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REASSEMBLING HETCH HETCHY: WATER SUPPLY WITHOUT O'SHAUGHNESSY DAM[1]

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ABSTRACT: The Hetch Hetchy System provides San Francisco with most of its water supply. O'Shaughnessy Dam is one component of this system, providing approximately 25 percent 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. 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. This model ignores institutional and political constraints and has perfect hydrologic foresight to explore water supply possibilities through reoperation of other existing reservoirs. The economic benefits of O'Shaughnessy Dam and its alternatives are measured in terms of the quantity of water supplied to San Francisco and agricultural water users, water treatment costs, and hydropower generation. Results suggest there could be little water scarcity if O'Shaughnessy Dam were to be removed, although removal would be costly due to additional water treatment costs and lost hydropower generation.

(KEY TERMS: water supply; dam removal; Hetch Hetchy; optimization; economics; filtration avoidance; restoration.)

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INTRODUCTION

O'Shaughnessy Dam, located in the Hetch Hetchy Valley of Yosemite National Park, was built by the City of San Francisco in 1923 as a component of the Hetch Hetchy water system. The Hetch Hetchy System has 10 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 controversial when proposed and built in the early 1900s. Throughout the past century, the idea of removing O'Shaughnessy Dam to restore Hetch Hetchy Valley has never entirely gone away, although today California is much different. Yosemite National Park is now one of the most loved and visited parks in the United States. California's Bay Area is a major urban region, with millions of residents requiring water delivery; the Tuolumne River now has several times more storage capacity with the construction of the New Don Pedro Reservoir; and water treatment technology and treatment standards have vastly improved. For Hetch Hetchy Valley restoration to be considered, the remainder of the Hetch Hetchy System or other alternative sources must be able to supply water without O'Shaughnessy Dam. The importance of O'Shaughnessy Dam must be evaluated in the context of the greater Hetch Hetchy System and other water supply and demand management options.

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This study provides quantitative estimates for the water supply feasibility of removing O'Shaughnessy Dam using a spatially refined economic engineering optimization model. It identifies cost minimizing alternatives for San Francisco's water supply and highlights how removing O'Shaughnessy Dam could change current operations, water supply, deliveries, hydropower generation, water treatment, and economic water supply costs (Null, 2003). Modeling can provide quantitative support for discussion or actions. This analysis indicates whether water scarcity would increase substantially without O'Shaughnessy Dam. Such information also might be useful as part of a more comprehensive benefit cost analysis of Hetch Hetchy Valley restoration, not undertaken here.

Removing O'Shaughnessy Dam could raise many institutional, political, and economic questions. However, this study ignores most institutional and political implications to focus on optimization of water supply and economic factors. It is helpful to ignore political and institutional constraints to understand the physical limitations of a water supply system. It then becomes clear whether human constraints or physical constraints are limiting factors. Recently, much has been written and discussed about removing O'Shaughnessy Dam (Jensen, 2004; Leal, 2004; Philp, 2004a-2004l; Rosekrans *et al.,* 2004). Tom Philp of the Sacramento Bee recently won the 2005 Pulitzer Prize for editorial writing based significantly on this study (Stanton, 2005). In addition, Governor Schwarzenegger's staff authorized California's Department of Water Resources (CDWR) to review this and other studies relating to O'Shaughnessy Dam and Hetch Hetchy Valley (CDWR, 2005).

This paper begins with a brief overview of Hetch Hetchy Valley, the Hetch Hetchy System, and potential O'Shaughnessy Dam removal decisions. CALVIN (CALifornia Value Integrated Network), the computer model used to evaluate alternatives to O'Shaughnessy Dam, is explained. A summary of model parameters, infrastructure modifications, benefits, and model limitations follow. Model runs are described, and results are discussed in terms of operational and economic performance. The paper concludes with a short discussion of the implications and water supply costs of removing O'Shaughnessy Dam and some larger institutional and economic factors regarding removal of O'Shaughnessy Dam.

Background

Prior to construction of O'Shaughnessy Dam, Hetch Hetchy Valley was similar to neighboring Yosemite Valley. Both valleys were formed from jointed granite bedrock, and they initially were cut by the Tuolumne and Merced Rivers, respectively. Glaciers then scoured the valleys, widening and polishing the surrounding granite. Both valleys once had natural lakes that filled with sediment, forming flat meadows (Huber, 1987).

In 1906, following the San Francisco earthquake, the shortcomings of San Francisco's water supply became clear. City water planners targeted Hetch Hetchy as a dam site for San Francisco's water supply (Hundley, 1992). San Francisco's voters approved the construction of a dam in Hetch Hetchy Valley by an 86 percent majority vote in 1908 (Sierra Club, 2002). In 1913, the Raker Act was passed in Congress, enabling a large reservoir to be built in a national park (Hundley, 1992). O'Shaughnessy Dam was completed in 1923, was raised in 1938, and has been used for the past 80 years.

O'Shaughnessy Dam has a storage capacity of 360,360 acre feet (af) (444.5 millions of cubic meters, mcm). Its current uses include water storage, hydropower generation, and some flood reduction (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 exceptionally large. Its 360 thousand acre feet (taf) (444 mcm) of surface water storage are approximately 25 percent of the surface storage in the Hetch Hetchy System and 14 percent of storage on the Tuolumne River. For this study, removal of O'Shaughnessy Dam applies only to the dam and its reservoir. No pipelines, diversion capacity, or conveyance facilities would be removed from the Hetch Hetchy System.

As illustrated in Figure 1, the Hetch Hetchy System consists of several reservoirs, power plants, and conveyance facilities. 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 water supply storage is usually provided by O'Shaughnessy Dam. Another much larger dam, New Don Pedro Reservoir, is downstream of O'Shaughnessy Dam, the Hetch Hetchy Aqueduct intake, and Cherry and Eleanor Reservoirs (City and County of San Francisco, 1999). New Don Pedro Reservoir is owned and operated by Modesto and Turlock Irrigation Districts, with a water banking arrangement allowing the City and County of San Francisco the use of 570 taf (703 mcm)of water storage.

Together, these reservoirs and water banking arrangements, with numerous Bay Area reservoirs and the connecting pipelines, make up the Hetch Hetchy System, operated by the San Francisco Public Utilities Commission (SFPUC). Total surface storage in the Hetch Hetchy System is approximately 1,500

