 10	Valley Floor west of San Joaquin R.	0	0	0
CVPM 11	Eastern San Joaquin Valley above Tuolumne R.	0	<1	<1
CVPM 12	Eastern Valley Floor between San Joaquin R. and Tuomune R.	0	0	<1
CVPM 13	Eastern Valley Floor between San Joaquin R. and Merced R.	0	0	0
	Annual Average Scarcity Cost ($1000/yr)	**0**	**5**	**11**
CVPM 10	Valley Floor west of San Joaquin R.	0	0	0
CVPM 11	Eastern San Joaquin Valley above Tuolumne R.	0	5	6
CVPM 12	Eastern Valley Floor between San Joaquin R. and Tuomune R.	0	0	5
CVPM 13	Eastern Valley Floor between San Joaquin R. and Merced R.	0	0	0

* Constrained to current operating policies
** Results do not change with loss of filtration avoidance

The eastern San Joaquin Valley above the Tuolumne River experiences scarcity, or periods when full demand is not delivered, during dry years with O'Shaughnessy Dam in the model (Figure 15). With O'Shaughnessy Dam, scarcity occurs during April 1929, April 1987- September 1987, and April 1988- September 1988. These are all drought periods. A maximum shortage of 6.7 taf occurs in July of 1987 and 1988. Monthly deliveries to this region are 150 taf. The marginal willingness to pay for additional water during these months is $30/af. Without O'Shaughnessy Dam, there is an additional 1 taf of scarcity to this agricultural region during October 1987, and an additional 1.5 taf of scarcity during March 1987 and 1988. The marginal willingness to pay for additional water remains at $30/af.

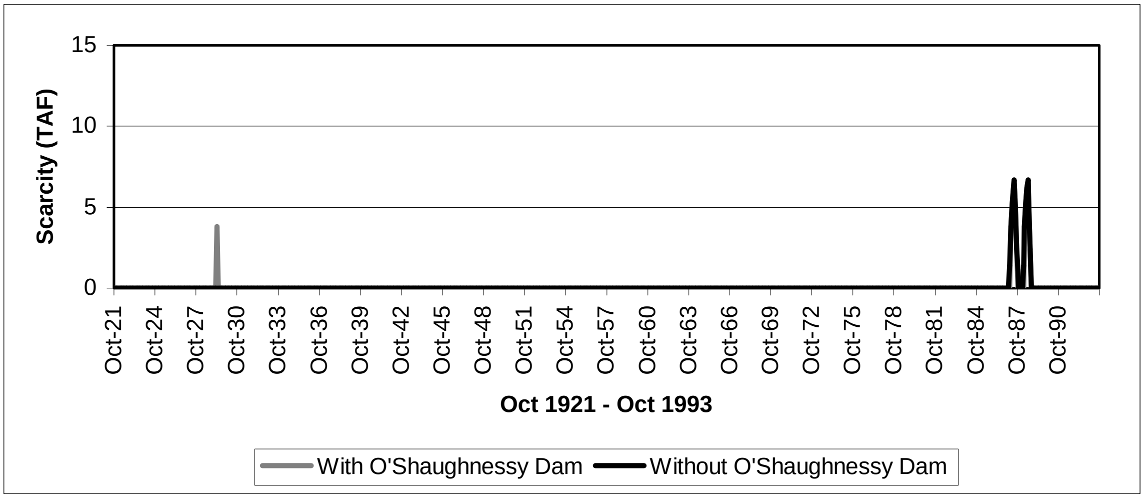

Figure 15. Monthly Agricultural scarcity for CVPM 11 (Eastern San Joaquin Valley above the Tuolumne River)

In the Eastern San Joaquin Valley floor between the Merced River and the Tuolumne River agricultural area (CVPM 12), full deliveries are met when O'Shaughnessy Dam is included in model runs. When O'Shaughnessy Dam is removed, full deliveries cannot be met in all years (Figure 16). Scarcity occurs in two of the same drought years, 1987 and 1988. A maximum 12.5 taf less water was delivered in July 1987 than the 166 taf demanded during that month. Marginal willingness to pay for additional water is $38/af.

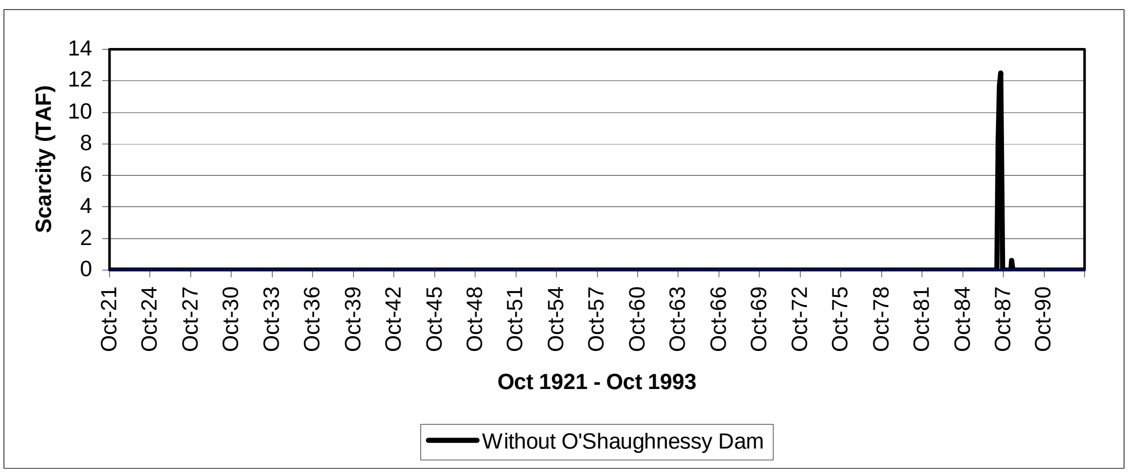

Figure 16. Monthly Agricultural scarcity to CVPM 12 (Eastern San Joaquin Valley floor between the Merced River and the Tuolumne River)

