ALLISON DVORAK

CENTRAL VALLEY GROUNDWATER BANK OPERATIONS: HYDROLOGY, GROUNDWATER OPERATING RULE, AND SYSTEM OPERATING RULE EFFECTS ON YIELD

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ABSTRACT

How would more aggressive operations of groundwater banks affect California’s SWP (State Water Project) and CVP (Central Valley Project) water supply deliveries? Modeling experiments using the California water system simulation model, DWRSIM, show that aggressive re-operation of groundwater storage, both north and south of the Delta, can increase long-term average project deliveries by as much as 114 TAF. However, to obtain these benefits, the entire system must be re-operated to take advantage of increased groundwater storage flexibility. To make the experimental studies comparable with the base studies, all studies were operated with the same acceptable amount of project delivery shortages and the same level of acceptable Shasta Reservoir storages. Re-operation was shown to always result in long-term annual average benefits and often result in both long-term and critical period annual average benefits to project deliveries.

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1 INTRODUCTION

1.1 Purpose and Scope of Project

As California's water demand increases due to rapid growth and the available water supply to urban and agricultural users decreases due to environmental restrictions, the need for reliable water management solutions is becoming increasingly important. The focus of this project, conjunctive use of groundwater and surface water, is a water management solution that can substantially augment water supplies. The purpose of this project was to determine how aggressive groundwater operations and conjunctive use of groundwater would affect California water supplies. To accomplish this, two sets of studies were modeled using the simulation model DWRSIM. The first set focused on re-operation and conjunctive use of North of Delta Groundwater Storage (NDGS) while the second set focused on re-operation and conjunctive use of South of Delta Groundwater Storage (SDGS). The re-operation process included experiments with natural recharge, the frequency of groundwater pumping, and changes in surface storage operations. Through analysis of these studies, the relationship between operation of groundwater and average values for long term and critical period supplies becomes apparent.

Chapter 1 gives an overview of the purpose and scope of the project described herein and background information regarding groundwater and conjunctive use operations. Chapter 2 gives an overview of the California water system including water supply and delivery considerations. Chapter 2 also contains definitions and current issues for conjunctive use of groundwater and surface water. Chapter 3 details different approaches for modeling water supply systems including several optimization techniques and simulation techniques. Chapter 4 explains the methods and results of modeling conjunctive use of groundwater north of the Delta while Chapter 5 focuses on the methods and results of modeling conjunctive use south of the Delta. Chapter 6 gives conclusions based on the information provided in chapters 1 through 3 and the modeling results provided in chapters 5 and 6.

1.2 Background

DWRSIM, a water supply and management model used by the California Department of Water Resources is used to model water management scenarios for the California water supply system. To model conjunctive use in DWRSIM, groundwater banks are modeled with a natural recharge rate, an artificial recharge rate, a pumping rate, a pumping frequency, and an imposed maximum storage. These combine to define the operation of a groundwater bank. While the maximum recharge and pumping rates are controlled by the hydrogeology of the aquifer, the pumping frequency is controlled by SWP operations. If a groundwater bank is operated less aggressively, the pumping rate and frequency is low compared to the natural and artificial recharge rates. The pumping frequency is set to only pump from groundwater during periods of low SWP deliveries, resulting in a groundwater benefit to total deliveries only during the critical periods of 1929 to 1934, 1976 to 1977, and 1988 to 1992. If the groundwater bank is operated more aggressively, the pumping rate and frequency is high compared to the natural and artificial recharge rates. Likewise, the pumping frequency is set to pump from groundwater at and below higher SWP deliveries, meaning that groundwater pumping occurs a higher percent of time. This results in more long-term groundwater contributions to overall deliveries.

To analyze the effects of groundwater operations and conjunctive use on California water supplies, this project uses DWRSIM to model the CVP and SWP water delivery system with consideration of aggressive groundwater operations and conjunctive use of groundwater. As a basis for comparison, studies using the same assumptions but without aggressive groundwater operations or conjunctive use were used as base studies. Results were analyzed based on end-of-period storage in the groundwater banks and the major North of Delta reservoirs as well as total deliveries made to water purveyors.

2 OVERVIEW OF THE CALIFORNIA WATER SYSTEM

California’s surface water system is comprised of two major statewide water projects and several smaller, local water projects. The first of the major water projects is the Central Valley Project, run by the federal government. The second is the State Water Project, run by the state government. Figure 1 shows the geography of these water projects. DWRSIM models these two projects together to simulate and predict project water deliveries.

2.1 Central Valley Project

The Central Valley Project (CVP), currently California’s largest water supplier is operated by the U.S. Bureau of Reclamation (Littleworth and Garner, 1995). Its main purpose is to supply water to agricultural areas in the Sacramento and San Joaquin Valleys (the Central Valley). Due to population growth, wheat farming was first attempted in the Central Valley. During 1874 and 1875, California produced more wheat than any other state in the nation, leading to an increased need for irrigation. During the 1870’s, expansive irrigation was developed throughout the valley. After the Wright Act of 1877 was passed, irrigation districts were created and state-wide irrigation increased. Because much of this water was being drawn from groundwater aquifers beneath the Valley, by the 1930’s the negative impacts of groundwater overdraft were apparent. This led to a “need” for a new source of water for the Valley. (Reisner, 1986)

The answer to this need was the Central Valley Project, first adopted as the Central Valley Project Act of 1933, part of the State Water Plan. However, due to the depression, the state could not afford the project and asked the federal government to build the project. The project was soon authorized by the federal government through

Figure 1**.** CVP and SWP Facilities (Littleworth and Garner, 1995).

the Rivers and Harbors Acts of 1935 and 1937, which state that dams and reservoirs may be built and operated by the federal government to provide for river regulation, irrigation and domestic use, and power (Littleworth and Garner, 1995).

The Central Valley project consists of three major reservoirs north of the Delta, Claire Engle Lake, Shasta Reservoir and Folsom Reservoir. Claire Engle Lake has a capacity of 2.5 MAF and stores surplus water from the Trinity River. (Surplus water is water flowing in the river that is not immediately needed to meet in-stream flow requirements or water supply demands.) Shasta Reservoir has a capacity of 4.6 MAF and stores surplus water from the Sacramento River. Folsom Reservoir has a capacity of 1.01 MAF and stores surplus water from the American River. These reservoirs operate together to provide water for irrigation, domestic, and industrial uses both North and South of the Delta, water quality in the Delta, and in-stream flows for fisheries.