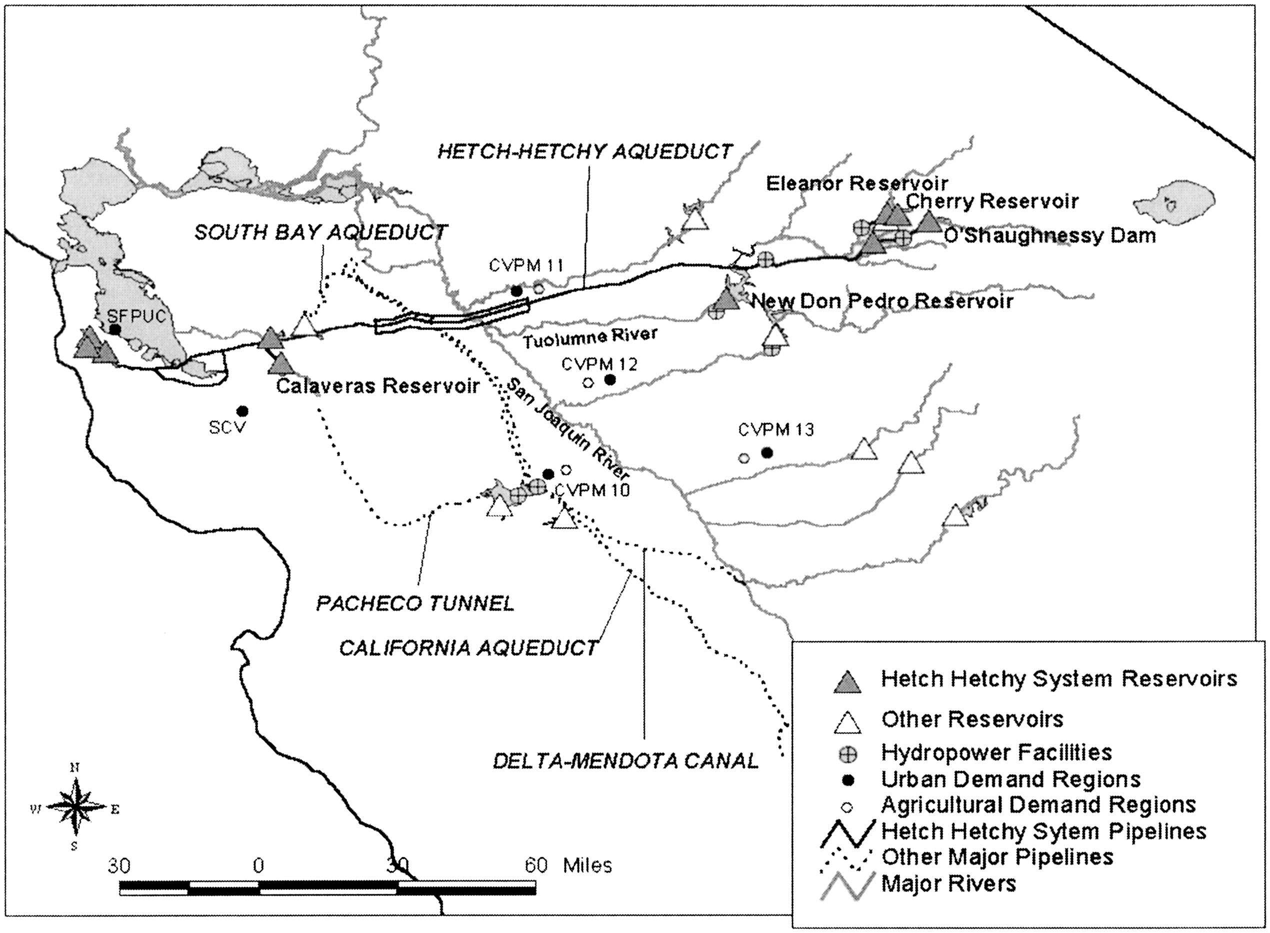

Figure 1. Map of San Joaquin and San Francisco Bay Regional CALVIN Model.

taf (1,850 mcm) (Table 1). In addition to the Hetch Hetchy System total, 1,460 taf (1,801 mcm) remains of 2,030 taf (2,504 mcm) New Don Pedro Reservoir storage capacity. The Hetch Hetchy System supplies water to 77 percent of urban uses in the City and County of San Francisco, as well as parts of San Mateo, Santa Clara, and Alameda Counties, supplying more than 2 million water users (USDOE, 1989). 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 and an important source of revenue for the SFPUC.

Although water storage is a priority for SFPUC and the Hetch Hetchy System, it is not the 360 taf (444 mcm) of water storage that makes O'Shaughnessy Dam valuable; rather water from O'Shaughnessy Dam has filtration avoidance status (SFPUC, 2005). Typically, filtration of urban surface water supplies is required by federal law. Filtration avoidance means O'Shaughnessy Dam impounds high quality water that meets water quality standards under the federal Surface Water Treatment Rule. Only minimal water treatment is currently required, such as addition of lime for corrosion control and chlorine or chloramine as a disinfectant (SFPUC, 2005). The watershed above O'Shaughnessy Dam is pristine; it lies within Yosemite National Park. O'Shaughnessy Dam is the only reservoir in the Hetch Hetchy System that has filtration avoidance (and one of only about a half-dozen sources nationally). Even Cherry and Eleanor Reservoirs, less than 10 miles (16 km) from O'Shaughnessy Dam, do not qualify for filtration avoidance.

Recently the SFPUC approved seismic retrofits for the Hetch Hetchy System as part of its Capital Improvement Program (SFPUC, 2002). Increased local San Francisco water storage would be valuable in case of an earthquake, terrorist act, or other emergency repair. For this study, all water storage is valued equally, regardless of location. However, because O'Shaughnessy Dam is at the upstream end of the system, it is of little value in the event of emergency interruptions in the conveyance system.

TABLE 1. Storage in the Hetch Hetchy System.

Reservoir	Capacity (taf)
Hetch Hetchy System Storage	
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 Hetch Hetchy System Storage	1,454
Other Tuolumne River Storage	
New Don Pedro (MID and TID)	1,460
Total Basin Storage	
All Reservoirs	2,914

*Filtration Avoidance Permit.

**Banking arrangement with City and County of San Francisco.

Notes: Total Storage in New Don Pedro Reservoir = 2,030 taf; MID = Modesto Irrigation District; TID = Turlock Irrigation District

Potential for Removing O'Shaughnessy Dam

There are valid arguments for both keeping and removing O'Shaughnessy Dam. Many arguments on both sides are 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 water users. Finally, some environmentalists believe O'Shaughnessy Dam is a poor choice for removal because its removal benefits no threatened or endangered species and would make only minor improvements for ecological connectivity on the Tuolumne River system. The land under the reservoir could be restored, but this is a small land area to justify removal on ecosystem restoration grounds.

Arguments for removing O'Shaughnessy Dam primarily center around ethical concerns and increasing open space in Yosemite National Park for tourism and recreation. It has been argued, most famously by John Muir, 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). Furthermore, Yosemite National Park is one of the most heavily visited national parks in the nation. Within the park, Yosemite Valley is grossly congested. Restoring Hetch Hetchy Valley could open a valley that is half the size of Yosemite Valley and nearly identical in terms of beauty. Revenue and increased local spending from tourism could offset some or all of the losses from removing O'Shaughnessy Dam. This problem can be thought of as weighing two scarce resources, water and space in Yosemite National Park.

In recent years, construction of new dams has declined due to economic factors, environmental considerations, and the best locations being already in use. This has led to the idea of increasing water efficiency without new infrastructure (Poff and Hart, 2002). Options for increasing the efficiency of water supplies are wide reaching, including coordinated use of existing water infrastructure, conjunctive use between surface water and ground water, water conservation, water transfers, and generally more sophisticated operations (CDWR, 1998). With this shift of ideology, the popularity of dam removal has risen dramatically. At least 467 dams were removed in the United States in the latter part of the 20th Century (Poff and Hart, 2002).