It should be stressed that water rights and the allocation of storage space to distinct operating agencies are not included in CALVIN. Essentially CALVIN assumes that SFPUC purchases a small amount of water from irrigation districts during shortage events, and this amount of water purchased increases slightly without O'Shaughnessy Dam. In reality, storage space in New Don Pedro Reservoir is allocated among three groups: the Modesto Irrigation District, and Turlock Irrigation District, and SFPUC. The

Modesto and Turlock Irrigation Districts have senior water rights, with rights pre-dating 1914. Therefore, these results should be interpreted as indicative of the amount of water scarcity that could be anticipated from the removal of O'Shaughnessy Dam. It is probable that scarcity would be passed on to other users based on water rights, or that water transfer agreements would occur between water users.

Using results from a modeling set constrained by current CVPIA operational policies from a previous study (which includes O'Shaughnessy Dam), water scarcity is observed in SFPUC and Santa Clara Valley residential demand area in 1921-1934, 1977, and 1986-1993. Over the entire 72 year time span, there is an average annual water scarcity of 6 taf for SFPUC and 10 taf for Santa Clara Valley. No agricultural demand areas face water scarcity (Jenkins et al., 2001).

Conveyance

Without O'Shaughnessy Dam, flows through the upper Hetch Hetchy Aqueduct (above New Don Pedro Reservoir) rarely reach the pipeline's capacity (Figure 17). However, in all years there is some flow through the upper aqueduct from Tuolumne River water capture and releases from Cherry/Eleanor Reservoir. Flows in the Tuolumne River above the O'Shaughnessy damsite do not change with removal of the reservoir. Only storage is eliminated. Thus, capture of considerable quantities of runoff could be possible at the damsite for much of most years. When flows in the upper Hetch Hetchy Aqueduct are examined seasonally, the importance of spring snowmelt can be seen (Figure 18). The upper aqueduct is always at capacity in April and May, the primary spring runoff months. During other months, flows through the upper aqueduct vary considerably based on streamflow.

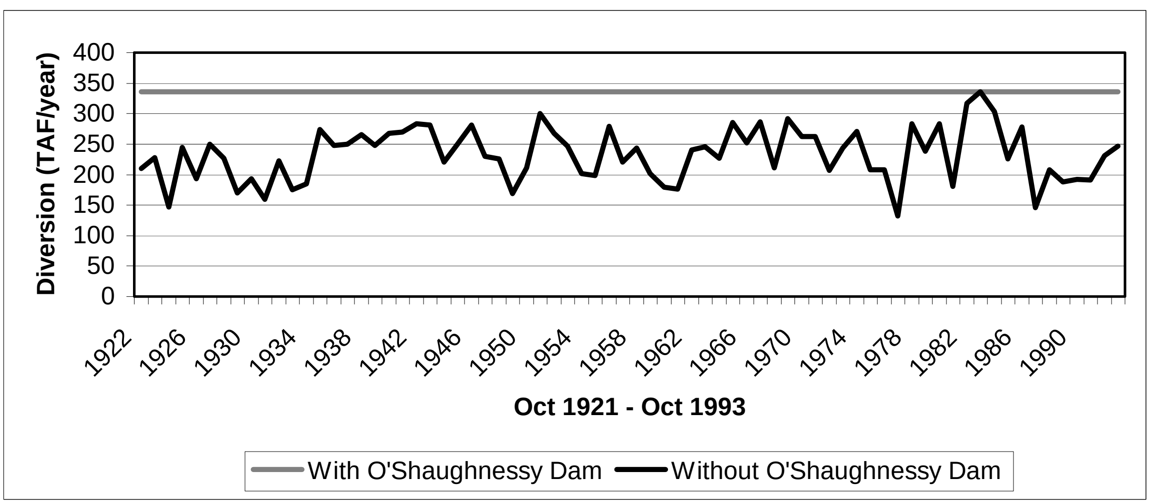

Figure 17. Average annual upper Hetch Hetchy Aqueduct flows (upstream of New Don Pedro)

