Reservoir Design and Operation with Variable Lake Hydrology

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Abstract: This research quantifies the impact of lake evaporation and rainfall on optimal reservoir capacity and water yield. A reservoir design and operation model was developed and applied to the Santa Ynez River basin of central California, which endures large evapotranspiration and extreme climatic variability. Reservoir design and average annual water yield were obtained in two cases. First, lake evaporation and rainfall fluxes were taken into account in the water balance of the reservoir system. Second, those same fluxes were ignored. The optimization-model results indicate that in-lake hydrology plays a considerable role on estimates of optimal reservoir capacity and yield. Furthermore, results indicate that the lack of proper consideration of in-lake hydrology leads us to err on the side of greater risk. Specifically, reservoir capacity and average water release are under and overestimated, respectively. The optimization model is particularly well-suited for modeling reservoir systems with active in-lake hydrologic fluxes and allows a variety of objective functions to be considered, thus, providing flexibility in the optimization of reservoir design and operation.

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Introduction

The Santa Ynez River basin of Santa Barbara County, Calif. is subject to diverse, and at times, conflicting water uses. The Santa Ynez River is the main source of water for municipalities, agriculture, and fisheries. Water is diverted via gravity tunnels from the Santa Ynez watershed to the south coast region of Santa Barbara County to serve the towns of Carpinteria, Goleta, Isla Vista, Montecito, Santa Barbara, and Summerland. Within its watershed, the Santa Ynez River supports urban water use in the towns of Buellton, Lompoc, Santa Ynez, and Solvang, as well as large-scale agriculture in the Lompoc Valley. Fig. 1 shows a map of the Santa Ynez River basin and water-resources infrastructure within it. The main water impounding structure is Bradbury Dam (at Cachuma Reservoir), which is supplemented by two small upstream diversion dams (i.e., Gibraltar and Juncal dams). Water is transferred from Cachuma Reservoir to Santa Barbara County's south coast via the Tecolote Tunnel shown in Fig. 1. The Mission and Doulton tunnels (also shown in Fig. 1) divert water from the Santa Ynez River at Bradbury and Juncal dams, respectively. Fisheries have been affected by the regulation of streamflow caused by Cachuma Reservoir. Specifically, the southern steelhead trout (*Oncorhynchus mykiss*) has been declared an endangered species in the Santa Ynez River due to declining fish-population levels during the last 4 decades.

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Reservoirs and diversion infrastructure in the Santa Ynez River were built to regulate its highly variable stream flow and to convey its water to urban areas in which water use has risen rapidly since the late 1800s (Eckman 1967; Loáiciga and Renehan 1997). Reliable water supply in the presence of recurrent drought has been an elusive goal for those who depend on Santa Ynez River water (Lawrence et al. 1994). This paper presents a reservoir design and operation model for the Santa Ynez River system. The model takes into account monthly water diversions, fishery flow requirements, and, in particular, includes an innovative technique for calculating reservoir evaporation and precipitation. A key objective of this paper is to show the effect that evaporation has on reservoir design and operation in regions of high-potential evapotranspiration such as central California. In addition, this paper addresses the role of initial reservoir storage on annual water yield and optimal reservoir capacity. Our reservoir design and operation model is built with the aim of flexible implementation and a parsimonious structure. Examples of the model's applicability complement its theoretical underpinnings.

Streamflow Variability

Fig. 2 shows a time series of unregulated Santa Ynez River annual streamflow into Cachuma Reservoir from water years 1917–1918 through 1992–1993. The mean and standard deviations of annual streamflow are 92.5×10^6 m^3 and 135.3×10^6 m^3, respectively. Shown in Fig. 2 are the droughts that occurred in that period. Hydrological droughts are defined herein as periods with four or more consecutive years of below-average annual streamflow (Loáiciga et al. 1992, 1993; Loáiciga and Leipnik 1996). There were six such events in the 1917–2000 period, or about one drought every 14 years. Fig. 2 shows sharp interannual fluctuations in streamflow. The persistence of dry runs is a matter of concern in the Santa Ynez River from a water-resources standpoint (Loáiciga and Renehan 1997). It is in this context of uncer-