METHODS

Although simulation is the most common modeling approach, optimization models offer another method for exploring solutions to water resource problems. Optimization methods can suggest promising solutions with the "best" performance from among many alternatives. Optimization models require explicit objectives to be maximized or minimized by modifying decisions within system constraints. Until recently, optimization models were too computationally burdensome to be practical for large systems or problems. Now, more powerful computers and software make optimization of large systems feasible (Labadie, 2004).

CALVIN is a network flow based economic engineering optimization model of California's inter-tied water management system. It was developed at the University of California-Davis, based on the U.S. Army Corps of Engineers' HEC-PRM reservoir optimization software (Jenkins *et al.,* 2001; Draper *et al.,* 2003).

The objective function for CALVIN is to minimize total economic costs, mathematically represented as

$$\text{Minimize } Z = \sum_i \sum_j c_{ij} X_{ij} \tag{1}$$

where Z is total cost (U.S. dollars), c_{ij} is the cost coefficient on arc ij (U.S. dollars), and X_{ij} is flow from node i to node j (taf), in space and time. Convex nonlinear costs can be represented as piecewise linear. CALVIN also has constraints representing physical or operational bounds. These include constraints for conservation of mass, upper bounds, and lower bounds, written mathematically as

$$\sum_i X_{ij} = \sum_i a_{ij} X_{ij} + b_j \qquad \text{for all nodes j} \qquad (2)$$

$$X_{ij} \le u_{ij} \qquad \text{for all arcs} \qquad (3)$$

$$X_{ij} \ge l_{ij} \qquad \text{for all arcs} \qquad (4)$$

where X_{ij} is the flow from node i to node j, a_{ij} is gains or losses on flows in arc ij (taf), b_j is external inflows to node j (taf), u_{ij} is upper bound on arc ij (taf), and l_{ij} is lower bound on arc ij (taf) (Jenkins *et al.,* 2001).

To represent hydrologic variability, CALVIN uses 72 years of monthly unimpaired historical data (1922 through 1993), during which the three worst droughts on record occurred, those of 1929 through 1934, 1976 through 1977, and 1987 through 1992. California's entire interconnected water system has been modeled with CALVIN (Jenkins *et al.,* 2001; Draper *et al.,* 2003). Additional CALVIN models of California have been used for various regional and climate change water management studies (Lund *et al.,* 2003).

Physical parameters in the model include infrastructure capacities, environmental requirements, and hydrology. Surface reservoirs and ground water basins have upper and lower bounds. Maximum surface reservoir capacity is limited by the seasonally varying flood storage level, and minimum capacity is set to dead storage. For ground water basins, the maximum capacity is the amount of water that can be stored in the aquifer, and the lower bound is the lowest historical level of that ground water. Pumping and conveyance capacities also are limited. Environmental requirements include minimum instream flows and flows to refuges. Due to the controversy inherent in economic valuation of environmental uses of water, environmental water requirements are modeled as constraints.

Economic parameters include economic penalty/demand functions and operating costs. The objective function of CALVIN (which drives the model) is to minimize the sum of water scarcity costs to urban and agricultural water users, lost hydropower benefits (compared with some ideal condition), pumping costs, water treatment operating costs, and water quality costs. Water scarcity costs are economic penalties imposed if agricultural and urban demands are not fully met. The economic value of water for agriculture is derived from the Statewide Agricultural Production Model (SWAP) (Howitt *et al.,* 2001). SWAP is a separate model of agricultural water and land use decisions that maximizes farm profits given crop production functions and limits on water, land, technology, and capital inputs. SWAP is similar to the Central Valley Production Model (CVPM) (USBR, 1997), except that values of water delivery can vary between months. For each agricultural region, SWAP is used to generate economic loss functions that decrease as water delivery increases. The economic loss represents the reduction in agricultural profits from limited water deliveries (higher marginal value of water), compared to ideal profits if water were not a limiting factor (marginal value equals zero).

Urban economic cost functions are based on demand curves for urban water use. These cost functions vary by month and are assumed to have constant seasonal elasticity (Jenkins *et al.,* 2001). CALVIN uses projected demands for the year 2020 for both agricultural and urban demand areas.

Operating costs correspond to variable costs, primarily for ground water pumping, surface pumping, and water treatment. Hydropower penalty curves often are nonlinear and thus are difficult to model. For this study, separate hydropower storage and release penalties were chosen to represent variable head facilities. These independent piecewise linear penalty functions were fit to the full multivariate nonlinear surface using a least squares approach (Ritzema, 2002).

CALVIN produces a monthly time series of water deliveries for each demand location that can be translated into scarcity costs based on economic value functions. For this paper, scarcity is defined as the difference between the quantity of water delivered and the maximum quantity demanded. Maximum demand delivery is derived from economic value functions at the point where marginal benefit of additional water is zero. Scarcity cost is the economic value of maximum water deliveries minus the economic value of water actually delivered. The marginal willingness to pay, or shadow value, for additional water is also output for each demand node and time step. This also is the slope of the economic value function at the delivered quantity of water.

Model Area and Assumptions

To examine the effects of removing O'Shaughnessy Dam, this study focuses on the San Joaquin and San Francisco Bay Regional CALVIN model (Figure 1). The model area includes 13 surface reservoirs, excluding O'Shaughnessy Dam, and five ground water basins. Major conveyance facilities include: the Hetch Hetchy Aqueduct, the California Aqueduct, the Delta

Mendota Canal, the South Bay Aqueduct, and the Pacheco Tunnel. Seven hydropower plants are included. Minimum instream flows are imposed 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 Goodwin Reservoir (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 CDWR's (1998) bulletin on per capita urban water use by county and detailed analysis unit (DAU). Demand for several smaller cities are represented as fixed 2020 demands (Ritzema and Jenkins, 2001).

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 (SCV) demand area includes Santa Clara Valley Water District, Alameda County Water District, and Alameda County Zone 7. The SFPUC and SCV water urban demand areas and all agricultural demand areas are represented using economic value functions (Ritzema and Jenkins, 2001).

Although the regional model is large enough to allow for coordinated use among many storage and conveyance facilities, the focus of this study is the Hetch Hetchy System (Figure 2). 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. Tiny Pilarcitos Reservoir (3 taf or 3.7 mcm) was omitted. Cherry and Eleanor Reservoirs are represented as a single reservoir because of the inability to disaggregate inflows into these reservoirs and the existence of an interconnecting tunnel. Nonstorage reservoirs in the Hetch Hetchy System, such as Early Intake and Moccasin Reservoir, are represented as junction nodes instead of reservoirs. Hydropower is included in the Hetch Hetchy portion of the model for Kirkwood, Holm, Moccasin, and New Don Pedro power plants. Minimum instream flows of 50 to 125 cfs (1.42 to 3.54 m^3/s) are imposed on the Tuolumne River downstream of New Don Pedro Reservoir (USBR, 1987).

Although raising the dam height at Calaveras Reservoir has been discussed to increase storage in the Hetch Hetchy System, Calaveras Reservoir is given a maximum capacity of 91 taf (112 mcm). Likewise, storage at this site has not been lowered to the current restriction of 28 percent of total maximum storage (SFPUC, 2006). While additional service area water storage is a priority for SFPUC and the Hetch Hetchy System in the event of a seismic event or terrorist act, this study assumes no new storage.