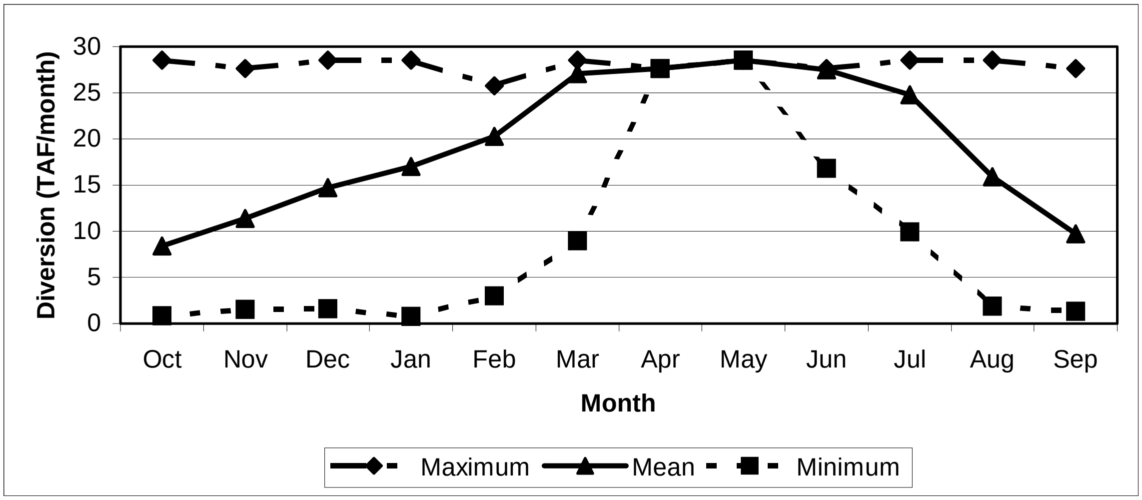

Figure 18. Seasonal flows in the upper Hetch Hetchy Aqueduct

Flows through a New Don Pedro inter-tie (a hypothetical inter-tie linking New Don Pedro Reservoir with the Hetch Hetchy Aqueduct) are the inverse of flows through the upper Hetch Hetchy Aqueduct (Figure 19). During April and May, flows through the New Don Pedro inter-tie are zero, because the Hetch Hetchy Aqueduct is already at capacity with diversions at O'Shaughnessy Dam (which can generate hydropower). During other months, as much water can be diverted from New Don Pedro into the inter-tie as is needed to bring the lower portion of the Hetch Hetchy Aqueduct to capacity. Thus, the lower Hetch Hetchy Aqueduct (downstream of New Don Pedro Reservoir) is always at capacity when flows through a hypothetical New Don Pedro inter-tie are incorporated (Figure 20). The New Don Pedro inter-tie adds flexibility to the Hetch Hetchy System. Were O'Shaughnessy Dam to be removed, additional flexibility and conveyance from New Don Pedro would be of great value.

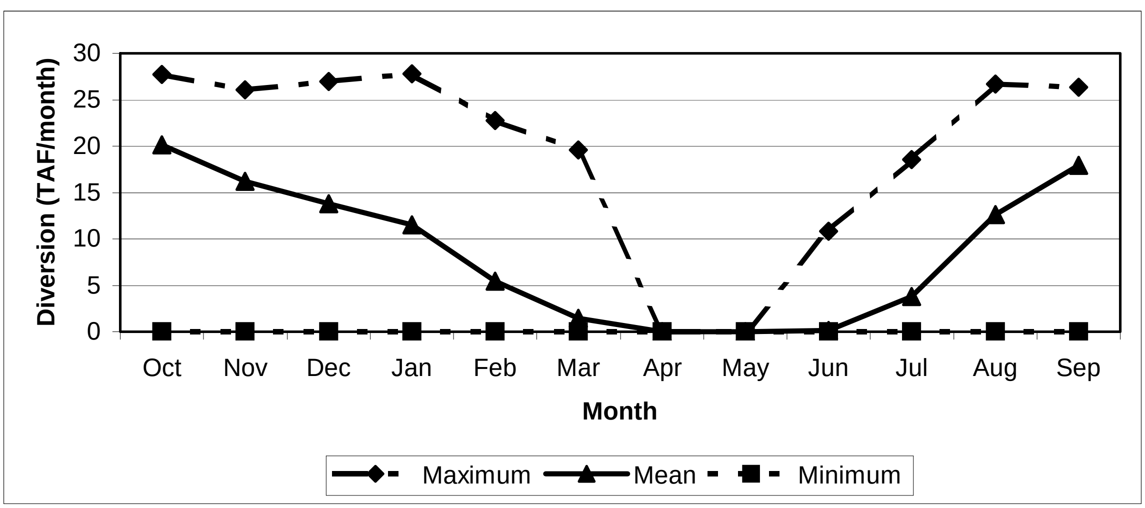

Figure 19. Monthly flows through a New Don Pedro inter-tie

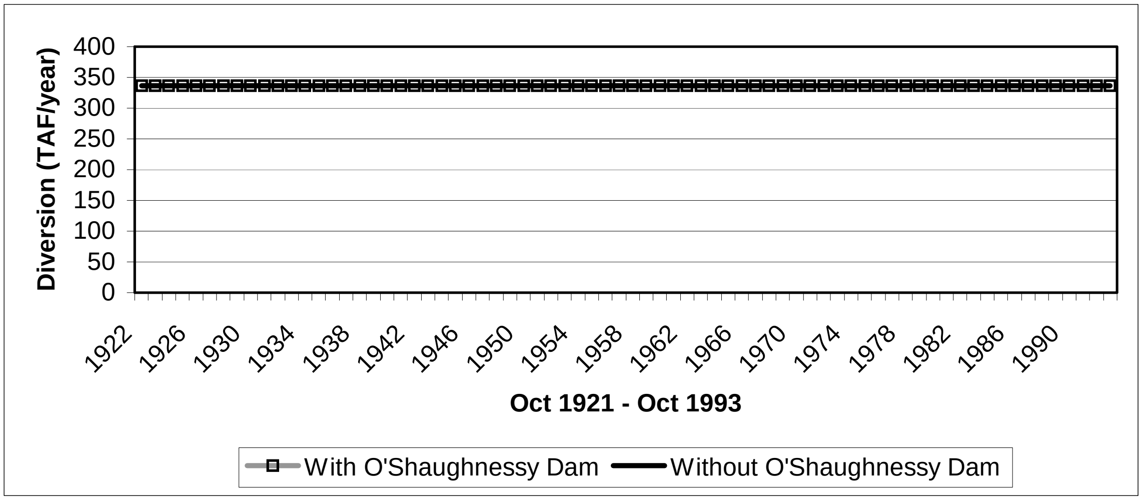

Figure 20. Average annual lower Hetch Hetchy Aqueduct flows (below New Don Pedro inter-tie)