As releases from these reservoirs reach the Delta, it is transferred through the Delta Cross-Channel and pumped from the Delta by the Tracy Pumping Plant into the Delta-Mendota Canal. From there, the canal carries the water to San Luis Reservoir and contractors south of the Delta.

The CVP has two major reservoirs south of the Delta, San Luis Reservoir and Millerton Lake. San Luis Reservoir has a capacity of 4 MAF with 2 MAF dedicated to CVP storage and the other 2 MAF dedicated to SWP storage. It is operated to increase the flexibility of south of the Delta CVP operations. Millerton Lake has a capacity of 0.5 MAF and controls San Joaquin River flows. It is operated for flood control, in-stream flows, and contractor deliveries via the Madera and Friant-Kern Canals.

2.2 State Water Project

The State Water Project (SWP) is run by the State of California Department of Water Resources. It currently supplies water to over 30 public agencies for agricultural, domestic, and industrial uses, both north and south of the Delta. It was first suggested in 1931 for the purpose of capturing surplus water from the Feather River, a tributary to the Sacramento River, and augment flows into the Delta. From the Delta, excess water would be transferred to areas with deficient supplies. Due to World War II, the SWP was only authorized until 1959 by the Burns-Porter Act with final voter approval in 1960. (Reisner, 1995)

The SWP has one major reservoir north of the Delta, Oroville Reservoir (see Figure 1). Oroville has a capacity of approximately 3.5 MAF and holds excess flows from the Feather River. As releases are made at Oroville, the water flows down the Feather River and joins the Sacramento River flowing into the Delta. From the Delta, water is either diverted by the North Bay Aqueduct serving Napa and Solano Counties or it is diverted by Harvey O. Banks pumping plant to the south of the Delta. Before the Banks pumping plant, there is a small regulatory reservoir, Clifton Court Forebay, to ensure reliability of pumping at Banks pumping plant.

Banks pumping plant pumps water into the California Aqueduct that carries the water 444 miles to deliver water to the Central Valley and Southern California. The South Bay Aqueduct branches off of the California Aqueduct and delivers water to Santa Clara.

San Luis Reservoir operation is coordinated between the SWP and CVP facilities to store excess supplies south of the Delta for periods of time with deficient supplies. The SWP is proposing to run the Kern Water Bank located south of the

Delta as well as a north of the Delta water bank to act as a supplement for water supplies during dry years. In this paper, these are referred to as South of the Delta Groundwater Storage and North of the Delta Groundwater Storage, respectively.

2.3 Project Deliveries

The state of California and the Bureau of Reclamation have contracts with water purveyors across the state for specified amounts of water to be delivered. Each year, depending on climatic and hydrologic conditions, estimations of the amount of water actually to be delivered are made based on available supplies and contractor demands. A shortage is a case in which these estimations are not met and the contractors do not receive the full estimated amount of water. Shortages can result in economic losses due to the lack of water available to properly irrigate crops that had been planted based on the original estimated deliveries. Interruptible deliveries are defined as deliveries made above the estimated amount of water for that year.

Project deliveries are limited by several factors. Environmental constraints including required Delta outflows, required in-stream flows, and pumping limits from the Delta all require that more water be left in-stream and less water is delivered to contractors. Other constraints include water temperature. Since anadromous fish, some of which are currently either endangered or threatened such as Steelhead and Chinook Salmon, require temperatures for spawning and migration, reservoir operations are constrained by their effects on stream temperature. Currently, Shasta Reservoir storages falling below 1900 or 1200 TAF are considered violations (“Shasta violations”) to operation criteria due to a decrease in the available cold-water pool within the reservoir and the subsequent detrimental effects on water temperature.

2.4 Conjunctive Use of Groundwater

Conjunctive use is “the operation of a groundwater basin in coordination with a surface water system to increase the total water supply availability, thus improving overall reliability of supplies” (DWR, 1994). The groundwater bank is naturally and artificially recharged in time periods with excess water. Artificial recharge is performed by either percolation ponds or injection wells (CALFED, 1999). Percolation ponds speed up groundwater percolation to shallow aquifers through higher water pressures while injection wells conduct recharge water through confining layers to deeper aquifers. Water is extracted from the bank through pumping in times of low supplies.

Ideally, the groundwater and surface storage facilities are operated as one source of water. Conjunctive use is a comprehensive water management program coordinating surface water and groundwater use. As in the case of the SWP proposed groundwater banking programs, the extraction and export of water from a groundwater basin to another area in the state raises questions about the legality of groundwater transfers. Currently, California’s Water Code encourages conjunctive use of groundwater and surface water by allowing for any water use that has been reduced due to conjunctive use may be “sold, leased, exchanged, or otherwise transferred” (Littleworth and Garner, 1995).

Benefits of conjunctive use and artificial recharge include increased water supply reliability, reduced costs for extraction, and reduction in adverse impacts from previous overdraft. However, conjunctive use also can have adverse impacts on the water system. If overdraft were to occur, land subsidence, water quality degradation, increased pumping costs, and reduced groundwater yields to both streams and wells could occur (DESA, 1975; Jermar, 1987).

Groundwater and conjunctive use currently play an important role in California's water system. Currently, about 20% of the total applied water in California is provided by groundwater, with 40% of the total applied urban and agricultural water provided by groundwater (DWR, 1994).

Conjunctive use programs are being developed and implemented throughout the state. To prevent saline intrusion to its groundwater aquifer, Alameda County Water District imports surface supplies to recharge its aquifer. Likewise, Westlands Water District and South Sutter Water District import surface supplies to ease dependence on groundwater supplies and reduce overdraft. Metropolitan Water District of Southern California implemented a seasonal groundwater storage program in 1989 to provide emergency supplies during drought periods. Yolo County Flood Control and Water Conservation District pumps groundwater during dry years to offset the demand on surface supplies while artificially recharging the aquifers during wet years. Projects like these are being planned and implemented throughout the state. Efforts for large-scale water banking programs with groundwater banking as a part of the entire program are currently being made, also. An example is the State Drought Water Bank, which began in 1991. This effort used water from land fallowing, stored water reserves, and groundwater exchange (DWR, 1996).