In CALVIN, storage space in New Don Pedro Reservoir is not divided between different owners and interests. Rather, the maximum capacity of New Don Pedro Reservoir was set to 2,030 taf (2,504 mcm), and water is allocated to different urban and agricultural demands as needed. Because CALVIN is economically driven, water scarcity is allocated to demands with lower economic values for water, usually agricultural areas. Here, results should be interpreted to indicate the extent of water scarcity. However, in the real world, water scarcity often occurs to demand areas based on water rights and contracts. In the Tuolumne River area, agricultural users with senior water rights would be unlikely to face scarcity unless they marketed water to other users.

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 rights to some 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 the Bay Area via the California Aqueduct (entailing significant quality degradation). 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. Inter-tie capacity is limited by the downstream Hetch Hetchy Aqueduct capacity of 465 cfs (13.17 m^3/s).

Water Treatment

Water treatment costs typically have high fixed costs and economies of scale. In CALVIN, treatment costs can only be modeled with unit costs on treatment links. Operating treatment costs from the Los Angeles Aqueduct System (another high quality system) were applied to the Hetch Hetchy System to estimate variable treatment costs from loss of the filtration avoidance permit. Additional fixed costs for constructing water treatment plants require a calculation outside of the model.

Detailed economic analysis of increased water treatment construction costs are beyond the scope of both CALVIN and this study. Removal of O'Shaughnessy Dam would prompt loss of filtration avoidance status, incurring considerable construction costs for new treatment facilities. This study could not include a detailed analysis of construction costs of new facilities. Although expansion of water treatment facilities

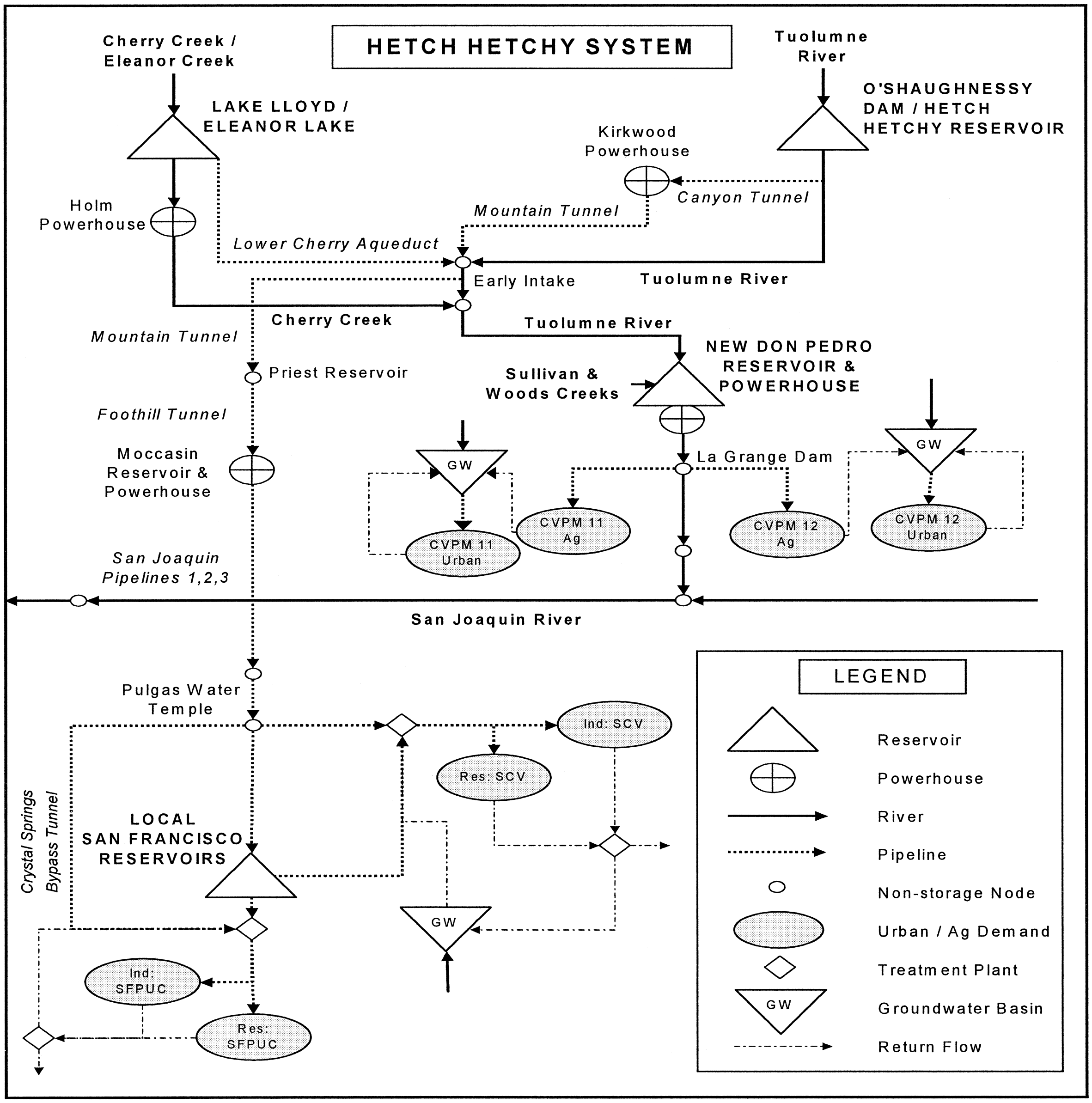

Figure 2. Hetch Hetchy System Model Schematic.

is a long term goal for the SFPUC, new treatment facilities are costly, and even deferral of such a large expense has considerable financial benefits. Rosekrans et al. (2004) estimates capital costs for expanding filtration facilities to treat all water supplies range from US$134.4 million to US$228 million above existing treatment cost plans. Avoiding such a capital expense makes keeping O'Shaughnessy Dam a priority for the SFPUC. More detailed economic studies of water treatment costs might be useful as part of a more comprehensive benefit-cost analysis (Null, 2003).

Year 2100 Demands and Dry Climate Warming

Year 2100 model runs uses a warm and dry hydrology representing effects of possible climate warming and roughly three times the current urban population. For this study, a warm and dry climate scenario (PCM) is used to develop a comprehensive hydrology for year 2100 model runs as a worst case scenario in terms of water supply (Zhu *et al.,* 2005). Population estimates for the year 2100 are from Landis and Reilly (2003). For a complete discussion see Lund *et al.* (2003, particularly Appendix A). These extreme model runs are used to examine the effects of removing

O'Shaughnessy Dam when water demand is much, much greater and climate 26 percent drier in the very distant future.

Additional changes for the "2100" model runs include: coastal demand regions have unlimited access to seawater desalination at a unit cost of US$1,000/af (US$811 per thousand cubic meters); urban wastewater recycling is available for up to 50 percent of return flows, also at a cost of US$1,000/af (US$811/tcm); some environmental demands increase, although no changes are made to environmental demands for links for the Tuolumne River; and operation and maintenance (O&M) water treatment costs increase to represent the loss of filtration avoidance by the year 2100. (Variable treatment costs were increased to the same level as 2020 model runs with higher treatment costs.)