Hydropower

Hydropower generation is reduced substantially without O'Shaughnessy Dam. This is primarily from elimination of hydropower generation at Kirkwood Power Plant, the facility directly below O'Shaughnessy Dam. The variable head hydropower algorithm used for Kirkwood Power Plant assumes no hydropower production is possible when no water is stored in O'Shaughnessy Dam. Hydropower generation continues at Holm, Moccasin, and New Don Pedro Hydropower Plants. Generation at Moccasin Power Plant is reduced significantly, and is reduced slightly at Holm Power Plant. There is an average annual loss of 113.2 GWhr/yr at Moccasin and 10.6 GWhr/yr at Holm. The loss of hydropower generation at Kirkwood and the reduction at Moccasin and Holm correlate into an average annual difference of 457 GWhr/yr (Figure 21). This translates to an average annual revenue loss of approximately $12 million/yr assuming monthly varying wholesale electricity prices (Table 5) (Ritzema, 2002).

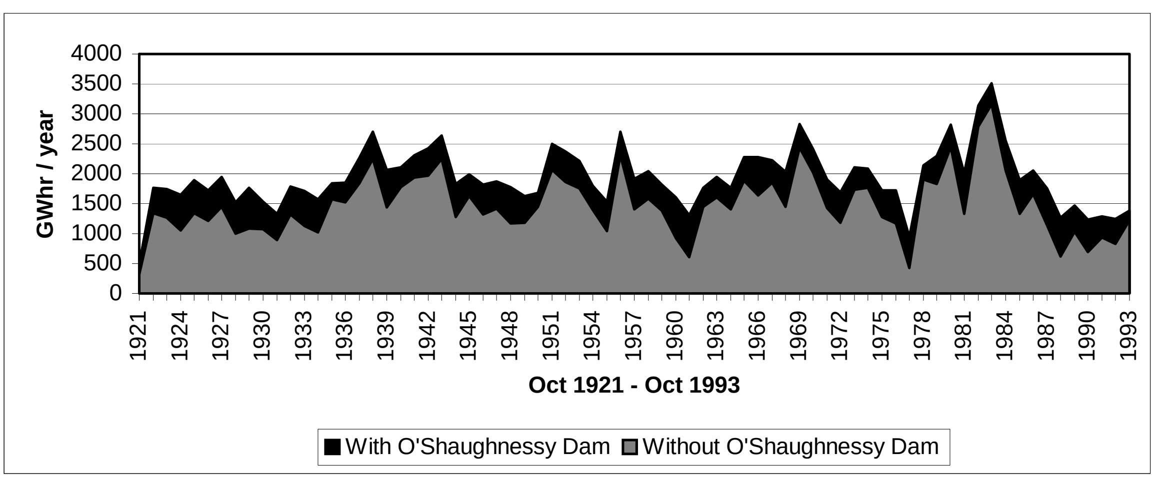

Figure 21. Average annual Hetch Hetchy System hydropower generation

Table 5. Wholesale electricity prices used in CALVIN (cents/kWhr)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2.0	2.0	2.0	1.8	1.8	1.8	3.0	3.0	3.0	2.6	2.6	2.6

Water Treatment

It is beyond the scope of this study to include construction costs of new facilities. Yet, removal of O'Shaughnessy Dam would prompt the filtration avoidance determination to be lost (if it were not lost already), incurring considerable construction costs for additional treatment facilities. For this reason, a very rough estimate of construction costs for new treatment facilities will be included. Construction costs are high; thus, the potential loss of filtration avoidance can fundamentally drive the debate to remove O'Shaughnessy Dam.

The Croton Water System, which supplies water for about 10% of New York City, is currently facing filtration facility construction costs of an estimated $950 million. If the much larger Catskills/Delaware System, also for New York City, were to lose its filtration avoidance determination, construction of treatment facilities are estimated to cost between $4 billion and $8 billion (NYC Independent Budget Office, 2000). The Catskills/Delaware Water System is much larger than the Hetch Hetchy System. Using it as a baseline for the Hetch Hetchy System, a rough estimate of costs for additional water treatment facilities could reach $2 billion. Although expansion of water treatment facilities is a long-term goal for the SFPUC, new treatment facilities are costly, and even deferral of such a large expense has considerable economic and financial benefits. This makes keeping O'Shaughnessy Dam a part of the Hetch Hetchy System a priority for the SFPUC. Even assuming filtration avoidance may someday be lost, every year that it could be postponed results in significant financial savings for the SFPUC. If construction of new treatment facilities is $2 billion, the value of delaying construction is approximately $100 million/year (using a discount rate of 5%).

Variable O&M costs are included in CALVIN, and thus can be assessed quantitatively. Filtration water treatment O&M costs are about $17/af, based on O&M costs for California cities with similar high quality source water. This corresponds to an average annual O&M cost of $13 million/year. Most likely, these costs would be passed on to urban water users, raising monthly water bills to rates comparable to other California cities. Additionally, a slight decline in water quality would occur from removing O'Shaughnessy Dam. Nevertheless, water quality would remain high because reservoirs such as New Don Pedro (which do not have filtration avoidance) have exceptional water quality (TID, 2002).