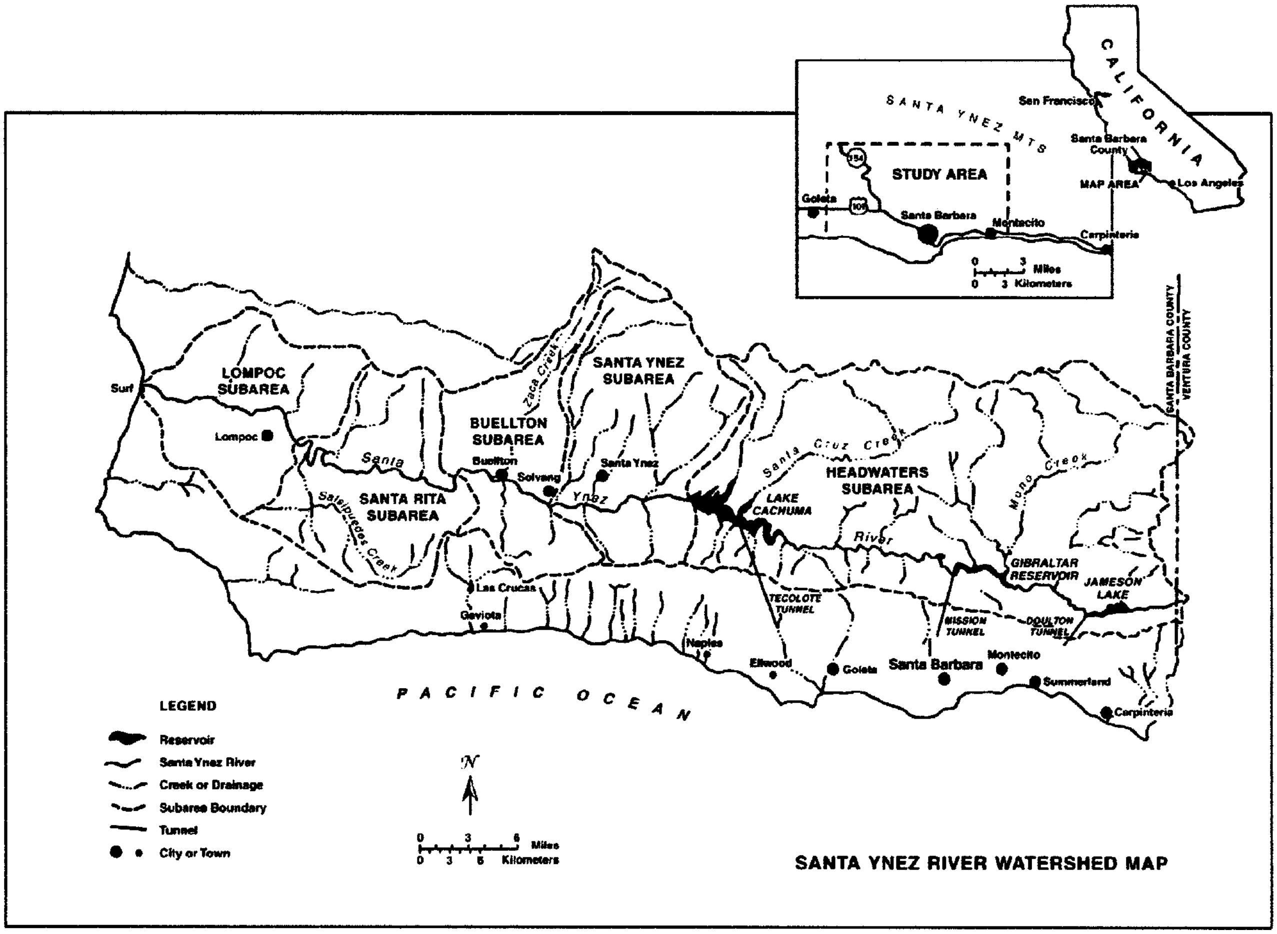

Fig. 1. The Santa Ynez River basin and major water resources infrastructure

tain water sources and growing water use that we have developed a mathematical programming model for the optimization of reservoir operation and design in the Santa Ynez River basin.