These programs show the ability and necessity of groundwater to increase the availability and reliability of water supplies. Conjunctive use programs can increase water quality, reduce land subsidence, and provide important supplies during periods of drought.

2.5 Current Issues in Conjunctive Use

As water demands continually increase and water supplies become more regulated and scarce, conjunctive use of surface water and groundwater becomes an important consideration in water management options. Recent research in conjunctive use has begun focusing on physical, operational, economic, and institutional factors as well as feasibility. As the literature shows, these factors are important considerations when planning and implementing a conjunctive use project.

2.5.1 Planning Considerations

Conjunctive use can increase water supply reliability. Ratkovich (1998) found that water supply deficiencies, including the frequency, grouping, and extent, decreased for conjunctive use operations when compared with solely surface water or solely groundwater operations.

Due to the apparent benefits, conjunctive use operations are being researched and implemented throughout the world to help solve water supply issues. In California, conjunctive use operations have been implemented to ease groundwater overdraft and increasing water demands in the Santa Clara Valley, the coastal plain of Los Angeles Country, the coastal plain of Orange County, and Kern County (Coe, 1990). Opincar et al. (1995) evaluated the feasibility of conjunctive use of Northern California water from the State Water Project to artificially recharge a desert groundwater basin for the Mojave Water Agency as an answer to increasing water demands and groundwater overdraft.

Physical constraints can affect the feasibility and reliability of conjunctive use. Lee et al. (1992) performed field studies to determine the chemical and physical effects of conjunctive use on groundwater resources. The study found that artificial recharge via ponding altered the sediment type at the surface, the water table rose slowly under the pond, water levels in wells indicated a migrating inverted water table, perching occurred at certain depths, and cation exchange resulted in the percolating water resembling the chemical character of the local groundwater. These results reveal that although conjunctive use may be a feasible water supply solution, there are consequences to soils and groundwater resources. Maddock and Hardan (1995) performed a similar study regarding the conjunctive use project in Kern County. The study reveals that the facilities and operation of a conjunctive use project can impact groundwater conditions and economic performance due to water supply availability and subsequent urban encroachment.

Unresolved socio-economic issues demonstrate the need for suitable policies regarding conepts of ownership of the resources, economics of the use of water for agriculture from each source, administrative and management structures, and energy issues (Prasad, 1989). In India, unresolved issues such as these regarding physical and socio-economic implications of conjunctive use are inhibiting the implementation of conjunctive use operations (Prasad, 1989). Likewise, implementation of conjunctive use operations is stalled in New Mexico and other western states due to issues regarding water rights considerations (Lieuwen, 1998). Lieuwen and others are exploring these issues in order to find reliable policy to guide conjunctive use operations.

2.5.2 Modeling Considerations

As socio-economic issues become resolved, physical implications of conjunctive use must be understood before widespread implementation can occur. To develop a better understanding of conjunctive use with regards to issues such as physical constraints, feasibility, and water supply, mathematical models are being developed.

The major physical constraint to conjunctive use is the feasibility of sustained groundwater yield with consideration to recharge and pumping. To help understand the relationships between groundwater aquifer constraints and yield, several models have been developed. To fully understand artificial recharge constraints, Wang et al. (1995) developed a model to study artificial recharge scenarios in the San Jacinto Basin. Using this model, it was determined that the rate of artificial recharge is optimal in dry conditions, with an 80% decrease in efficiency during wet periods. Peralta et al. (1995) developed an integrated groundwater flow simulation/optimization model to determine optimal pumping as well as recharge strategies for sustained groundwater yield in conjunctive use operations.

Models are also used to help plan conjunctive use operations. Andrews et al. (1992) developed a network flow programming based simulation model to help the California Department of Water Resources plan and implement the proposed Kern Water Bank conjunctive use program. This model accounts for physical constraints such as groundwater pumping and recharge while trying to maximize water supply benefits. A model developed by Chiew et al. (1992) was used to plan and study the feasibility of conjunctive use in irrigated and non-irrigated areas in the Campaspe River Basin in Australia for salinity control. Later, Cheiw et al. (1995) further developed the model to examine surface and groundwater processes, including interactions between the two, to determine sustainable long-term groundwater pumping yields and the economic merits of conjunctive use operations.

Since there are many issues facing conjunctive use planning including supply, water quality, policy, and economics, models have been developed to take into account one or more of these issues to aid in the planning process. To resolve issues regarding conflicting water supply and water quality objectives, Ejaz and Peralta developed a simulation/optimization model. This model could assist water resources analysts for selecting planning strategies to maximized conjunctive use and keep water quality parameters within acceptable limits. Economic impacts of conjunctive use were modeled by Bredehoeft and Young (1988) for the South Platte River system in Colorado. They found that conjunctive use greatly increased the economic benefits derived from the existing water supply system. As an attempt to model the combined impacts of operations, policy, and associated economics of conjunctive use, Onta et al. (1991) developed a multistep planning model. This model selects the most satisfactory plan for system design, capacities, and allocation policies. In order to combine impacts of conjunctive use with regards to physical, social, legal, and economic factors, Kholghi et al. (1995) developed a multiobjective optimization model for conjunctive use operations in Iran.

Although each of the models described above gives insight into planning conjunctive use operations, it is important to keep in mind the limitations of mathematical modeling. El-Kadi (1989) analyzed several techniques employed to simulate conjunctive use and found that the large number of processes the models simulate prohibits detailed analysis of any process. Without detailed analysis of each process, the impacts and effects of conjunctive use cannot be fully determined.

3 RESERVOIR SYSTEM OPERATION MODELING THEORY

Water resources management involves consideration of all factors affecting water location, quality, and availability. A water resource system is a collection of components including reservoirs, river channels and aqueducts. However, because reservoirs allow for the ability to capture excess water and release that water in times of need, reservoirs are the major component of California’s water supply system. Over the past few decades, due to the increased need for water use efficiency and optimal reservoir operations, several mathematical modeling techniques for analyzing reservoir systems have been developed. The two major analysis techniques are optimization modeling and simulation modeling for reservoir storage, reservoir release, and diversions within the system.