Shadow values of select facilities

Because CALVIN uses an economics-based objective function, model results include the economic value (shadow value) of an additional unit of water at any location and time in the network, and the economic value of any small change in any facility capacity. The values of additional storage at New Don Pedro Reservoir, and local San Francisco area reservoirs are negligible and do not change with the removal of O'Shaughnessy Dam from the model (Table 6). There is little value for expanding storage in these reservoirs. There is a small increase in marginal value for storage at

Cherry / Eleanor Reservoir. This implies water storage here is valuable; however, this is driven more by hydropower production than by storage for water supply.

Table 6. Shadow values of selected facility expansion options

Facility	Physical Capacity	Average Annual Marginal Expansion Value ($/yr/af)		
		Additional Water Treatment*		**Filtration Avoidance**
		With OS	**Without OS**	**With OS**
Surface Reservoirs	TAF			
O'Shaughnessy	360 / 0	3	0	3
Cherry and Eleanor	301	24	24	24
New Don Pedro	2,030	2	2	2
San Francisco area and Calaveras reservoirs	798	0	0	0
Conveyance	TAF/month			
Cherry Creek Aqueduct	9.5	0	0	0
Upper Hetch Hetchy Aqueduct	28	283	40	283
Lower Hetch Hetchy Aqueduct	28	0	254	0
New Don Pedro to Hetch Hetchy Aqueduct	0 / unlimited	245	0	245

* Additional water treatment costs of $15/af

Improved water conveyance options are more valuable than additional water storage with the removal of O'Shaughnessy Dam. Shadow values of an extra unit of conveyance in the Hetch Hetchy System highlight areas where expansion would be beneficial. In all model runs (including those with O'Shaughnessy Dam), additional capacity in the Hetch Hetchy Aqueduct has considerable value (Table 6).

An inter-tie linking New Don Pedro Reservoir to the Hetch Hetchy Aqueduct is valuable regardless of the removal of O'Shaughnessy Dam. In model runs with O'Shaughnessy Dam, a New Don Pedro inter-tie has a value of $245/yr/af. This underscores a possible improvement to the Hetch Hetchy System regardless of the existence of O'Shaughnessy Dam or the stability of filtration avoidance. Without O'Shaughnessy Dam, the marginal cost of additional capacity in the hypothetical New Don Pedro inter-tie is zero because this link is unconstrained in model runs. In effect, it is constrained by the capacity of the lower Hetch Hetchy Aqueduct, its downstream link. Thus, shadow values for runs without O'Shaughnessy Dam are similar to those of the lower Hetch Hetchy Aqueduct.

Year 2100 Results

By year 2100, the entire region is short of water due to population growth, but not short of storage. In model runs with "year 2100" demands, scarcity to urban demand regions occurs and scarcity to agricultural demand regions is extensive. There is simply not enough water, despite a surplus of surface reservoir storage space. This underscores an important distinction; water and storage space are not the same. In year 2100, water is generally not stored in surface reservoirs for extended periods, it is used promptly to meet increased demands. Surface storage actually costs water through evaporation. However, it should be noted again, year 2100 model runs ignore possible climate change effects. Were the precipitation patterns of California to change, most likely resulting in less snowfall and more rainfall in the Sierra Nevada Mountains, it is possible that some of the surplus storage seen in these results could be utilized.

Storage increases in groundwater basins implying a greater reliance on conjunctive use strategies as demand increases in the future. Despite options for additional water supplies from seawater desalination and water recycling, model runs no not utilize these supplies because the marginal willingness to pay for additional water remains less than $1000/af, the price of desalted or recycled water in the model. This highlights another important finding, some water scarcity may be optimal.

Year 2100 Water Deliveries and Scarcity

In both year 2100 model runs there is a small amount of water scarcity to urban water users. Residential water users in San Francisco face an average annual 5 taf of water scarcity, and Santa Clara County water users face an average annual 1 taf of water scarcity (Table 7). Full deliveries are made to all other urban demand areas. There is extensive water scarcity to all agricultural demand areas (Table 8). All agricultural demand areas have at least an average annual 100 taf of water scarcity. CVPM 13 has the most scarcity, with an average annual 250 taf or water scarcity. Surprisingly, there is a slight increase in scarcity in the year 2100 demand model run with O'Shaughnessy Dam. This can be attributed to greater evaporative losses with O'Shaughnessy Dam than without O'Shaughnessy Dam.

Table 7. Urban deliveries, scarcity, and scarcity cost with projected year 2100 demand

	Average Deliveries (taf/yr)		Average Scarcity (taf/yr)		Average Scarcity Cost ($K/yr)	
Demand Region	With O'Shaughnessy Dam	Without O'Shaughnessy Dam	With O'Shaughnessy Dam	Without O'Shaughnessy Dam	With O'Shaughnessy Dam	Without O'Shaughnessy Dam
SFPUC: Industrial	26	26	0	0	0	0
SFPUC: Residential	233	233	5	5	3539	3529
SCV: Industrial	91	91	0	0	0	0
SCV: Residential	836	836	1	1	547	547
CVPM 10 Urban	90	90	0	0	0	0
CVPM 11 Urban	379	379	0	0	0	0
CVPM 12 Urban	292	292	0	0	0	0
CVPM 13 Urban	412	412	0	0	0	0
TOTAL	**1948**	**1948**	**6**	**6**	**4086**	**4076**

Table 8. Agricultural deliveries, scarcity, and scarcity cost with projected year 2100 demand