Storage Dynamics in Santa Ynez River Reservoir System

Conceptual Representation of Reservoir System

Consider the schematic representation of the reservoir system in the Santa Ynez River shown in Fig. 3. Cachuma Reservoir and two small diversion dams (Gibraltar and Juncal) are depicted along with the various fluxes that determine the water balance above Bradbury Dam at Cachuma Reservoir. For comparison, the tributary drainage areas above Bradbury, Gibraltar, and Juncal dams are 1106, 553, and 36 km^2, respectively. The diversions shown in Fig. 3 represent interbasin water transfers from the Santa Ynez River watershed to Santa Barbara County's south coast, across the Santa Ynez Mountains (Fig. 1). For all practical purposes, the storages behind Gibraltar and Juncal dams are negligible. Therefore, these two dams are treated strictly as water-diversion nodes along the Santa Ynez River.

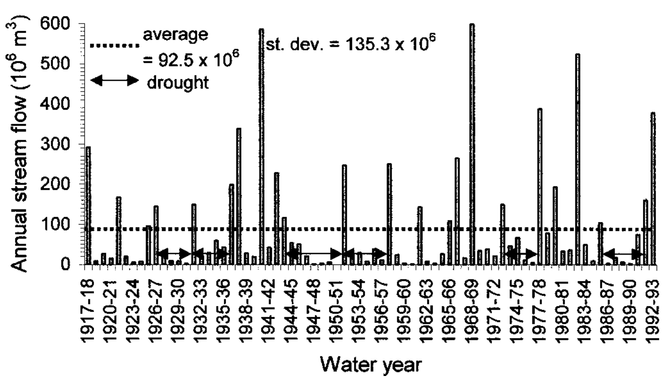

Fig. 2. Santa Ynez River stream flow into Cachuma Reservoir, 1917–1918 through 1992–1993. (Source: Santa Barbara County Water Agency)

Lake Evaporation and Rainfall

Fig. 4 shows the annual evaporation and the rainfall in Cachuma Reservoir from 1917–1918 through 1992–1993. It is seen in Fig. 4 that rainfall is more variable and smaller than evaporation. The mean annual Cachuma evaporation and rainfall are 179 and 46 cm/year, respectively. For comparison, the reference crop evapotranspiration in the study region has been estimated at 126 cm/year (Davidoff et al. 1999). Therefore, evaporation depletes reservoir storage at an average rate of 133 cm/year. The precipitation into Cachuma Reservoir is measured in a standard National Weather Service rain gauge located at Bradbury Dam. The reservoir evaporation equals pan evaporation multiplied by a lake coefficient. Pan evaporation is measured by means of a standard National Weather Service evaporation pan situated at Bradbury Dam. Monthly lake coefficients for Cachuma Reservoir have been calculated by the Santa Barbara County Water Agency (Alroth

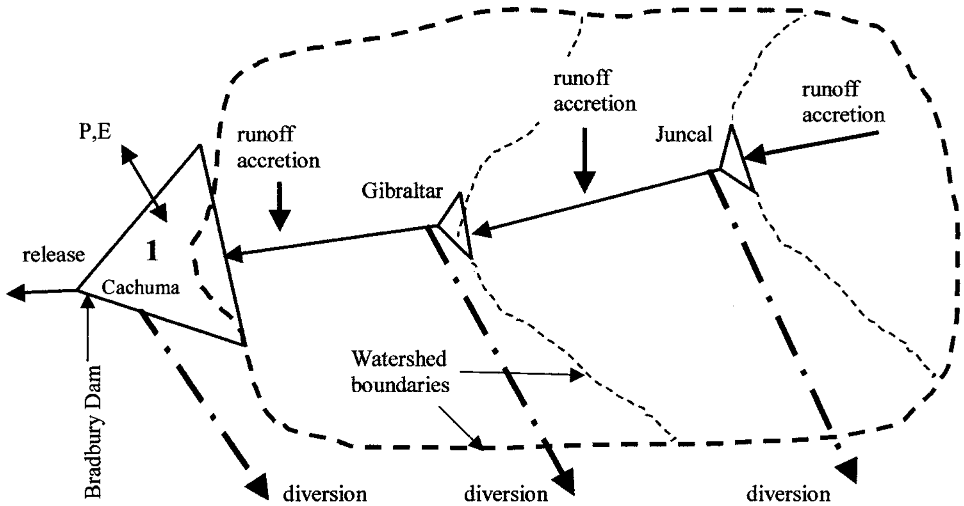

Fig. 3. Schematic of Santa Ynez River reservoir system. P and E denote reservoir rainfall and evaporation, respectively. Drawing not at scale.