3.1 Overview

Reservoir system models recognize and use area configuration, area hydrology, physical characteristics of the system including reservoirs and channels, reservoir operating rules, and water demands. Area configuration involves using nodes or control points as locations of reservoirs, inflows to the system, or diversions from the system. Area hydrology includes natural streamflows and reservoir evaporation rates. Physical characteristics include reservoir capacities or channel capacities. Operating rules regulate the releases of the reservoirs and the allocation of deliveries. Operating rules allocate storage capacity and streamflow between multiple users, balance risks of shortages and flooding, and maintain suitable habitats. Water demands include accounting for the consumptive use of all water diverted from the system and return flows from those diversions. The return flows from users make more water available for down-stream users. (Wurbs, 1996)

The period of analysis and time step of the analysis can affect the outcome of the analysis. Generally, models are run for a particular hydrologic period for which hydrologic data are readily available. The choice of time-step for the model depends on the variability of the components being modeled and acceptable computational costs. Most water supply models are run using several decades for the period of analysis and a monthly time step. (Votruba, 1988)

3.2 Optimization

Optimization models use mathematical and numerical methods to suggest the best way to achieve an operating performance objective stated as an objective function. Optimization models use a formal algorithm to determine decision variable values which maximize or minimize the objective function. In terms of reservoir system modeling, the objective often is to find the optimal operating rules that provide the greatest deliveries with the least amount of associated risk. Optimization models can screen alternatives by identifying those deserving greater evaluation (Lund and Ferreira, 1996). Several methods of optimization modeling exist including linear programming, network flow optimization, nonlinear programming, and dynamic programming.

3.2.1 Linear Programming

Linear programming is a technique that can be applied to maximize reservoir yield in a multi-reservoir system, as is the case of the studies in this work. It maximizes or minimizes an objective function in the form of

$$x_0 = \sum_{j=1}^{n} c_j x_j$$

subject to $\sum_{j=1}^{n} a_{ij} x_j \le b_i$ for i=1,2,…,m

and $x_j \ge 0$ for i=1,2,…,n

where x_0 is the objective function, x_j are the decision variables, c_j, a_{ij}, an b_i are constants, n is the number of decision variables, and m is the number of constraints (Wurbs, 1996). Here the objective function and constraints are linear with respect to the decision variables. Many commercial subroutines written in FORTRAN or other languages can be used to solve a linear system such as this using the simplex algorithm. Firm yield analysis, maximized reservoir releases, and priority based water allocation are some examples of applications of linear programming.

For a system of reservoirs in parallel, or not on the same stream, the following algorithm can determine the maximum system yield. Here the reservoirs are assumed to be in place with known capacities. Also, the reservoirs are operated using its own and other's available storages and inflows as variables so that the monthly contributions of each reservoir vary from year to year.

Let:

s_i = storage in reservoir i at the beginning of the month

x_i = yield of reservoir i

ip_i = inflow to reservoir i

$w_i^{(+)}$ = spill during the month from reservoir i

$w_i^{(-)}$ = empty capacity in reservoir i at the end of the month

c_i = total capacity of reservoir i

α_i = fraction of future inflow to reservoir i

T = total system yield

To minimize the system spill and distribute unused capacity between reservoirs at the end of the month, the following linear programming mathematical model is used

Minimize $$z = \sum_{i=1}^{n} w_i^{(+)}$$

subject to $$w_i^{(+)} - w_i^{(-)} + x_i = s_i + ip_i - c_i \qquad \text{i = 1,2,3,…}$$

$$\sum_{i=1}^{n} x_i = T$$

$$w_i^{(-)} - \alpha_i * \sum_{i=1}^{n} w_i^{(-)} = 0$$

$$x_i, w_i^{(+)}, w_i^{(-)} \geq 0$$

This system is a linear programming version of the space rule, which minimizes spill while maximizing system yield (Lund and Guzman, 1998). This linear system uses future inflows predicted from regression equations to specify the fraction of future inflow to a reservoir in accordance with the space rule for the allocation of emptiness rule. This means that the total available capacity within the system will be distributed between reservoirs in an advantageous way. Iterations of this system are performed using varying values of total system yield (T) beginning with a conservative value until one of the reservoirs obtains a negative storage. The last iteration before reservoir storage becomes negative is the maximum system yield. (ReVelle, 1999)

This method was used by Tracy and Al-Sharif (1992) to optimally manage a conjunctive use system with interconnected surface and groundwater supplies. By optimizing groundwater use while meeting surface water rights, the authors showed that more supplies were available to agricultural users.

3.2.2 Network Flow Optimization

Network flow optimization models use nodes to define storage, diversion, or inflow points and arcs connecting each of these nodes. The nodes and arcs combine to form a network. If the relations between all nodes can be defined in a mathematically linear fashion, an optimal solution for routing water through the system can be found using the following minimum cost pure network flow algorithm:

minimize: $$\sum_{t=1}^{P}\sum_{l\in A} c_{lt} x_{lt}$$

subject to: $$\sum_{j\in O_i} x_{jt} - \sum_{k\in I_i} x_{kt} = 0$$ for all $i \in$ N; for all t = 1, …, P

$$l_{lt} \le x_{lt} \le u_{lt}$$ for all $l \in$ A; for all t = 1, … , P

Here, P is the time period being modeled, A is the set of all arcs, N is the set of all nodes, O_i is the set of all arcs originating at node I, I_i is the set of all arcs terminating at node I, x_{lt} is the flow rate in arc l during period t, c_l are the weighting factors per unit of flow rate in arc l during period t; l_{lt} is the minimum flow in arc l; u_{lt} is the maximum flow in arc l (Labadie, 1998).

In this type of model, the minimum cost of routing water through the network at each arc is found using the weighting factors. The optimal solution is the path though the network satisfying all constraints with the minimum cost.

3.2.3 Nonlinear Programming

Relationships between nodes and system constraints cannot always be mathematically described in a linear fashion. In these cases, nonlinear programming methods must be used to optimally solve the system. The most widely used and powerful nonlinear programming methods include successive linear programming (SLP), successive quadratic programming (SQP), and augmented Lagrangian method.