	Average Deliveries (taf/yr)		Average Scarcity (taf/yr)		Average Scarcity Cost ($K/yr)	
Demand Region	With O'Shaughnessy Dam	Without O'Shaughnessy Dam	With O'Shaughnessy Dam	Without O'Shaughnessy Dam	With O'Shaughnessy Dam	Without O'Shaughnessy Dam
CVPM 10	1521	1521	177	177	15428	15428
CVPM 11	719	719	148	148	15248	15248
CVPM 12	629	629	174	174	18358	18244
CVPM 13	1637	1640	254	251	26431	25834
TOTAL	**4506**	**4509**	**753**	**749**	**75466**	**74754**

Although additional water could have been obtained from desalination and recycling facilities in CALVIN, these went unused. Model results show the marginal willingness to pay for additional water by urban users varied between $650-$800/af. The marginal willingness to pay for agricultural users was far less, between $100-$200/af. Both desalination and recycled water was given a price of $1000/af. Thus, users opt to face some scarcity (reducing water use) rather than pay for additional water from these sources unless costs of desalinization decrease significantly.

Year 2100 Water Storage

Water storage in O'Shaughnessy Dam dropped drastically with year 2100 demand (Figure 22). In model runs representing year 2020 demand, water storage in O'Shaughnessy Dam fills and empties following climatic shifts in wet and dry years (Figure 23). With projected demands for year 2100, O'Shaughnessy Dam empties to the dead storage level nearly every year. This could lead to aesthetic problems. Sometimes the reservoir nears capacity during the spring runoff months.

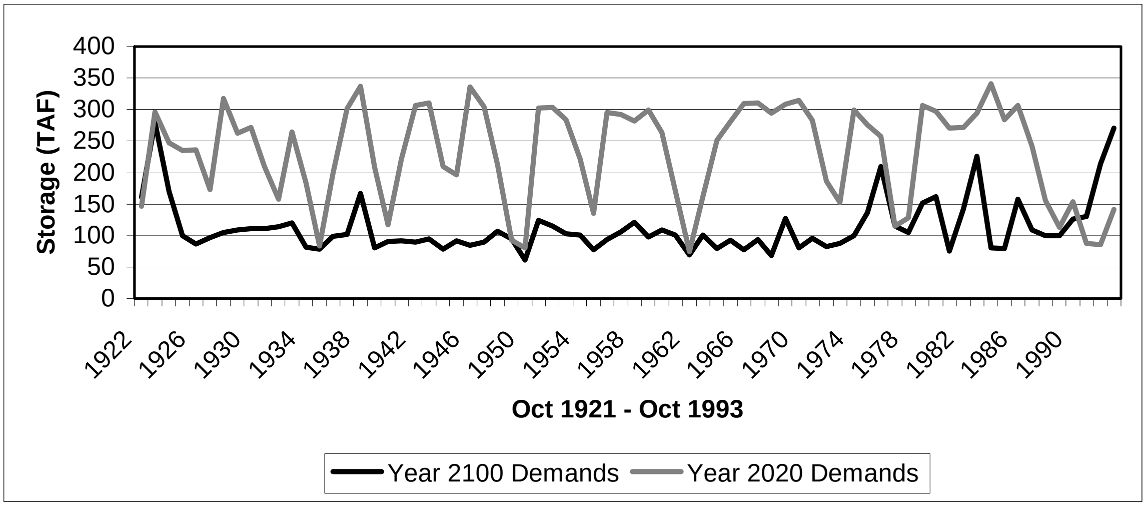

Figure 22. Average annual storage at O'Shaughnessy Dam with year 2020 demands and year 2100 demands

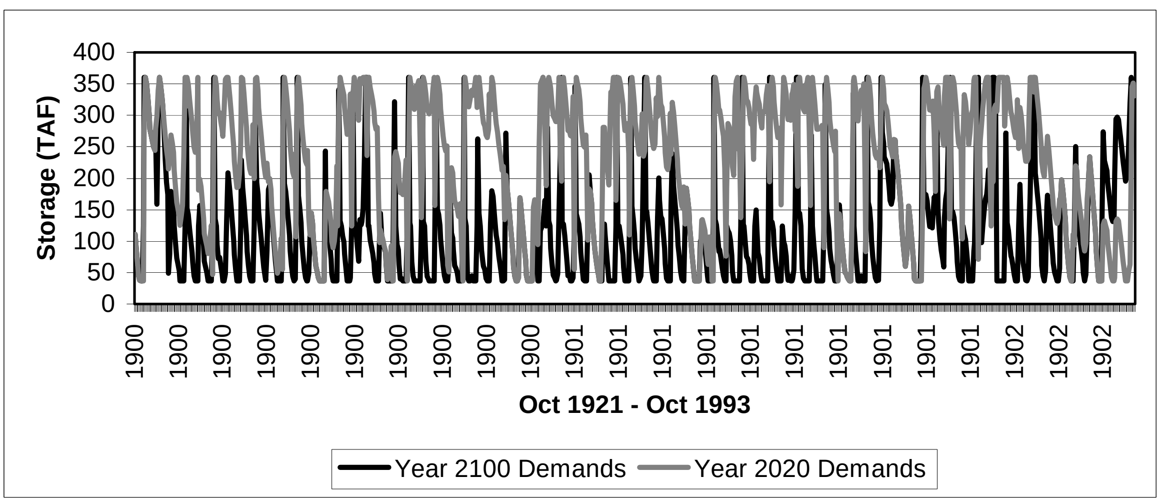

Figure 23. Monthly storage at O'Shaughnessy Dam with year 2020 demands and year 2100 demands

In the model run for year 2100 where O'Shaughnessy Dam has been removed, slightly more water is stored in New Don Pedro Reservoir during May through September. Like year 2020 model runs, the Hetch Hetchy Aqueduct below New Don Pedro Reservoir remains full despite the removal of O'Shaughnessy Dam with year 2100 demands. There is always less surface storage in the remaining Hetch Hetchy System reservoirs in year 2100 models than in year 2020 models (Table 9). This implies that despite considerable storage space, there is not enough water to meet demands. There is rarely excess water to be stored for future years, rather it is usually sent to demand areas within a year.

