DECISION ANALYSIS AND OPTIMIZATION MODELING FOR COMPLEX WATER RESOURCE SYSTEMS

L. Jeffrey Lefkoff[1] and Donald R. Kendall[2]

AUTHORS: [1]Principal Hydrologist, Hydrologic Consultants, Inc., 455 Capitol Avenue, Suite 605, Sacramento, California 95814, and [2]General Manager, Calleguas Municipal Water District, 2100 Olsen Road, Thousand Oaks, California, 91362
REFERENCE: *Proceedings of the 1997 Georgia Water Resources Conference*, held March 20-22, 1997, at the University of Georgia, Kathryn J. Hatcher, Editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. Managers of a large municipal water distribution system want to increase system reliability and reduce operational costs. To achieve these goals, two projects are proposed: a conjunctive use storage facility and a major inflow pipeline. This paper describes an evaluation of the projects using optimization modeling within a decision analysis framework. Analytic results quantify the available trade-offs between reliability and cost for alternative facility configurations. Results were used by the water managers to choose the conjunctive use project.

INTRODUCTION

Complex water-resource systems are commonly characterized by multiple hydrologic sources, competing demands by water users, multi-scale environmental impacts, and a high management priority on system reliability. Management goals include maximization of water supply and flood protection, and minimization of economic costs and environmental impacts. A methodology is needed to quantify the inherent trade offs between conflicting goals, such as supply and cost.

Decision analysis and optimization modeling are analytic tools that can quantify the inherent trade-offs between management goals (Wurbs, 1993; Karamouz, et al., 1992; Loucks, et al., 1981). Successful application requires that the analyst understands the broad economic and political concerns of the water managers and is able to incorporate those concerns into the modeling analysis. Water managers have little use for the traditional optimization approach, where a model is used to prescribe the best solution to an idealized problem that is mathematically well behaved but excludes actual management concerns that can not be quantified.

This paper demonstrates the application of decision analysis and optimization modeling to two proposed facility improvement projects, located in Ventura County, California. One project is a conjunctive use facility, where the regional ground-water basin would be used to store imported water. The second project is a new pipeline to convey imported water into the regional municipal distribution system.

While the application is specific to Ventura County, the general approach is applicable to many complex water-resource systems, all of which share common features.

WATER MANAGEMENT ISSUES

Improving Reliability of the Calleguas System

The Calleguas Municipal Water District is a wholesale distributor of municipal water in Ventura County, California. Calleguas delivers treated water to about a dozen major retailers, who in turn provide water to about 520,000 people. Annual demand varies from about 90 to 110 thousand acre feet (taf).

Calleguas is dependent on a single source of imported supply. The District purchases treated and untreated water from the Metropolitan Water District of Southern California, which obtains imported supplies from northern California through the State Water Project (SWP). Calleguas receives its supply through a single pipeline, which is subject to disruption by drought and regulatory actions.

Recognizing the vulnerability of the District's supply, Calleguas managers want to enhance the reliability of their system. During the early 1990's, two projects were being considered. The Las Posas Basin Project would store and recover imported water in a 300 taf ground-water basin within the District boundaries. The Happy Camp Feeder Project would construct a new pipeline through which imported water can be conveyed into the District's system. In addition to improving system reliability, the proposed projects could reduce operational costs by allowing seasonal shifting of water purchases to occur at off-peak (winter) prices.

The primary water management issue faced by the District's Board was whether facilities should be constructed to increase system reliability. The question addressed in the analysis was: For various alternative project configurations, what are the increases in system