Model Runs

Six model runs are compared for this study, one constrained to current operating policies with 2020 demands, three unconstrained runs from the year 2020 modeling set, and two model runs with year 2100 demands and a warm, dry hydrology representing possible effects of climate warming (Table 2). Two unconstrained year 2020 runs include O'Shaughnessy Dam. One has increased water treatment costs to represent loss of filtration avoidance; the other has no change to water treatment costs to represent filtration avoidance being maintained. All runs without O'Shaughnessy Dam have an inter-tie from New Don Pedro Reservoir to Hetch Hetchy Aqueduct and higher O&M water treatment costs, reflecting an end of filtration avoidance. Results from a base case modeling set represent 2020 conditions with current operating and allocation policies (Jenkins *et al.,* 2001). Some of these results are included for comparison and are referred to as base case results. Both model runs with year 2100 water demands have increased water treatment costs. In one run O'Shaughnessy Dam is removed and an inter-tie linking New Don Pedro Reservoir with the Hetch Hetchy Aqueduct is added.

Limitations

Consequences of O'Shaughnessy Dam removal could be substantial. The complexities of the system and management options require a quantitative approach, for which computer modeling is well suited. However, several limitations apply to the approach taken here. As with all modeling studies, management and river systems are simplified. Economic benefits from recreation are currently neglected. Recreation and tourism in Hetch Hetchy Valley would likely be substantial, providing revenue and benefits to Yosemite National Park and nearby towns, but this is not a comprehensive benefit cost analysis. Another important limitation with CALVIN is perfect hydrologic foresight. This allows the model to prepare for and aggressively operate during droughts, reducing water scarcity and associated costs. This limitation tends to be less important when large amounts of storage (including ground water) are available (Draper, 2001). Urban and agricultural economic demands are assumed to be fixed, and ground water basins are extremely simplified. Jenkins *et al.* (2001) provides more on the limitations of CALVIN.

All model runs, except the base case, are unconstrained by current institutional and legal allocation policies. This reduces water scarcity since water operations and allocations have perfect institutional flexibility. However, removing current policy constraints do show what could be possible with existing infrastructure. In these model runs, operations and water allocation are only economically driven. Absence of institutional implications and public or political support for the idea is perhaps the greatest limitation. These are not part of this model but are nevertheless driving factors. Additional examination of these factors would be useful.

RESULTS

Overall, year 2020 model runs show little water scarcity when O'Shaughnessy Dam is removed and an

TABLE 2. Model Runs by Filtration Condition, Dam Status, and Year.

	Keep Filtration Avoidance	**Lose Filtration Avoidance**
O'Shaughnessy Dam Retained	2020	2020
	2020 Base Case	2100
Remove O'Shaughnessy Dam With New Don Pedro Inter-tie	Scenario modeled, produced no new results	2020
		2100

inter-tie added between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct. Although storage at the O'Shaughnessy Dam site is eliminated, flow in the Tuolumne River does not change. Capture of significant quantities of water into the upper Hetch Hetchy Aqueduct remains possible. Adding an inter-tie between New Don Pedro Reservoir and the Hetch Hetchy Aqueduct allows capture of Tuolumne River water at 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 removing O'Shaughnessy Dam, removal could be costly. Hydropower generation suffers without water storage at O'Shaughnessy Dam. Also, removing this reservoir ends SFPUC's filtration avoidance and creates a need for additional water treatment facilities. Filtration avoidance is important and valuable 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. Without O'Shaughnessy Dam, storage drops by approximately 350 taf (432 mcm), the capacity of O'Shaughnessy Dam, in all water years. To assess whether the storage space lost from removing O'Shaughnessy Dam is critical to meet water deliveries, storage in the other Hetch Hetchy System reservoirs is evaluated. 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. Model runs indicate that much storage is never used in local San Francisco reservoirs. Thus, considerable storage remains in the overall Hetch Hetchy System without O'Shaughnessy Dam.

Water Deliveries and Scarcity

With and without O'Shaughnessy Dam, full deliveries are made to urban demand areas for all optimized 2020 model runs (Table 3). Although it is possible to deliver water to San Francisco and Santa Clara Valley urban areas via the Hetch Hetchy Aqueduct, the Pacheco Tunnel, or the South Bay Aqueduct, deliveries via all these pipelines are unaffected by removing O'Shaughnessy Dam. This indicates that removing O'Shaughnessy Dam would change operation of the Hetch Hetchy System but need not affect surrounding water resources. When model runs are constrained to current operational constraints (base case), a small amount of scarcity occurs to urban water users (Jenkins *et al.,* 2001; Ritzema and Jenkins, 2001).

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.

A slight decrease in deliveries to agricultural demand areas occurs in model runs without O'Shaughnessy Dam. Total annual average deliveries to agricultural areas is 5,257,983 af/yr (6,485.63 mcm/yr) with O'Shaughnessy Dam but average 575 af/yr (0.71 mcm/yr) less without O'Shaughnessy Dam.

TABLE 3. Average 2020 Deliveries, Scarcity, and Scarcity Cost.

	Base Case With O'Shaughnessy*	**With O'Shaughnessy Dam**	**Without O'Shaughnessy Dam****
	Urban Regions		
Annual Average Deliveries (taf/yr)	1,424	1,440	1,440
Annual Average Scarcity (taf/yr)	16	0	0
Annual Average Scarcity Cost (US$K/yr)	15,290	0	0
	Agricultural Regions		
Annual Average Deliveries (taf/yr)	5,259	5,258	5,257
Annual Average Scarcity (taf/yr)	0	1	1.5
Annual Average Scarcity Cost (US$K/yr)	0	5	11

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

In the driest year this increases scarcity to 72.5 taf (89.43 mcm). It slightly reduces water delivered during dry years to Turlock Irrigation District (CVPM 11) and Modesto Irrigation District (CVPM 12) (Figure 3). There is a small transfer of water from agricultural uses to urban uses during a few very dry years. Additional urban water conservation would reduce water transfer amounts.

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. These results indicate the minimum level of water scarcity from removing O'Shaughnessy Dam.

Using results from the base case modeling set, constrained by 1997 operating policies (including O'Shaughnessy Dam), water scarcity is observed in SFPUC and Santa Clara Valley residential demand area in 1921 through 1934, 1977, and 1986 through 1993. Over the entire 72-year time span, average annual water scarcity is 6 taf (7.4 mcm) for SFPUC and 10 taf (12.3 mcm) for Santa Clara Valley (Jenkins et al., 2001).

Conveyance

Without O'Shaughnessy Dam, flows through the upper Hetch Hetchy Aqueduct (above New Don Pedro Reservoir) are less but remain considerable. Flows in the Tuolumne River above the O'Shaughnessy Dam site do not change with removal of the reservoir. Only storage is eliminated. Thus, considerable quantities of runoff could be diverted at the dam site in much of most years. Seasonal flows in the upper Hetch Hetchy Aqueduct illustrate the importance of spring snowmelt (Figure 4). The upper aqueduct is always at capacity in April and May from spring runoff. During other months, flows through the upper aqueduct vary considerably with streamflow.