and Naftali 1997). For the purpose of water balance calculations in Cachuma Reservoir, the rainfall and evaporative fluxes (in volume per unit time) are calculated by multiplying their rates (in length per unit time) times the reservoir area (in length squared). The area A versus storage S function for Cachuma Reservoir is given by the following equation in which the area and storage are given in 10^3 m^2 and 10^3 m^3 respectively (MNS Engineerings, Inc. 1998):

$$A(10^3\ \ \mathrm{m}^2) = 1300.7 + 0.05054 \cdot S \quad (r^2 = 0.97) \tag{1}$$

in which r^2 is the correlation coefficient of the regression between area and storage. Eq. (1) plays a central role in Cachuma Reservoir's water balance.

Monthly Water Balance in Cachuma Reservoir

Let us denote the Cachuma Reservoir storage at the end of period i by S_i and the reservoir storage capacity by C. Consider a time horizon of n periods (one period = 1 month in the application), and let $i = 0,1,2,\ldots,n$ be the time index as shown in Fig. 5. The total number of months equals the number of (water) years times 12. The period of analysis in this work encompasses the water years 1917–1918 through 1992–1993, which implies that $n = 76 \times 12 = 912$. In Fig. 5, E_i, P_i, r_i, w_i, and D_i denote reservoir evaporation, reservoir rainfall, streamflow accretion, reservoir release, and water diversions during the ith month, respectively. The

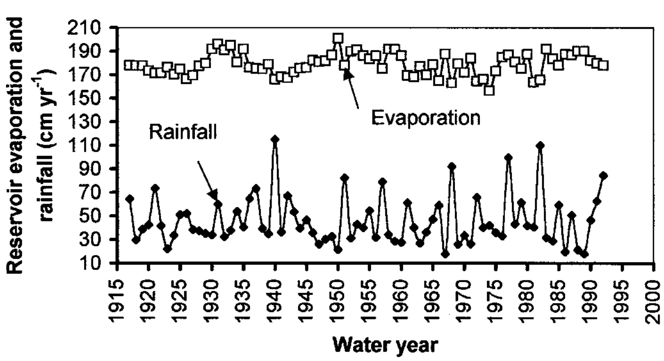

Fig. 4. Measured evaporation and rainfall in Cachuma Reservoir (Source: Santa Barbara County Water Agency).

water-balance equation for Cachuma Reservoir, given that the starting or initial reservoir storage is $S_0 = g \cdot C$, where g is a fraction between 0 and 1, is as follows:

$$S_i = S_{i-1} + r_i + P_i - D_{1,i} - D_{2,i} - D_{3,i} - w_i - E_i \quad i = 1,2,\ldots,n \tag{2}$$

in which $D_{1,i}$ is the diversion from Cachuma Reservoir; $D_{2,i}$ and $D_{3,i}$ are the diversions at Gibraltar and Juncal dams, respectively; r_i is the streamflow into Cachuma Reservoir produced by runoff from its entire upstream drainage area (i.e., equal to 1,106 km^2). Other terms in Eq. (2) were defined above. In Eq. (2), the precipitation P_i and evaporation E_i during the ith month are calculated based on the average reservoir area $(A_{i-1} + A_i)/2$, expressed in 10^3 m^2, times the measured rain p_i (in meters) and evaporative rate e_i (in meters) during the ith month, respectively. The reservoir area is related to its storage by Eq. (1). All fluxes and storages that appear in Eq. (2) are in thousands of cubic meters (10^3 m^3). Bradbury Dam at Lake Cachuma does not serve flood-control purposes. The riparian and flood zone downstream from and in the vicinity of Bradbury Dam is essentially grazing rangeland. Therefore, the reservoir releases that keep the reservoir capacity from overtopping (maximum-storage constraints are imposed in the reservoir model presented below) incorporate an implicit flood-control rule curve, which is to avoid excessive storage. Bradbury Dam, through a combination of spillway and sluice gate discharges is well-equipped to control reservoir level without concerns for downstream damages. The issue of flood control, in any event, is more relevant for hourly real-time operation during high-inflow events (typically associated with intense rainfall that falls during 1 to 2 days in strong El Niño years) rather than for the monthly operation time frame adopted in this paper. Another aspect of reservoir water balance, that concerns seepage losses, is shrouded in uncertainty. The best hydrologic information suggests that the net seepage losses (i.e., groundwater accretions minus groundwater losses to reservoir storage) are negligible compared to streamflow, precipitation, and evaporation (Alroth and Naftali 1997). Therefore, seepage losses are not considered further in this paper.