Computationally, SLP is considered the most efficient optimization method. It relies on nonlinear functions that are linearized around an initial solution based on use of the first two terms of the Taylor Series expansion. Using this initial solution, an iterative process is begun with convergence being the optimal solution. The iterative solutions must be contained within a “trust region” where the nonlinear function can be approximated with a linear function. The major drawback of this method is that there is not always convergence to an optimal solution (Labadie, 1998).

The SQP approach uses quadratic expressions to approximate nonlinear functions. In this case, the nonlinear function is approximated using a quadratic function based on use of the first three terms of the Taylor Series expansion. The actual function being optimized is the Lagrangian function for the problem that combines quadratic approximations of the objective function with constraints and their Lagrangian multipliers. Iterations converge to a KKT point (Karush-Kuhn-Tucker point), which is the optimal solution for the problem. This method typically converges rapidly, but can be computationally expensive (Labadie, 1998).

The augmented Lagrangian method uses a Lagrangian function similar to the SQP method, but with penalty coefficients. This is done to replace constrained linear optimization problems with unconstrained problems to relieve computational expense. This method has been shown to converge rapidly but to a less accurate solution than other nonlinear programming methods (Labadie, 1998).

Nonlinear programming methods use complex mathematical approximations of the system to find the optimal solution for routing water through the system. These methods are computationally expensive but can be very useful for solving more complex systems with hydropower constraints (Labadie, 1998).

3.2.4 Dynamic Programming

Dynamic programming separates the entire system into a set of smaller systems that are solved sequentially. This is applicable to reservoir systems since operation decisions are made sequentially in the system. The solution is found by calculation of the optimal return function representing the minimum cost accumulated from the current period through the final period conditioned by a storage vector for all reservoirs. The optimal return function is in the following form:

$$F_t(s_t) = \max or \min\left[\alpha_t f_t(s_t, r_t) + F_{t+1}(s_{t+1})\right]$$

Where F_t is the optimal return function, s_t is the storage vector, α_t and r_t are release decisions, f_t is stage return, and t is the time stage for the calculation (Labadie, 1998).

By separating the problem into smaller pieces, an increase in the number of stages is less computationally expensive than in other optimization techniques. However, the viability of dynamic programming requires that solutions be found over all discrete combinations of releases and the optimal solution be chosen from those solutions for each step. Therefore, a complex multiple reservoir system is computationally expensive. Methods to overcome the dimensionality problem have been developed and include coarse grid/interpolation techniques, dynamic programming successive approximations, and differential dynamic programming (Labadie, 1998). Each of these methods attempts to reduce the number of grid points where calculations are made to reduce the computational expense. This is done by methods such as lumping reservoirs or lumping time steps, which can alter the accuracy of the solution (McMahon and Mein, 1986). Lienden and Lund (2000) show that reductions in spatial complexity that can result from lumping nodes significantly reduce the accuracy of the solution.

Optimization algorithms such as these can take complex systems and find promising solutions for operating rules. Also, release decisions can be made simultaneously, so that a more optimal solution can be found. However, the shortcoming of optimization models is that it requires all objectives be stated mathematically. Stating objectives in this way can result in oversimplification of operating rules, objectives, and hydrology (Wurbs, 1996).

3.3 Simulation

Simulation is a modeling technique that uses mathematical procedures to determine the dynamic behavior of a reservoir system. The reservoir system combines water demands and water use requirements with historical hydrology data. It then uses physically based equations and operating rules to compute various states for each node at each timestep. Some of these calculations are as follows:

Water Balance:

$$\frac{dS}{dt} = Inflow - Outflow$$

$$discretized : S_{t+\Delta t} = S_t + Inflows - Outflows$$

Reservoir Evaporation: $E_i = A_i e_i$ where $A_i = \left(A_t + A_{t+\Delta t}\right)/2$

Hydrologic Routing (based on):

$$\frac{S_{t+\Delta t} - S_t}{\Delta t} = \frac{I_t + I_{t+\Delta t}}{2} - \frac{O_t + O_{t+\Delta t}}{2}$$

Where S is storage, E is evaporation, A is reservoir surface area, e is the evaporation rate, I is inflow, and O is outflow (Wurbs, 1996). In the case of a reservoir system simulation, one modeling method is as follows. First the inflow hydrograph is routed to the first node. The outflow hydrograph is then computed depending on diversions, inflows, outflows, gains, or losses. That hydrograph is then routed to the next node. Diversions, inflows, outflows, gains, and losses are all inputs based on water demands and basin hydrology. At nodes with reservoirs, operating rules are imposed. At some nodes in a stream, in-stream flow requirements are imposed. All of these are considerated when computing the outflow hydrograph from the node.

Multipurpose reservoirs often are simulated in reservoir simulation models using sequential simulation. In these cases, the reservoir is divided into sections with an allocated volume of storage, or “pool”, for each type of water use. Operating rules are assigned to the reservoir and releases are made for the particular use as long as the reservoir has the available storage for its active pool. Therefore, calculations are made for each purpose separately before calculating the final outflow hydrograph to determine how much yield is supplied to each type of use.

A major limitation of simulation modeling is the large number of model runs needed to study a single alternative, especially in large and complex systems. This results in large amounts of time spent on each alternative. A solution to this is to combine simulation and optimization modeling (Lund and Ferreira, 1996).

Simulation and optimization can be combined in reservoir system modeling. An optimization model can be used to determine optimal operation rules. These rules can then be tested in a simulation model. Belaineh et al. (1999) use this method in a conjunctive use study to combine linear reservoir operation rules with detailed simulations of stream/aquifer interactions. This study revealed that a detailed linked model could result in more efficient system operations. Dandy et al. (1997) show that although optimization modeling assumes perfect foresight and simulation models do not find optimal solutions, a combination of the two present a “reasonable compromise” with high system yields and achievable operating rules (1997).