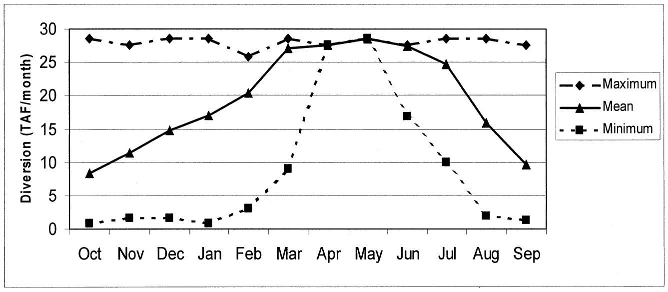

Figure 4. Seasonal Flows in the Upper Hetch Hetchy Aqueduct.

Flows through a New Don Pedro inter-tie to the lower Hetch Hetchy aqueduct are the inverse of flows through the upper Hetch Hetchy Aqueduct (Figure 5). During April and May, flows through the New Don Pedro inter-tie are zero because the aqueduct is already at capacity with diversions at the O'Shaughnessy Dam site. During other months, water is diverted from New Don Pedro 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. 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 remain of value.

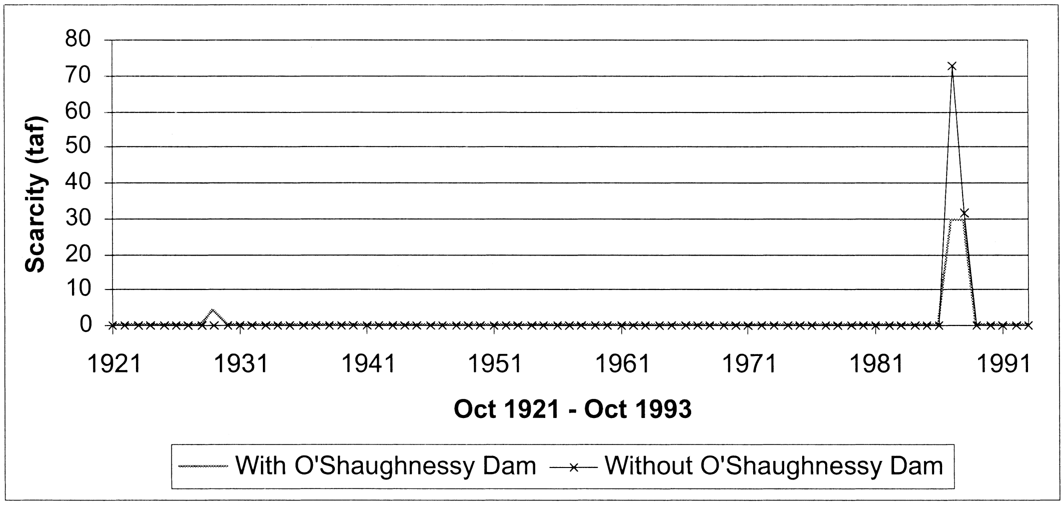

Figure 3. Total Annual Agricultural Scarcity.

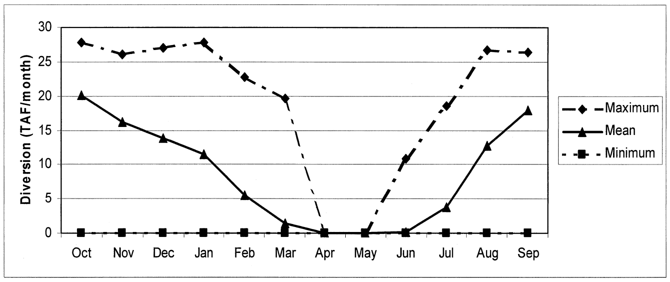

Figure 5. Monthly Flows Through a New Don Pedro Inter-Tie.

Hydropower and Water Treatment

Hydropower generation is reduced substantially without O'Shaughnessy Dam, primarily from eliminating hydropower generation at Kirkwood Power Plant, which requires head from O'Shaughnessy Dam. Generation at Moccasin Power Plant is reduced significantly and is reduced slightly at Holm Power Plant. The loss of hydropower generation at Kirkwood and the reduction at Moccasin and Holm average 457 GWhr/yr. The average annual hydropower revenue loss is approximately US$12 million/yr, assuming monthly varying wholesale electricity prices (Ritzema, 2002).

Filtration treatment O&M costs of US$17/af (US$13.79/tcm) are used based on operating filtration costs for other California cities with high quality source water. If filtration avoidance were lost, treatment operating costs could rise to US$17/af (US$13.79/tcm), or US$6 million/yr. Most likely, these costs would be passed on to urban water users, raising monthly water bills to rates comparable to other California cities. Overall, water quality would remain high because reservoirs such as New Don Pedro (which do not have filtration avoidance) also have good water quality.

Year 2100 Results

In model runs with projected year 2100 demand and a warm, dry hydrology (having 26 percent less average inflow) representing possible climate warming changes, the entire region is short of water but not short of storage capacity. In these runs, water scarcity is extensive, especially for agricultural areas. This underscores an important distinction: water and storage space are not the same. In year 2100 runs, water is generally not stored in surface reservoirs for extended periods; it is used promptly to meet increased demands, reducing evaporative losses to water supply.

The year 2100 model run with O'Shaughnessy Dam stores an annual average 180 taf (222 mcm) in Hetch Hetchy Reservoir. It fills and empties the reservoir nearly each season, filling to capacity in 46 percent of the years and emptying to dead storage 74 percent of the years. The year 2100 model run without O'Shaughnessy Dam stores an annual average of 115 taf (142 mcm) more water in New Don Pedro Reservoir. There is always less surface storage in the remaining Hetch Hetchy System reservoirs in year 2100 models than in year 2020 models. Despite considerable storage space, there is not enough water to meet demands. Excess water rarely exists to be stored for future years; rather it is usually sent to demand areas within a year. More ground water is used for drought storage in year 2100 models than in year 2020 models. As demand increases in the future, conjunctive use (which reduces evaporative losses) may become more widespread. Little difference in ground water storage exists between the year 2100 results with and without O'Shaughnessy Dam.

The lower Hetch Hetchy Aqueduct was not at capacity for one month of one year in the model run with O'Shaughnessy Dam and without the New Don Pedro inter-tie. The Hetch Hetchy Aqueduct below New Don Pedro Reservoir remains full despite the removal of O'Shaughnessy Dam with year 2100 demands. The inter-tie may be desirable even with O'Shaughnessy Dam.

In both year 2100 model runs there is water scarcity to urban water users. Residential San Francisco users average 12.7 taf/yr (15.7 mcm/yr) of water scarcity, and Santa Clara County water users average 25.5 taf/yr (31.5 mcm/yr) of water scarcity (Table 4). Maximum monthly scarcity to these regions is 3 taf and 6.3 taf (3.7 mcm and 7.8 mcm), respectively. Combined average scarcity to other Central Valley urban demand areas is 13.5 taf/yr (16.7 mcm/yr). Removing O'Shaughnessy Dam does not change urban water deliveries or scarcity. Water scarcity to all agricultural demand areas ranges from 429 taf/year to 1,265 taf/year(529 mcm/yr to 1,560 mcm/yr) for runs with and without O'Shaughnessy Dam.