Table 9. Average monthly storage in Hetch Hetchy System Reservoirs (taf)

	Year 2020 Demand Model Runs		Year 2100 Demand Model Runs	
	With O'Shaughnessy Dam	Without O'Shaughnessy Dam	With O"Shaughnessy Dam	Without O"Shaughnessy Dam
O'Shaughnessy Dam	232	n/a	113	n/a
Cherry / Eleanor Reservoirs	129	128	81	82
New Don Pedro Reservoir	1615	1594	1218	1219
Local San Francisco storage	55	55	45	45

More groundwater is used for drought storage in year 2100 models than in year 2020 models. This shows that as demand increases in the future, conjunctive use (which reduces evaporative losses) will probably become more widespread. There is little difference in groundwater storage between the year 2100 models with and without O'Shaughnessy Dam.

Hydropower

Slightly less hydropower is generated with year 2100 demands than with year 2020 demand (Table 10). Like previous results, hydropower generation drops when O'Shaughnessy Dam is removed from the year 2100 model (Figure 24). Energy generation remains approximately the same at Holm and New Don Pedro Power Plants, but decreases at Kirkwood and Moccasin Power Plants. Hydropower generation drops by an average 262 GWhr/yr at Kirkwood and by an average 118 GWhr/yr at Moccasin. In total, 378 GWhr/yr are lost when O'Shaughnessy Dam is removed from model runs with projected future demands. This correlates into a loss of $9.5 million per year in foregone energy revenue (using the same monthly varying prices from year 2020 model runs, see Table 5).

Table 10. Average monthly hydropower production (GWhr/month)

	With O'Shaughnessy Dam		Without O'Shaughnessy Dam	
	Year 2020	Year 2100	Year 2020	Year 2100
Holm	62	54	61	54
Kirkwood	29	22	0	0
New Don Pedro	49	47	49	47
Moccasin	24	24	14	14

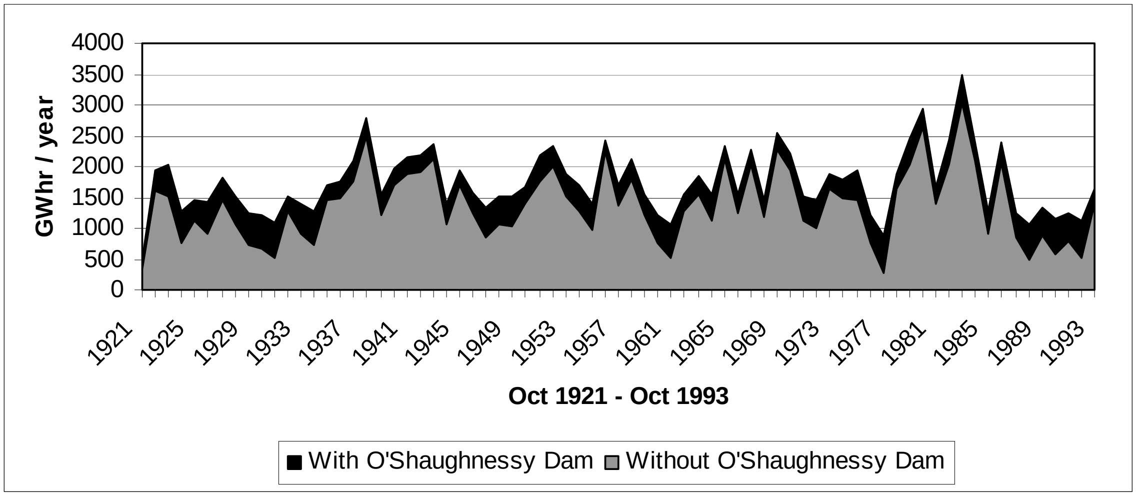

Figure 24. Average Annual Hetch Hetchy System Hydropower Generation with year 2100 demands

CHAPTER FIVE
DISCUSSION

This study indicates a stable water supply for the San Francisco peninsula could be maintained with removal of O'Shaughnessy. The numerous reservoirs and pipelines in the Hetch Hetchy System provide considerable flexibility for delivering water to downstream users. Addition of an inter-tie linking New Don Pedro Reservoir with the Hetch Hetchy Aqueduct makes it possible for little change to occur to water deliveries when O'Shaughnessy Dam is removed. This inter-tie from New Don Pedro Reservoir allows for the potential isolation of O'Shaughnessy Dam decisions from other parts of the San Joaquin and Bay Area. Water storage space in New Don Pedro Reservoir is shared between three entities: SFPUC, the Modesto Irrigation District, and the Turlock Irrigation District. This inter-tie would also allow water transfers, exchanges, or other forms of flexible operations among these agencies in the event of a long drought.