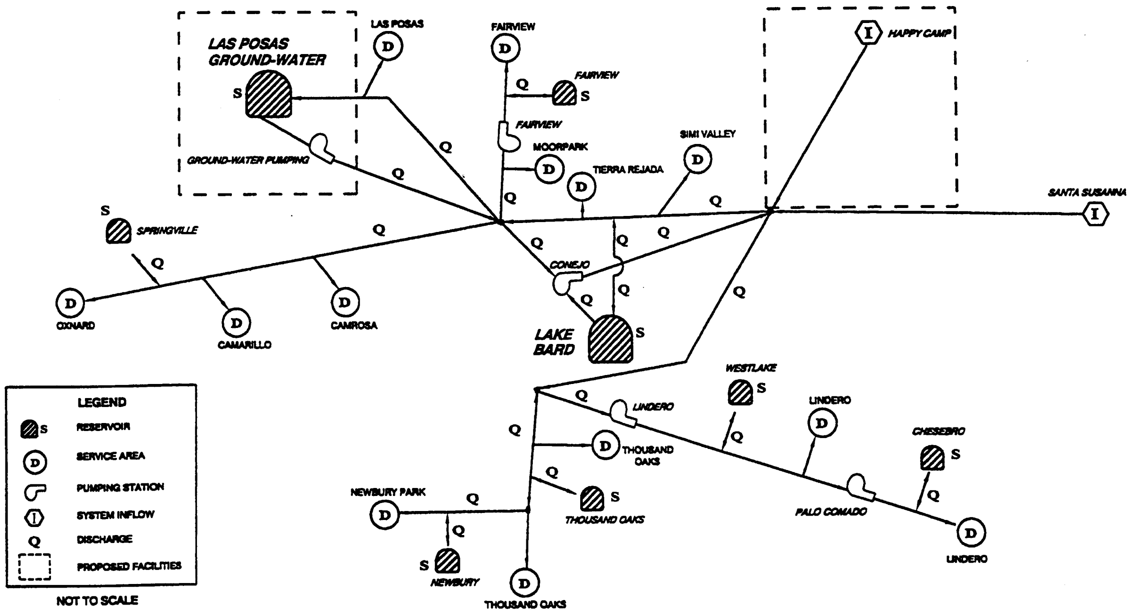

Figure 1. The Calleguas distribution system as represented in the optimization model.

reliability and what are the capital and operational costs? In the discussion below, this is referred to as the "regional problem".

Integration with the California State Water Project

A secondary issue raised by Calleguas management addressed the relation between the Las Posas Basin Project and the State Water Project. Conjunctive use is recognized throughout the state as a means of increasing storage without creating the environmental impacts associated with new surface reservoirs. As water demands increase and the threat of drought continues, increased storage capacity is needed state-wide.

The California State Water Project. The State Water Project (SWP) transports water from northern to southern California. Water is stored and released from Lake Oroville into the Sacramento-San Joaquin River Delta (the "Delta"), where it mixes with other released water and natural flows. Water is exported from the south Delta into the California Aqueduct, from which SWP deliveries are made throughout Southern California.

The operation of the SWP must comply with complex regulatory standards imposed by federal and state agencies. Many of the standards apply in the Delta, where they impose considerable restrictions on project operations. Periods of highest demand coincide with low flows through the Delta, which, in turn, create landward hydraulic gradients and seawater intrusion from San Francisco Bay. High salinity within the Delta threatens drinking water supplies and irrigation deliveries and degrades the aquatic habitat for several fish species. The standards limit Delta exports to occur within narrow time windows and hydrologic conditions. Project operators thus place a large value on south-of-Delta storage, which provides the ability to export more water during high flow conditions. New surface storage reservoirs are problematic, however, due to adverse environmental impacts and political opposition.

The secondary water management issue was raised by Calleguas in the context of needed SWP facilities. By providing south-of-Delta storage that is environmentally benign, the Las Posas Project might provide benefits to the SWP that justify financing of Las Posas facilities by sources outside of Calleguas. The question addressed in the analysis was: What are the potential benefits of Las Posas to the SWP? In the discussion below, this is referred to as the "SWP problem".

THE REGIONAL PROBLEM

Analytic Approach

The approach taken to the regional water management problem used optimization modeling within a decision analysis framework. The water managers were to be provided with results that characterize their decision alternatives in terms of quantitative trade-offs between enhanced reliability and cost. Costs were separated into capital costs of constructing new facilities and operating costs for the system with the alternative facility configurations.

No attempt was made *a priori* to impart relative values to reliability, operating costs, and capital costs. Valuations remained the purview of the water managers; the analysis provided results needed to make informed value judgments. Although it is common to combine operating and capital costs into a single parameter using discount rates, political and financial issues faced by the water managers make these distinct decision variables.

Optimization modeling was used to compute the points on the trade-off curves. The model minimized operating costs while maintaining deliveries at pre-specified demand levels. The model was run repeatedly for alternative facility configurations.

Model Formulation

Figure 1 shows the model's representation of the Calleguas distribution system. The model solves for monthly values of the decision variables at all locations shown. The decision variables are pipe discharge Q, user delivery D, and reservoir storage S. The model is run for twenty years, using various projections of available water supply to reflect alternative future hydrologic scenarios.

Objective function. The optimization model finds solutions that minimize operating costs. Costs are incurred by purchasing water from the two inflow sources, treating water after being stored in the surface reservoir, and pumping water from the Las Posas basin. Rates for water purchases vary seasonally. The operating strategy identified by the model balances the cost savings of winter purchases against the treatment and pumping costs required by seasonal storage. The objective function is:

$$Minimize\ Z = \sum_{t=1}^{T} \left[P_S I_S + P_H I_H + P_L Q_L + P_T Q_T \right]$$

where
P_S = price of water from Santa Susanna feeder ($/ac-ft),
I_S = monthly inflow from Santa Susanna (acre-ft),
P_H = price of water from Happy Camp feeder ($/ac-ft),
I_H = monthly inflow from Happy Camp (acre-ft),
P_L = unit cost to pump water from Las Posas ($/ac-ft),
I_L = monthly pumping from Las Posas (acre-ft),
P_T = unit treatment cost from surface storage ($/ac-ft),
I_T = monthly release from surface reservoir (acre-ft).