During times of water scarcity, maximum monthly marginal willingness to pay for additional water varied between US$929 to US$969/af (US$754 to US$786/tcm)for San Francisco and Santa Clara Valley urban areas. Maximum marginal willingness to pay for more water in Central Valley urban demand areas varied between US$412 to US$522/af (US$334 to US$423/tcm). The maximum monthly marginal willingness to pay for agricultural users was far less, between US$267 to US$352/af (US$217 to US$286/tcm). The large difference in marginal willingness to pay between coastal urban water users and other

Central Valley urban and agricultural users arises because the lower Hetch Hetchy Aqueduct is at maximum capacity. Despite water scarcity to urban regions, more water cannot be delivered without additional conveyance capacity.

TABLE 4. Average 2100 Deliveries, Scarcity, and Scarcity Cost.

	Climate Change Hydrology	
	With O'Shaughnessy Dam	Without O'Shaughnessy Dam
Urban Regions		
Average Deliveries (taf/yr)	2,314	2,314
Average Scarcity (taf/yr)	52	52
Average Scarcity Cost (US$K/yr)	22,748	22,730
Agricultural Regions		
Average Deliveries (taf/yr)	2,537	2,536
Average Scarcity (taf/yr)	2,722	2,723
Average Scarcity Cost (US$K/yr)	18,087	18,090

Both desalination and recycled water was available at a price of US$1,000/af (US$811/tcm). Additional desalination and recycling facilities in CALVIN were used in only two months in year 2100 runs. The run with O'Shaughnessy Dam used a total of 28 taf (35 mcm) of recycled and desalinated water. The run without O'Shaughnessy Dam used a total of 24 taf (30 mcm). Overall, scarcity was extensive and the urban marginal value of water was high before recycled or desalinated water was used. Users opt to face some scarcity (reducing use by conservation efforts) rather than pay for additional water from these sources (unless costs of desalination decrease significantly). Some scarcity can be optimal.

DISCUSSION

A stable water supply for the San Francisco peninsula could be maintained after removing O'Shaughnessy Dam. The numerous reservoirs and pipelines in the Hetch Hetchy System provide considerable flexibility for delivering water. Adding 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 by 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 or operational interruptions to facilities upstream.

When O'Shaughnessy Dam is removed in combination with a warmer drier hydrology and water demands increased to projected year 2100 demands, there are surprisingly few effects of dam removal on water deliveries and operation of the Hetch Hetchy System. Some water scarcity occurs to urban residential demand areas and considerable water scarcity to agricultural demand areas regardless of the existence of O'Shaughnessy Dam. Scarcity occurs because insufficient water exists in the system despite unused surface water storage and the lower Hetch Hetchy Aqueduct remaining at capacity at all times. Although water desalination and water recycling are available, some water scarcity costs (for water conservation) are preferable to higher costs of additional water supplies. With increased future demands, water storage in ground water basins increases, suggesting greater conjunctive use in the future.

Removing O'Shaughnessy Dam carries considerable financial costs. These include lost hydropower revenue, construction costs for additional water treatment facilities, increased treatment operating 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 economic and political.

Filtration avoidance makes O'Shaughnessy Dam extremely valuable for SFPUC and the Hetch Hetchy System, saving the SFPUC 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 might offset lost hydropower revenue and increased treatment costs. However, if Hetch Hetchy Valley was opened to recreation, the economic benefits would go primarily to the National Park Service, concessionaires, and the local economy, while SFPUC would incur most costs. Further thought and research are needed to examine these possibilities and changes.

Water management in California is dynamic. Changes in climate, water laws, water markets, and technology could alter the way water is moved and valued. It is beyond the scope of this project to provide a comprehensive 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. 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. These benefits of restoration could then be compared with losses from lower hydropower production and other costs. Additional research on institutional aspects of water transfers or exchanges among SFPUC, the Modesto Irrigation District, and the Turlock Irrigation District also would be useful.

CONCLUSIONS

Removing O'Shaughnessy Dam need not substantially increase water scarcity. Without O'Shaughnessy Dam, capture of considerable quantities of runoff could be possible at the dam site for much of most years. Only storage is eliminated. Flow in the Tuolumne River above the O'Shaughnessy dam site does not change with removal of the reservoir. If New Don Pedro Reservoir is connected directly with the Hetch Hetchy Aqueduct, almost all demands can be satisfied without affecting the larger region outside the Tuolumne Basin. This substantially reduces the need for difficult large-scale coordinated use agreements.

Conveyance sometimes can substitute for water storage. Connecting 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. Even with O'Shaughnessy Dam remaining in the Hetch Hetchy System, the inter-tie improves delivery reliability.

Removing O'Shaughnessy Dam reduces hydropower generation and reduces revenues by approximately US$12 million/yr.

The loss of filtration avoidance that would occur with removal of O'Shaughnessy Dam may be a predominant economic factor in the debate to remove O'Shaughnessy Dam. Construction costs of additional filtration facilities would be high. Removing O'Shaughnessy Dam could increase Bay Area drinking water costs significantly, to levels common for most California cities.

Even with much greater future water demands and a drier warmer future climate, removing O'Shaughnessy Dam has little effect on the Hetch Hetchy System and water deliveries to demand regions. Although there is unused surface storage space with projected future demands, there are not enough water inflows. Water and surface storage are not interchangeable.

Optimization modeling is useful in identifying potentially effective reoperations for water resource systems to support restoration. This optimization approach found an unexpected level of public acceptance as a basis for a series of Pulitzer Prize winning editorials in a major metropolitan newspaper, perhaps indicating a greater potential for such methods for public policy purposes.

Water delivery to urban and agricultural users may be limited by political and institutional constraints rather than water storage or other physical components of the Hetch Hetchy System. It is hoped that technical studies such as this will help enlighten deliberations and suggest opportunities.

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LITERATURE CITED

CDWR (California Department of Water Resources),1998.The California Water Plan Update. Bulletin 160-98, California Department of Water Resources, Sacramento, California.

CDWR (California Department of Water Resources), 2005. Hetch Hetchy Restoration Study. *Available at* http://hetchhetchy.water.ca.gov/. *Accessed in* April 2005.

City and County of San Francisco, 1999. San Francisco Water and Power: A History of the Municipal Water Department and Hetch Hetchy System. City and County of San Francisco, San Francisco, California.

Draper, A.J. 2001. Implicit Stochastic Optimization With Limited Foresight for Reservoir Systems. Ph.D. Dissertation, University of California-Davis. Davis, California.

Draper, A.J., M.W. Jenkins, K.W. Kirby, J.R. Lund, and R.E. Howitt. 2003. Economic-Engineering Optimization for California Water Management. Journal of Water Resources Planning and Management 129(3):155-164.

Howitt, R.E., K.B. Ward, and S.M. Msangi. 2001. CALVIN Water Management Appendix A: Statewide Water and Agriculture Production Model. *Available at* http://cee.engr.ucdavis.edu/

faculty/lund/CALVIN/Report1/Appendices/AppendixA.pdf. *Accessed in* March 2005.

Huber, N.K. 1987. The Geologic Story of Yosemite Valley. U.S. Geological Survey Bulletin 1595, Washington, D.C., 64 pp.