The water-balance Eq. (2) is of a recursive nature, i.e., the end-of-period storage depends on the beginning-of-period storage. Taking advantage of that property and substituting the area versus storage Eq. (1) into Eq. (2), the Cachuma Reservoir stor-

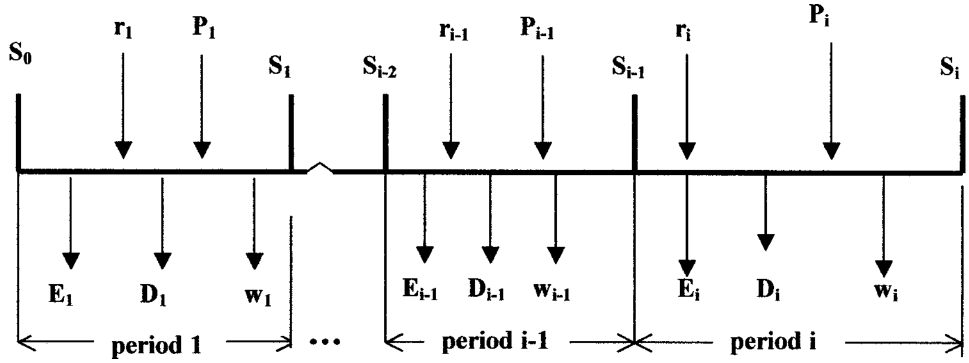

Fig. 5. Time diagram for the reservoir-analysis problem. S_i=reservoir storage at end of period i; P_i=rainfall into lake during period i; r_i=lake streamflow in i; D_i, E_i, w_i=water diversion, lake evaporation, and reservoir release in month i, respectively. See text for definition of units.

age at the end of the ith month may be written in terms of the initial storage $S_0 = g \cdot C$:

$$S_i = g \cdot C \cdot A_i + \sum_{m=1}^{i} C_m^{(i)} \cdot (r_m - D_{1m} - D_{2,m} - D_{3m} - w_m) + B_i \qquad i = 1,2,\ldots,n \tag{3}$$

in which

$$A_i = \prod_{m=1}^{i} K_m \tag{4}$$

$$B_i = \sum_{m=1}^{i} \left(R_m \prod_{q=m+1}^{i} K_q \right) \quad \text{with} \quad \prod_{q=i+1}^{i} K_q \equiv 1 \tag{5}$$

$$C_m^{(i)} = T_m \prod_{q=m+1}^{i} K_q \quad \text{with} \quad \prod_{q=i+1}^{i} K_q \equiv 1 \tag{6}$$

$$K_v = \frac{1 + \frac{b}{2}(p_v - e_v)}{1 - \frac{b}{2}(p_v - e_v)} \quad \text{where } v = m \text{ or } q \tag{7}$$

$$R_m = \frac{a(p_m - e_m)}{1 - \frac{b}{2}(p_m - e_m)} \tag{8}$$

$$T_m = \frac{1}{1 - \frac{b}{2}(p_m - e_m)} \tag{9}$$

In Eqs. (7) through (9), p_v and e_v (where $v = m$ or q) are the rainfall and pan evaporation in the vth period respectively (in meters); $a = 1300.7$ and $b = 0.05054$ are the intercept and slope coefficients in the area versus storage Eq. (1) respectively.

The storage Eq. (3) expresses the storage at time i in terms of the initial storage ($g \cdot C$) and all other reservoir fluxes. In particular, it accounts for the effect that a changing reservoir area has on the evaporative losses of lake storage. This has an important effect on reservoir capacity and water yield. Notice that the intermediate storage values S_i, $i = 1,2,\ldots,n$ have been eliminated from the water balance Eq. (3), leaving in it as unknowns the storage capacity C and the reservoir releases w_i ($i = 1,2,\ldots,n$).