Constraints. Solutions to the optimization model must satisfy several constraints. Equality constraints maintain mass balance between inflows, deliveries, discharges, and changes in storage. Inequality constraints maintain storage levels and discharge rates within physical capacity of system facilities and maintain inflows within available levels. Inequality constraints also maintain deliveries above required minimum values. These values were provided as model input and were chosen incrementally for different model runs in order to generate points on delivery-cost curves (Figure 2).

Results

Model results were converted into a series of trade-off curves, each for a different set of facility configurations and projected weather conditions. Figure 2 shows one set of curves, developed for a 5-year drought characterized by a 25% reduction in water availability from normal conditions. With current facilities in place, the system can deliver only 80% of demand during the drought. Management could choose a delivery level anywhere on the uppermost curve, which shows the trade-off between potential delivery level and annual operating cost if no new facilities are constructed.

If District management invests in both proposed facility improvements, future trade-off options can be selected from the lowermost curve. With both new facilities in place, 100% of demand could be delivered throughout the drought. The intermediate curves show the trade-off for the separate projects.

The optimization results shown in Figure 2 do not rely on pre-determined judgments regarding qualitative values placed on capital costs, operating costs, and improved system reliability. Using the decision analysis framework and the analytic results, the managers are free to exercise those judgments during their evaluation of alternatives. The managers know the capital costs and financing issues for the four investment options. Analytic results show what the benefits are, in terms of future operational cost savings and delivery levels, of the current investment options.

The value of optimality. Trade-off curves similar to those shown in Figure 2 could be constructed without the

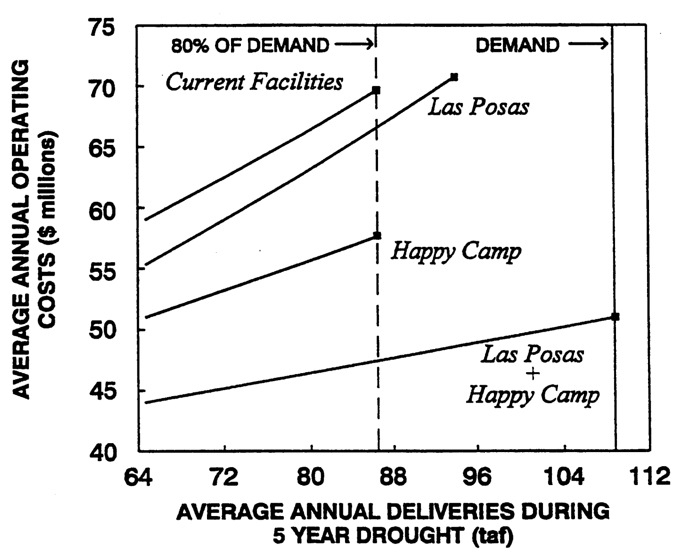

Figure 2. Results for a 5-year drought.

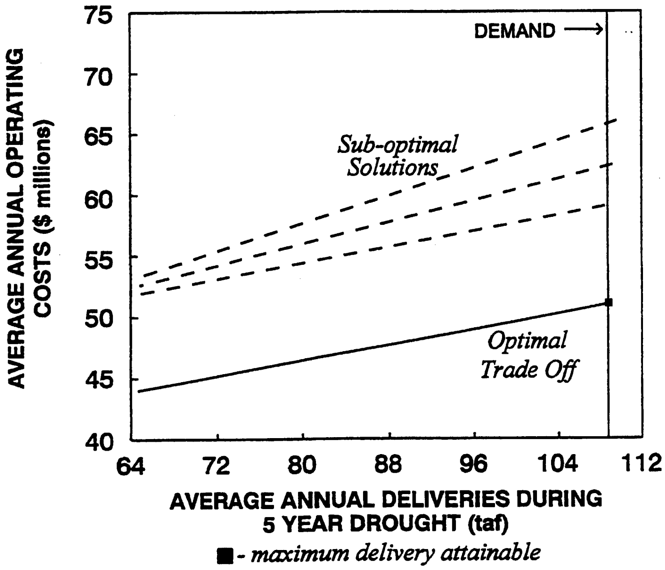

Figure 3. Optimal trade off curve and sub-optimal solutions.

use of an optimization model. The results, however, would provide trade-offs that are sub-optimal, distorting the comparison between alternative facility improvements.