3.4 Operating Rules

Operating rules are an important aspect to simulation modeling of reservoir systems. A set of operating rules is established for each reservoir and includes consideration of inflows, needs for releases, evaporation, and total storage volumes. Operating rules depend on the type of reservoir system (single reservoir, reservoirs in series, reservoirs in parallel, or general multi-reservoir systems) as well as the function of each reservoir (flood control, navigation, environmental, recreation, water supply) (Lund, 1996; Lund and Guzman, 1999).

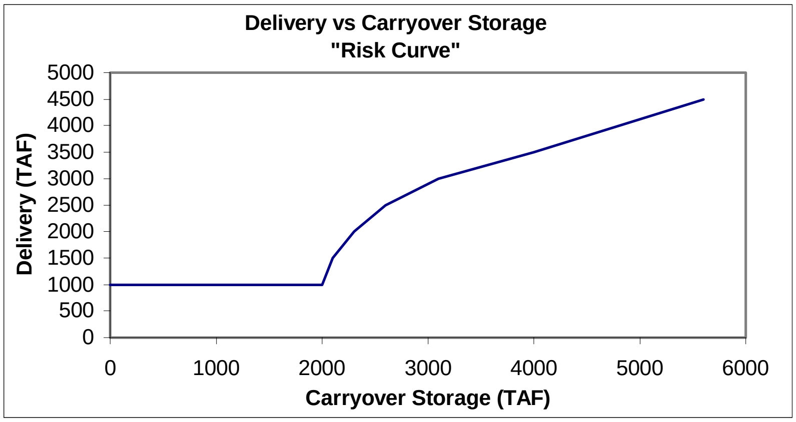
Operating rules are initially assumed and later refined to find an acceptable set of rules resulting in efficient operations of the reservoir for project purposes (water supply, flood control, etc.). Due to variability in water availability seasonally, desirable reservoir levels change throughout the year. The definition of desirable reservoir levels is given by the reservoir rule curve. The rule curve is usually based on an examination of historical data and results from simulation runs with modified rule curves.

Operating rules can be very complex for multipurpose reservoirs due to different desirable reservoir levels for each purpose and throughout the year. In simulation models these variations are accounted for with extensive input. Accounting for multipurpose reservoirs and seasonal variability results in more modeling flexibility but is also computationally expensive (Goodman, 1984; Hufschmidt and Fiering, 1966).

Operating rules are not only a theoretical modeling practice. These rules are developed for and used by reservoir operators. Needham et al. (2000) reveal that operating rules can significantly alter the ability of reservoirs to act for flood control purposes. Therefore, faulty operating rules can result in real social and economic impacts.

3.5 Carryover Storage & Risk

Figure 2. Example of a Delivery vs Carryover Storage "Risk Curve".



Risk for a water supply system is a measure of the likelihood of failures in providing water deliveries. In reservoir system models, an operating rule known as a hedging rule is applied as an input to the model defining an acceptable level of risk for delivery shortages. Hedging rules reduce reservoir releases at target levels to reduce the frequency of severe shortages in dry years (years with low reservoir storage and inflow) (Lund, 1996). A hedging rule used in these studies, often called the delivery versus carryover “risk curve”, defines the amount of delivery available given the amount of carryover in the reservoir. Figure 2 shows an example of a delivery versus carryover “risk curve”. In this case, if carryover storage is below 2000 TAF (thousand acre-feet) at the beginning of the delivery season, the delivery target will be set to

1000 TAF. If carryover storage is 4000 TAF, the delivery target will be 3500 TAF. If at a carryover of 4000 TAF, a delivery target of 4000 TAF was assigned, there would be a higher probability that a shortage could occur due to a lack of stored water. However, if at a carryover of 4000 TAF, a delivery target of 3000 TAF were assigned, there would be a higher probability of spills occurring from the reservoir due to lack of available storage. This is because less water is released from the reservoir to make deliveries, resulting in more water left in the reservoir and less space left to catch high inflows. If too many spills occur from the reservoir, the risk curve input to the model is not aggressive enough. Conversely, if too many delivery shortages occur, the risk curve is too aggressive.

3.6 DWRSIM

An analysis of conjunctive groundwater use and reservoir management operations was performed using the Sacramento-San Joaquin River Basin simulation model, DWRSIM. The hydrologic time period for this model uses hydrologic input data from the water years 1922 to 1994, with calculations made on a monthly time-step. DWRSIM uses nodes in its calculation schematic. For every month, diversions, inflows, flow requirements, evaporation, and any other applicable parameters are calculated at each node. Although reservoir system models produce volumes of output, much of this output is unrelated to the effects of groundwater operations on project deliveries. More detailed information regarding DWRSIM can be found at the California Department of Water Resource’s Operations web page (Web 1). For the purposes of this study reservoir storages, project deliveries, and shortages were analyzed.

4 NORTH OF DELTA GROUNDWATER STORAGE RE-OPERATION

CALFED is a coalition of state and federal agencies that provides management and regulatory direction in developing “a long-term comprehensive plan that will restore ecological health and improve water management for beneficial uses of the Bay-Delta System” (CALFED, 1999). As part of this endeavor, modeling of the California water system is used to plan future water supply and allocation options. In initial studies for CALFED consideration, North of Delta Groundwater Storage (NDGS) was modeled with natural and artificial recharge (CALFED, 1999). However, the placement of the proposed NDGS could be in an area with little or no natural recharge. This set of four studies reveals the reaction of the system to removal of natural recharge as well as to varied levels of aggressive NDGS operations with no natural recharge. First, it shows how operations changed with the removal of natural recharge was examined. Next, it shows how more aggressive operations of NDGS would affect system yield was studied.

4.1 Motivation

Since NDGS is operated as part of the SWP, it contributes to the total storage available North of the Delta to meet delivery, in-stream flow, and Delta outflow requirements. The first concern addressed in these studies was the removal of natural recharge from NDGS. Removal of natural recharge would decrease the rate at which the groundwater bank is filled after a period of extended pumping. If NDGS was not aggressively recharged, as in the case of these studies, this could result in a longer period of time necessary to refill and less available water for pumping. Less water available from NDGS would increase reliance on the major reservoirs North of the

Delta, affecting the total North of Delta water supply. Therefore, removal of natural recharge would tend to decrease both long term and critical period deliveries.