When O'Shaughnessy Dam is removed and water demands are increased to represent projected year 2100 demands, there are surprisingly few effects on water deliveries and operation of the Hetch Hetchy System. There is some water scarcity to urban residential demand areas, and considerable water scarcity to agricultural demand areas, regardless of the existence of O'Shaughnessy Dam in the system. Scarcity occurs because there is not enough water in the system to meet demand, despite unused surface water storage and the lower Hetch Hetchy Aqueduct flowing at capacity at all times. Although water desalination and water recycling are made available, some water scarcity costs (for water conservation) are preferable to higher costs of acquiring additional water supplies. With increased future demands, water storage in groundwater basins increases, suggesting greater utilization of conjunctive use strategies in the future.

This study also found that removing O'Shaughnessy Dam carries considerable financial costs. These include lost hydropower revenue, construction costs for additional water treatment facilities, increased treatment costs, and dam removal costs. Expanded opportunities for tourism and recreation in Hetch Hetchy Valley and resulting regional economic development would be needed to justify dam removal and restoration economically. If urban, agricultural, and environmental water demands can be met without O'Shaughnessy Dam, the decision to remove the reservoir and restore Hetch Hetchy Valley becomes an economic one.

The importance of the filtration avoidance determination of O'Shaughnessy Dam cannot be emphasized enough. Filtration avoidance makes O'Shaughnessy Dam extremely valuable for SFPUC and the Hetch Hetchy System, saving the SFPUC several tens of millions of dollars each year in operating and deferred capital costs. It is very possible that this filtration avoidance status will drive decisions regarding dam removal. However, if filtration avoidance status were lost, O'Shaughnessy Dam would lose most of its value to the Hetch Hetchy System. In that case, economic value and revenues from recreation and tourism in Hetch Hetchy Valley could offset lost hydropower revenue and increased treatment facility operation costs. However, if Hetch Hetchy Valley was opened to recreation, the economic benefits would go primarily to Yosemite National Park, though SFPUC would incur most of the costs due to lost hydropower generation and additional water treatment costs. Further research is needed to examine these possibilities and changes.

Finally, it should be stressed that water use in California is very dynamic. Changes in climate, water laws, water markets, or technology could change the way water is moved and valued considerably. It is beyond the scope of this project to provide an economic benefit-cost analysis or an estimate of public support for removal of O'Shaughnessy Dam. A thorough benefit-cost analysis of potential dam removal would be useful. Travel cost surveys and contingent valuation surveys could be used to estimate the economic benefits and public support for expanded recreation potential. Estimates of increased regional economic development also would be useful. These benefits could be evaluated for Yosemite Valley, and then compared with losses from lower hydropower production and other costs. Additional research on the institutional aspects of possible water transfers or exchanges between SFPUC, the Modesto Irrigation District, and the Turlock Irrigation District would also be useful. Future ecological studies include creating a restoration plan for Hetch Hetchy Valley, and measuring the impacts of dam removal on the Tuolumne River and surrounding ecosystems.

CHAPTER SIX
CONCLUSIONS

1) *Removing O'Shaughnessy Dam need not substantially increase water scarcity*.

a) *Without O'Shaughnessy Dam, capture of considerable quantities of runoff could be possible at the damsite for much of most years*. Only storage is eliminated. Flow in the Tuolumne River above the O'Shaughnessy damsite does not change with removal of the reservoir.

b) *Removing O'Shaughnessy Dam does not affect water system operations outside the Hetch Hetchy System, if New Don Pedro Reservoir is connected directly with the Hetch Hetchy Aqueduct*. This substantially eliminates the need for difficult institutional, economic, and political coordinated use agreements. Within the Hetch Hetchy System, reservoir storage changes little with the removal of O'Shaughnessy Dam, reducing need for changes in current operations.

2) *Conveyance can sometimes substitute for water storage*. Tying New Don Pedro Reservoir with the Hetch Hetchy Aqueduct allows operators of the SFPUC flexibility to use different reservoirs most effectively to meet full water deliveries to demand regions.

3) *An inter-tie linking New Don Pedro Reservoir with the Hetch Hetchy Aqueduct is valuable regardless of the existence of O'Shaughnessy Dam*. Assuming an inter-tie from New Don Pedro Reservoir, the lower Hetch Hetchy Aqueduct remains at capacity without O'Shaughnessy Dam. This remains true even with projected future demands. With O'Shaughnessy Dam remaining in the Hetch Hetchy System, the shadow value for an added unit of conveyance between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct is greater than $200 af/month.

4) *Removing O'Shaughnessy Dam substantially reduces hydropower generation and revenues*. Approximately $12 million/year would be lost from hydropower revenue, primarily from decreased hydropower generation at Moccasin and Kirkwood power plants. With projected demands for the year 2100, approximately $9.5 million/year would be lost from hydropower without O'Shaughnessy Dam.

5) *The loss of filtration avoidance, which would occur with removal of O'Shaughnessy Dam, may be driving factor in debate to remove O'Shaughnessy Dam*. Construction costs of additional filtration facilities would be huge ($2 billion is a rough estimate). With resulting capital costs of roughly $100 million/year, and O&M costs around $13 million/year, removing O'Shaughnessy Dam could increase Bay Area drinking water costs significantly, to levels common for most California cities.

6) *There is little effect on the Hetch Hetchy System and water deliveries to demand regions from removing O'Shaughnessy Dam with projected future demands*. Although there is unused surface storage space with projected future demands, there is not enough water. Water and surface storage are not interchangeable.

7) *Optimization modeling is useful in identifying effective re-operations for water resource systems potentially undergoing restoration*.

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