Consider the trade-off curves shown in Figure 3, with both projects in place. The solid curve is the solution from the optimization model. Any one of the dashed curves might be developed from a methodology that does not utilize optimization, but attempts through trial-and-error to find the lowest operational cost at each demand level. The estimated costs are too high, so that the potential benefit of the capital investment is distorted. In addition, the solution is non-unique, and the degree of sub-optimality may differ for each facility improvement, creating additional distortion in the comparisons between investment alternatives.

THE SWP PROBLEM

Analytic Approach

A more traditional optimization approach was taken to the secondary, state-wide analysis. Maximum yield from the SWP was computed with and without the Las Posas Project in place. The difference in the yields indicates the potential benefit of the new facility.

A non-linear optimization model was developed that accounts for the major hydrologic, facility, and regulatory features of the SWP. Most of the system responds linearly to simulated decisions, but non-linearities occur in two areas. Operational decisions have a non-linear effect on salinity conditions in the Delta and on compliance with delivery contracts. The non-linear optimization model is described by Lefkoff and Kendall (1996a, 1996b). Solutions where obtained using the MINOS code of Murtagh and Saunders (1987). The use of non-linear optimization modeling for multiple reservoir systems is reviewed by Yeh (1985).

Results

Results are shown in Figure 4. Annual SWP deliveries without the new facility are shown on the bottom portion. The additional deliveries that are achievable with Las Posas in place are shown on the top portion. The conjunctive use facility increases potential long-term SWP yield state-wide by 6%.

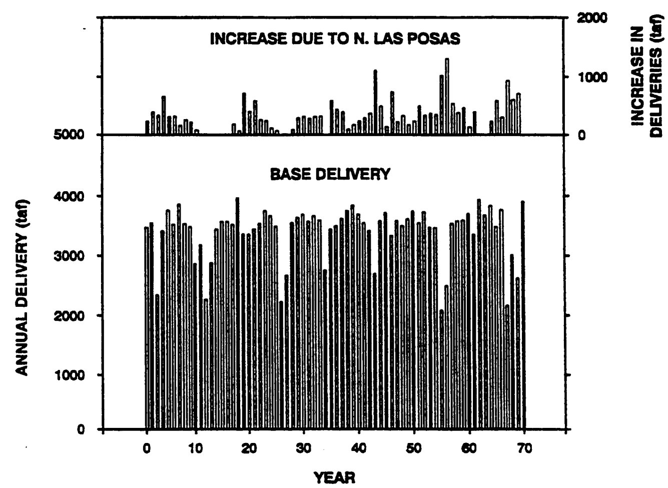

Figure 4. Annual SWP deliveries with and without the Los Posas basin project.

CONCLUSIONS

The results of the analysis were provided to Calleguas water managers. After consideration of the trade-offs between increased reliability, reduced operating costs, and required capital investment, the Las Posas Basin project was chosen. The facilities, which are now under construction, will consist of 25 large capacity injection and extraction wells and associated pipelines to link the wells into the regional distribution system. The Happy Camp Feeder project was rejected due to the unfavorable trade off between costs and reliability, as well as political difficulties.

The results of the SWP problem demonstrated the potential benefit of the Las Posas Basin to state-wide deliveries by the State Water Project. Political factors, however, precluded integration of the Las Posas into the SWP; state and federal policies regarding the Delta are in flux, and new facilities can not be constructed until new policies are established. This process is beyond the control of the Calleguas managers, and outside sources of funding for the Las Posas facility improvements were not pursued.

LITERATURE CITED

Karamouz, M., M.H. Houck, and J.W. Delleur, 1992. Optimization and Simulation of Multiple Reservoir Systems. ASCE, Journal Water Resources Planning and Management 118(1):71-81.

Lefkoff, L.J., and D.R. Kendall, 1996a. Yields from ground-water storage for California State Water Project, *ASCE Journal of Water Resources Planning and Management*, 122:72-74.

Lefkoff, L.J., and D.R. Kendall, 1996b. Optimization modeling of a new facility for the California State Water Project, *Water Resources Bulletin*, 32:451-463.

Loucks, D.P., J. R. Stedinger, and D. A. Haith, 1981. Water Resource Systems Planning and Analysis. Prentice-Hall, Englewood Cliffs, New Jersey.

Murtagh, B.A., and M.A. Saunders, 1987. MINOS 5.1 User's Guide. Stanford University, Stanford, California.

Wurbs, R. A., 1993. Reservoir-System Simulation and Optimization Models. ASCE, Journal Water Resources Planning and Management 119(4):455-472.

Yeh, W. W-G., 1985.Reservoir Management and Operation Models: A State-of-the-Art Review. Water Resources Research 21(12):1797-1818.