On the other hand, operating NDGS more aggressively can have a positive impact on long term and critical period deliveries, storages, and shortages. By operating NDGS more aggressively, there is less reliance on the major reservoirs North of the Delta so they are better able to meet system demands at critical times. Another possible solution is to move reservoir carryover storage to groundwater instead of operating groundwater more aggressively. This would allow more aggressive operations of surface reservoirs, but possibly with some impacts on stream temperatures and flows. Due to minimum streamflow requirements and reservoir cold water pool requirements used in these cases, this option is infeasible. Therefore, the hypothesis of these studies was that any reduction in system deliveries due to removal of natural recharge could be compensated by more aggressive operations of groundwater. However, excessively aggressive groundwater storage operations may be limited by constraints associated with aquifer materials (DESA, 1975).

4.2 Assumptions

North of Delta Groundwater Storage is proposed to be located near the Sacramento River below the Feather River confluence, but above the American River confluence. Table 1 summarizes the assumptions made when modeling NDGS re-operation. The assumptions represent current and/or expected physical and operational aspects of the systems. These assumptions were developed using rules prescribed for CALFED’s modeling analysis as a basis, with the only differences being groundwater characteristics (CALFED, 1999).

Table 1. Modeling assumptions for NDGS re-operation experiments.

	Studies 1A, 1B	Studies 2A, 2B
Hydrology	2020	2020
Demands	1995	2020
Surrogate	Cap @ 300 TAF	Cap @ 500 TAF
Interruptible	Max 84 TAF/Mon	Max 134 TAF/Mon
Trinity	815 TAF	815 TAF
ERPP	Yes	Yes
Upstream AFRP	Yes	Yes
Delta b (2)	Yes	Yes
EBMUD American River Diversion	No	No
Joint Point	Yes	Yes
SWP Wheeling for CVP	Joint Point Type Unlimited	Joint Point Type Unlimited
South Delta Improvements	Yes 10,300 CFS Banks	Yes 10,300 CFS Banks
Dec 15 – Mar 15 Corp Banks Limit	8500 CFS	8500 CFS
NOD Land Fallow	2% @ 70% all DA's (100 TAF)	5% @ 70% all DA's (300 TAF)
SOD Land Fallow	500 TAF Total	500 TAF Total
Shasta Enlargement	0 (4552) TAF	288 (4840) TAF
NDGS Storage	500 TAF	500 TAF
NDGS Withdrawal Capacity	200 CFS Oct-Sep @ 70 %	200 CFS Oct-Sep @ 70 %
NDGS Active Recharge Capacity	150 CFS Oct-Apr 250 CFS May–Sep 15% Loss	150 CFS Oct-Apr 250 CFS May–Sep 15% Loss
NDSS Cap	N/A	Sites @ 2000 TAF Shasta @ 288 TAF
NDSS Fill Cap	N/A	5000 CFS
NDSS Release Cap	N/A	5000 CFS
Sac Flow before NDGS Fill	0 CFS	0 CFS
Sac Flow before NDSS Fill	N/A	10,000 CFS
SDGS Storage	1800 TAF	1800 TAF
SDGS Recharge Capacity	1200 CFS Oct-Apr 1500 CFS May-Sep 15% Loss	1200 CFS Oct-Apr 1500 CFS May-Sep 15% Loss
SDGS Withdrawal Capacity	800 CFS Oct-Sep @ 70 %	800 CFS Oct-Sep @ 70 %
Transfer Benefit	Dry to Urban, then AG	Dry to Urban, then AG
Facility Benefit Allocation	Dry to Urban, then AG	Dry to Urban, then AG
Environmental Flexibility	Study 1A -level 12 Study 1B -level 7	Study 2A -level 12 Study 2B -level 7
E/I relaxation	75% Aug-Sep	75% Aug-Sep

Studies 1A and 1B use 1995 demands and 2020 hydrology to simulate less demand due to environmental restrictions. Studies 2A and 2B are based on 2020 demands and 2020 hydrology to simulate increased demands from urban users. Studies denoted by A are modeled with a low level of pumping restrictions in the Delta for anadromous fish (48 days of the year in the months of April to June) while studies denoted by B are modeled with a higher level of pumping restrictions for anadromous fish (103 days of the year in the months of December, January, and March to June).

Table 2 shows the study characteristics based on environmental considerations. Low demand levels are 1995 demand levels due to increased environmental water allocations. High Delta pumping restriction levels are pumping restrictions occurring 103 days of the year. Study 1A has low demands and low pumping restrictions, resulting in low stress on the system. Study 2B has high demands and high pumping restrictions, resulting in high stress on the system.

Table 2. Study characteristics based on environmental restrictions.

	1A	**1B**	**2A**	**2B**
Demand Level	Low	Low	High	High
Delta Pumping Restriction Level	Low	High	Low	High

In all studies, NDGS has a maximum storage of 500 TAF, a variable recharge rate of 150 cfs October through April and 250 cfs May through September with a 15% loss, and a pumping rate of 200 cfs. The variable recharge rate is due to higher ambient soil moisture conditions October through April, resulting in a decreased attainable recharge rate. In the original studies, NDGS was operated with natural recharge. Withdrawal, or pumping, frequency was set at a 70% SWP delivery trigger. The 70% delivery trigger means when SWP deliveries are at or below 70% of the total

SWP demand, (3600 TAF for Studies 1A and 1B, 4200 TAF for studies 2A and 2B) withdrawal is made from NDGS before releases from North of Delta Surface Storage (NDSS) or Oroville Reservoir. However, there are no NDGS releases during the typically wettest period of the year between January and March.

4.3 Methods

As stated before, the first step in the analysis was to remove natural recharge from NDGS. This was accomplished by changing the “nodstr.dat” input file to DWRSIM. This file contains a set of data defining a lookup table to specify natural recharge into the NDGS facility as a function of empty capacity in NDGS at the beginning of each month. By setting the natural recharge to zero for each empty capacity in NDGS at the beginning of each month, natural recharge was removed from these simulations.