Optimization Model for Santa Ynez River System

The optimization model can be used for any of the following purposes (these are called modeling scenarios):

1. To obtain the optimal reservoir capacity given specified water demands and reservoir releases. In this case, the decision variable is the reservoir capacity C. The cost of building 10^3 m^3 of reservoir capacity equals $K = \$1.3 \times 10^3$ (Loáiciga and Renehan 1997);
2. To obtain optimal reservoir releases given the storage capacity and water demands. In this case, the decision variables are the reservoir releases w_i, $i = 1,2,\ldots,n$;
3. To obtain optimal reservoir capacity and reservoir releases given design and operational objectives. The decision variables are C and w_i, $i = 1,2,\ldots,n$.

The third, most general, modeling scenario was chosen in this work. The corresponding objective function in this case is to minimize the net cost of building and operating the reservoir system. The net cost equals the cost of building reservoir capacity minus the revenue associated with water production. Specifically,

$$\min K \cdot C - \sum_{i=1}^{n} G_i w_i \tag{10}$$

in which G_i=value of one unit of water release $G_i = \$1.3 \times 10^3$ per 10^3 m^3 (Loáiciga and Renehan 1997). The objective function is subject to several constraints. Eq. (3) is used in the constraints that involve Cachuma Reservoir storage.

Maximum storage, $S_i \leqslant C$, $i = 1,2,\ldots,n$:

$$g \cdot C \cdot A_i + \sum_{m=1}^{i} C_m^{(i)} \cdot (r_m - D_{1m} - D_{2,m} - D_{3m} - w_m) + B_i \leqslant C \tag{11}$$

Minimum storage, $S_i \geqslant 0$, $i = 1,2,\ldots,n$:

$$g \cdot C \cdot A_i + \sum_{m=1}^{i} C_m^{(i)} \cdot (r_m - D_{1m} - D_{2,m} - D_{3m} - w_m) + B_i \geqslant 0 \tag{12}$$

Table 1. Minimum Cachuma Fisheries Releases F_i in $10^3\ m^3$ Per Month

October	November	December	January	February	March	April	May	June	July	August	September
183	183	183	183	183	183	183	183	367	367	367	367

Reservoir releases must equal or exceed fisheries-flow requirements:

$$w_i \geqslant F_i \quad i=1,2,\ldots,n \tag{13}$$

The fisheries-flow requirements F_i are presented in Table 1 (Entrix, Inc. 2000). Diversions from Cachuma Reservoir D_{1i} and at Gibraltar and Juncal dams, D_{2i} and D_{3i}, respectively, are given in Table 2. All decision variables (i.e., C and w_i, $i=1,2,\ldots,n$) are nonnegative in the linear optimization model defined by Eqs. (10)–(13).

Results

Reservoir Capacity

The optimization problem defined by Eqs. (10)–(13) was coded in a Microsoft (Redmond, Wash.) Excel Spreadsheet and solved with its mathematical (linear) programming package Solver. Fig. 6 depicts the calculated relationship between the optimal Cachuma storage capacity C and the initial storage fraction g. Two cases are presented in Fig. 6: In the first case, lake evaporation and rainfall effects on reservoir capacity were considered (labeled ''with lake hydrology'' in Fig. 6); in the second case, lake evaporation and rainfall were neglected (labeled ''without lake hydrology''). It is seen in Fig. 6 that in the first case the optimal reservoir capacity increases with decreasing initial storage when the initial storage is less than $0.4 \cdot C$. In the second case, the optimal reservoir capacity increases with decreasing initial storage when the initial storage is less than $0.3 \cdot C$. Otherwise, the optimal capacity is independent of the initial storage in both cases. In the with lake hydrology case, the optimal Cachuma capacity was found to be $204 \times 10^6\ m^3$ whenever the initial storage exceeds the threshold $0.4 \cdot C$. If reservoir evaporation and rainfall fluxes were ignored, the optimal capacity would be $160 \times 10^6\ m^3$. The actual capacity of Cachuma Lake is $234 \times 10^6\ m^3$.