Hundley, N., 1992. The Great Thirst: Californians and Water, 1770s-1990s. University of California Press, Berkeley and Los Angeles, California.

Jenkins, M.W., A.J. Draper, J.R. Lund, R.E. Howitt, S. Tanaka, R. Ritzema, G. Marques, S.M. Msangi, B.D. Newlin, B.J. Van Lienden, M.D. Davis, and K.B. Ward, 2001. Improving California Water Management: Optimizing Value and Flexibility. Center for Environmental and Water Resources Engineering. *Available at* http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/Report2/CALVINReport2001.pdf. *Accessed on* February 7, 2006.

Jensen, A., 2004. Hetch Hetchy Reclaimed: Hetchy Clients Need Equal Water Supply; 9/7/04. *Sacramento Bee*, Sacramento, California.

Labadie, J.W., 2004. Optimal Operation of Multireservoir Systems: State-of-the-Art Review. Journal of Water Resources Planning and Management 130(2):93-111.

Landis, J.D. and M. Reilly, 2003. How Will We Grow: Baselines Projections of California's Urban Footprint Through the Year 2100. Working Paper 2003-2004, Department of City and Regional Planning, Institute of Urban and Regional Development, University of California-Berkeley, Berkeley, California. *Available at* http://www-iurd.ced.berkeley.edu/pub/WP-2003-04-screen.pdf. *Accessed on* February 7, 2006.

Leal, S., 2004. Hetch Hetchy Reclaimed: SF: Proceed with 'Extreme Caution' at Hetch Hetchy; 9/12/04. *Sacramento Bee*, Sacramento, California.

Lund, Jay R., Richard E. Howitt, Marion W. Jenkins, Tingju Zhu, Stacy K. Tanaka, Manuel Pulido, Melanie Tauber, Randall Ritzema, and Inês Ferriera, 2003. Climate Warming and California's Water Future. *Available at* http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/ReportCEC/CECReport2003.pdf. *Accessed in* March 2005.

Muir, J., 1912. The Yosemite. The Century Co., New York, New York.

Null, S., 2003. Re-Assembling Hetch Hetchy: Water Supply Implications of Removing O'Shaughnessy Dam. Master's Thesis, University of California-Davis, Davis, California.

Philp, T., 2004a. Hetch Hetchy Reclaimed: Looking Again at Hetch Hetchy. *Sacramento Bee*, 8/22/04, Sacramento, California.

Philp, T., 2004b. Hetch Hetchy Reclaimed: The Lost Yosemite. *Sacramento Bee*, 8/22/04, Sacramento, California.

Philp, T., 2004c. Hetch Hetchy Reclaimed: CALVIN Says the Dam Can Go. *Sacramento Bee*, 8/29/04, Sacramento, California.

Philp, T., 2004d. Hetch Hetchy Reclaimed: The Dam Downstream. *Sacramento Bee*, 8/29/04, Sacramento, California.

Philp, T., 2004e. Hetch Hetchy Reclaimed: In 1987, an Attempt to Bring Back the Valley. *Sacramento Bee*, 8/30/04, Sacramento, California.

Philp, T., 2004f. Hetch Hetchy Reclaimed: Editorial - San Francisco's Paradox. *Sacramento Bee*, 8/30/04, Sacramento, California.

Philp, T., 2004g. Hetch Hetchy Reclaimed: Muir's Plea. *Sacramento Bee*, 9/5/04, Sacramento, California.

Philp, T., 2004h. Hetch Hetchy Reclaimed: Yosemite on the Cheap. *Sacramento Bee*, 9/7/04, Sacramento, California.

Philp, T., 2004i. Hetch Hetchy Reclaimed: Addiction Explained. *Sacramento Bee*, 9/12/04, Sacramento, California.

Philp, T., 2004j. Hetch Hetchy Reclaimed: A River's 'Rajahs.' *Sacramento Bee*, 9/19/04, Sacramento, California.

Philp, T., 2004k. Hetch Hetchy Reclaimed: Drain It, Then What?. *Sacramento Bee*, 9/19/04, Sacramento, California.

Philp, T., 2004l. Hetch Hetchy Reclaimed: Hetch Hetchy's Future: It is Time for New Chapter, New Champions. *Sacramento Bee*, 9/20/04, Sacramento, California.

Poff, L.N. and D.D. Hart. 2002. How Dams Vary and Why it Matters for the Emerging Science of Dam Removal. Bioscience 52(8):659-668.

Ritzema, R.S., 2002. CALVIN Climate Warming Appendix D: Hydropower in the CALVIN Model. *Available at* http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/ReportCEC/AppendixD.pdf. *Accessed in* March 2005.

Ritzema, R.S. and M.W. Jenkins, 2001. CALVIN Water Management Appendix 2C. Region 3 Results: San Joaquin and South Bay Area. *Available at* http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/Report2/Appendix2C.pdf. *Accessed in* March 2005.

Rosekrans, S., N.E. Ryan, S.H. Hayden, T.J. Graff, and J.M. Balbus, 2004. Paradise Regained: Solutions for Restoring Yosemite's Hetch Hetchy Valley. Environmental Defense, New York, New York.

SFPUC (San Francisco Public Utilities Commission), 2002. Water System Improvement Program. *Available at* http://sfwater.org/main.cfm/MC_ID/7/MSC_ID/6. *Accessed in* February 2006.

SFPUC (San Francisco Public Utilities Commission), 2005. SFPUC Releases 2004 Water Quality Report. *Available at* http://sfwater.org/detail.cfm/MSC_ID/51/MTO_ID/63/MC_ID/10/C_ID/2525/holdSession/1. Accessed in February 2006.

SFPUC (San Francisco Public Utilities Commission), 2006. Calaveras Dam Replacement. *Available at* http://sfwater.org/main.cfm/PRJ_ID/141/MC_ID/7/MCS_ID/90. *Accessed in* February 2006.

Sierra Club, 2002. Hetch Hetchy Timeline. *Available at* http://www.sierraclub.org/ca/hetchhetchy/timeline.asp. *Accessed in* January 2005.

Stanton, S., 2005. Bee Editorial Writer Wins Pulitzer Prize. *Sacramento Bee*, 4/4/2005, Sacramento, California.

USBR (U.S. Bureau of Reclamation), 1987. Hetch Hetchy: A Survey of Water and Power Replacement Concepts. Sacramento, California.

USBR (U.S. Bureau of Reclamation), 1997. Central Valley Project Improvement Act: Draft Programmatic Environmental Impact Statement. Documents and Model Runs. U.S. Department of the Interior, Bureau of Reclamation, Sacramento, California (2 CD-ROMS).

USDOE (U.S. Department of Energy), 1989. Hetch Hetchy, Striking a Balance: A Review of the Department of the Interior's Survey of Water and Power Replacement Concepts for Hetch Hetchy. U.S. Department of Energy, Washington D.C.

Zhu, T., M.W. Jenkins, and J.R. Lund. 2005. Estimated Impacts of Climate Warming on California Water Availability Under Twelve Future Climate Scenarios. Journal of the American Water Resources Association (JAWRA) 41(5):1027-1038.