The need for a larger reservoir size associated with a smaller initial storage might be intuitive. Low initial storage may lead to violations of minimum release constraints during dry years following the beginning of operation. To avoid nonfeasibility of the constraint set, the model results call for inordinately large reservoir capacity when the initial storage is close to zero. This drastic drought-hedging effect vanishes when the initial storage increases, as shown in Fig. 6. Clearly, the start time of reservoir operation and the specific hydrology to which the reservoir system is subject to are crucial in the model prediction of optimal reservoir capacity. Given that most water-supply reservoirs do not start operation until they have reached at least half their capacity, the parts of the graphs shown in Fig. 6 that are of greatest practical interest are those for which the initial storage fraction is $g \geqslant 0.5$. In that instance, our results indicate a nonnegligible optimal reservoir capacity underestimation equal to $44 \times 10^6\ m^3$ attributable to the lack of consideration of lake hydrology. This represents close to a 22% underestimation of the optimal reservoir capacity in a practical context. It may be concluded that proper consideration of evaporative lake losses calls for a more conservative reservoir-design approach, whereby the optimal reservoir capacity is larger than what would be inferred if such losses were not accounted for.

Average Annual Water

Fig. 7 shows the average annual release from Cachuma Reservoir. This water has environmental and economic value because it supports downstream steelhead habitat and meets urban and agricultural demands. The average annual release is seen to either remain constant or to increase with increasing initial storage in the case in which evaporative and rainfall fluxes are considered (i.e., with lake hydrology in Fig. 7) as well as that in which they are not (without lake hydrology curve in Fig. 7). In the former case, the average annual release is constant when the initial storage is less than $0.36 \cdot C$, while it is constant when the initial storage is less than $0.2 \cdot C$ in the latter case. Releases are kept at their minimums at low initial storage and it is not feasible to decrease the total cost [Eq. (10)] by larger releases without offsetting that cost improvement with large increases in reservoir capacity and thus, with larger reservoir cost. Another interesting feature evident in Fig. 7 is that the average annual release calculated when evaporation and rainfall are ignored exceeds that associated with the case in which they are considered. The average annual water yield overestimation is 37 and 11% when the initial storage is 50 and 100% of the reservoir capacity, respectively. It was argued above that the range $g \geqslant 0.5$ is that of greatest practical interest. The magnitude of the water-yield overestimation poses potential risks to water management because the analysis without the consideration of evaporative losses would suggest a reservoir yield that is, in fact, unattainable.

Fig. 8 summarizes the relationship among optimal average annual water, optimal reservoir capacity, and the initial storage (represented by the fraction g of reservoir capacity). It is seen in Fig. 8 that in the case in which lake hydrology is considered, the average annual release increases while the optimal reservoir storage is kept at a constant level of $204 \times 10^6\ m^3$ whenever the initial

Table 2. Water-Supply Diversions D_{ji}, $j=1, 2, 3$ in $10\ m^3$ Per Month

	October	November	December	January	February	March	April	May	June	July	August	September
Cac.[a]	1300	920	888	856	793	1616	2062	3614	4534	5833	5770	3520
Gib.[b]	469	328	316	300	282	379	469	565	610	707	661	565
Jun.[c]	284	232	232	217	207	279	289	313	259	67	54	35

[a]Cac.: Cachuma Reservoir.

[b]Gib.: Gibraltar Dam.

[c]Jun.: Juncal Dam.

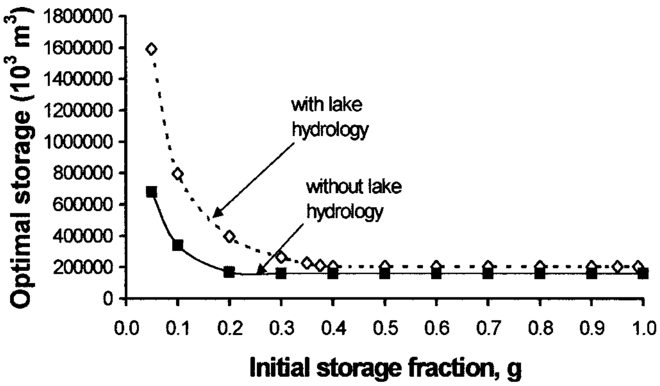

Fig. 6. Optimal Cachuma storage as a function of initial storage and lake-hydrology scenarios

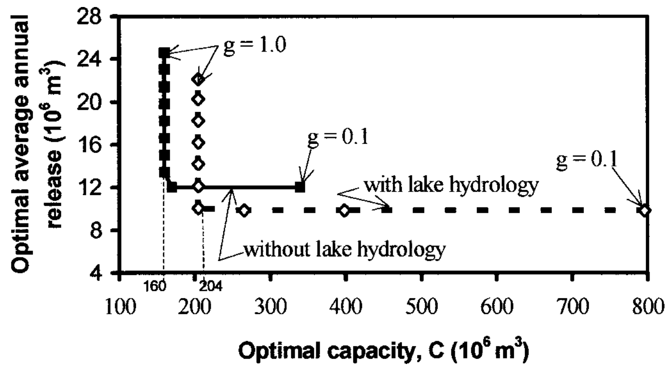

Fig. 8. Optimal average annual release versus optimal reservoir capacity. The initial storage fraction g is in increments of 0.1 beginning with 0.1 and increasing clockwise to 1.0 for the "with lake hydrology" and "without lake hydrology" graphs.

storage is larger than 40% of the reservoir capacity. The implication in that instance is that the total cost is minimized by keeping the reservoir size at an optimal minimum while increasing the water releases as much as reservoir size and hydrologic conditions permit it. The same pattern is observed in Fig. 8 for the case in which lake hydrology is not considered and whenever the initial storage is greater than 30% of the reservoir capacity, except that in that case the optimal reservoir capacity is 160×10^6 m^3, lower than that associated with the with lake hydrology case. In either case, i.e., with or without lake hydrology considered, it is seen in Fig. 8 that when the initial storage approaches zero, the reservoir capacity rises rapidly to satify minimum release constraints while the average annual yield is kept at a constant minimum level. The upward displacement of the "without lake hydrology" graph relative to the "with lake hydrology" one is caused in this instance by the overestimation of the average annual yield in the latter case as pointed out above.

Conclusion

The results of this work provide concrete evidence about the impact that lake evaporation has in our estimates of optimal reservoir capacity and reservoir yield. A reservoir design and operation model was developed and implemented to the Santa Ynez River basin of central California, situated in a region of large potential evaporation and extreme climatic variability. In addition, the Santa Ynez River's largest reservoir exhibits large surface-area changes with changing storage. The results of this work indicate that in-lake hydrology plays a considerable role on estimates of optimal reservoir capacity and average annual water release. Furthermore, this work's results indicate that the lack of proper consideration of in-lake hydrology leads us to err on the side of greater risk. Concretely, reservoir capacity and average water release are under and overestimated, respectively. It is worth noting that there are alternative methods for sizing reservoirs. The mass-curve method, for example, is a classical one (Linsley and Franzini 1979). That method is hindered by the fact that reservoir precipitation and evaporation cannot be accurately accounted for in the analysis. Nor are reservoir constraints easily incorporated in the mass-curve method either.

The optimization approach presented in this paper accounts for all factors, natural or man-made, that affect reservoir storage, and it is particularly well-suited for modeling reservoir system with active in-lake hydrologic fluxes (e.g., evaporation). It also allows a variety of objective functions to be considered in the analysis, and thus provides convenient flexibility in the optimization of reservoir design and operation. Further work is needed to test the type of reservoir relationships identified in this paper in reservoir systems either larger or smaller than the Santa Ynez River system.

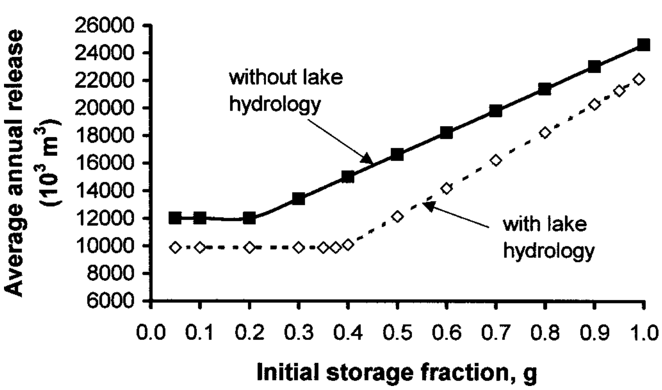

Fig. 7. Average annual water releases from Cachuma Reservoir under two lake-hydrology cases

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