While examining the effects of removal of natural recharge from the base study, groundwater storage was operated conservatively for long-term benefits. To see how more aggressive operation would affect project benefits, the NDGS trigger value was modified. This, again, was accomplished by changing the percent delivery value below which pumping occurs in the “nodstr.dat” DWRSIM input file. In these experiments, the trigger value was varied from 70% to 100%, including 85%, 90%, and 95% to examine how the delivery trigger affects groundwater operations as well as total SWP and CVP deliveries.

One trigger value was chosen for each study to try to optimize the benefits from more aggressive operations of NDGS. To do this, the entire system’s operational characteristics were varied to exercise Oroville Reservoir more (increase storage and release frequency) and reduce spills. This was accomplished by varying the SWP curve that defines delivery target at a particular level of storage carryover. This curve is referred to as the SWP “risk curve” since variation in the delivery target for a particular carryover can change the number of project delivery shortages. By optimizing the risk curve, less carryover is demanded at Oroville Reservoir for a particular delivery level, so that more water is available as water supply. The CVP risk curve was not modified because operations of Shasta and Folsom reservoirs are less flexible. Small changes in the CVP risk curve result in unacceptable project delivery shortages.

4.4 Results

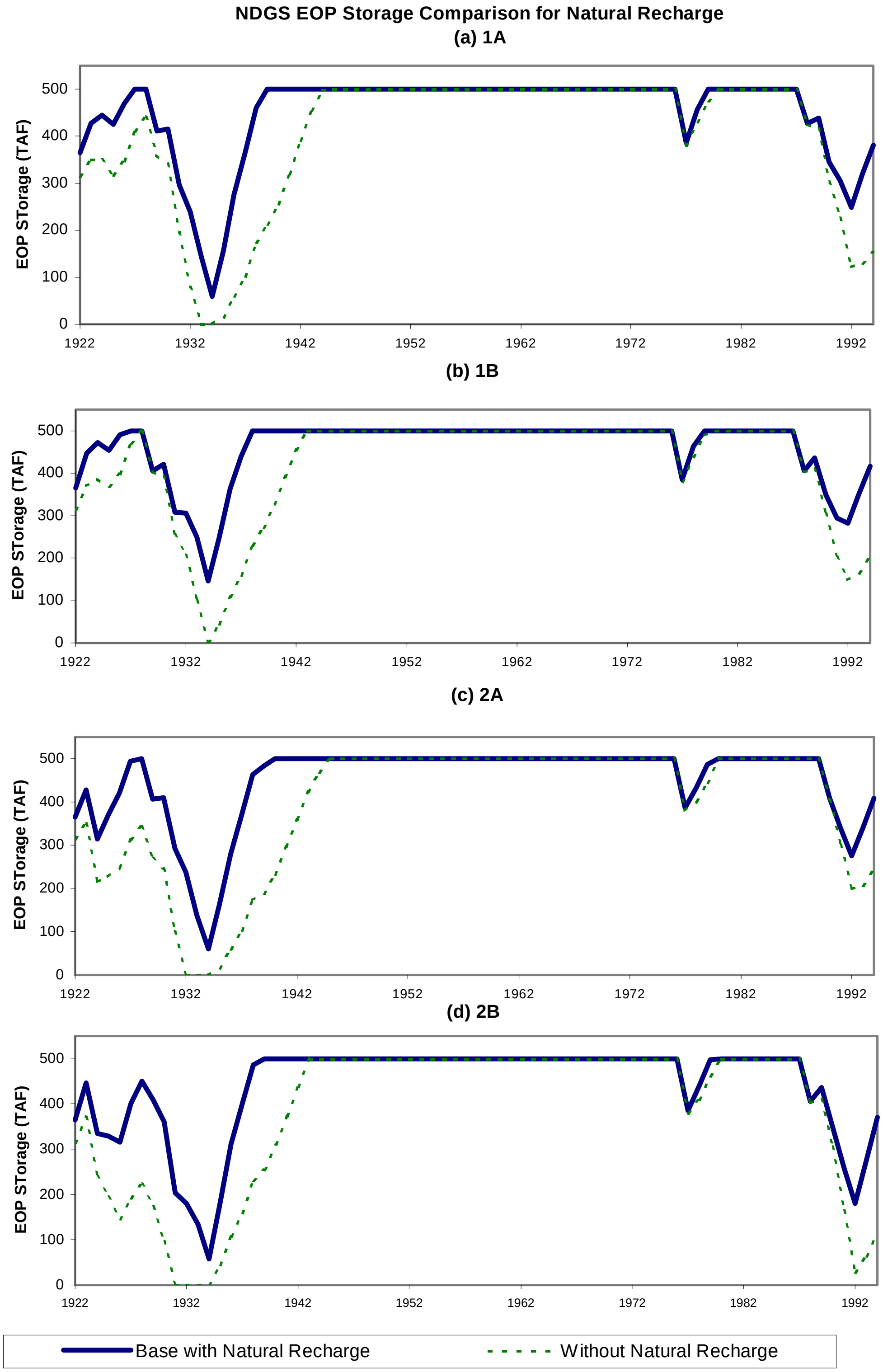
Since each step of the process to re-operate NDGS produced important results leading the next step of the process, results are organized into three groups: removal of natural recharge, re-operation of SDGS, and SWP re-operation.

4.4.1 Removal of Natural Recharge

Removal of natural recharge was the first experiment performed to simulate the newly proposed location for NDGS. Table 3 and Figures 3(a) through (d) show the results of removing natural recharge. In these tables, “long term” refers to average annual deliveries over the entire period of record while “critical period” refers to average annual deliveries during the critical periods of 1929 to 1934, 1977 to 1979, and 1988 to 1993.

Figure 3 is a graphical comparison of NDGS end-of-period storage to examine the effects of removal of natural recharge. In these figures, the lines represent the storage level throughout the time period and the slope between two points represent the rate of recharge (positive slope) or pumping (negative slope).

Figures 3(a-d). Comparison of NDGS at the end of the water year for the base study with natural recharge and a study without natural recharge.



In Figure 3, the solid line is the base study and the dotted line is the study with removal of natural recharge. As this figure demonstrates, for each study, when natural recharge is removed the end-of-period storage begins lower at the start of the first critical period (1929 to 1934) and takes longer to refill due to reduction in the recharge capacity. This is expected and is due to the fact that only artificial recharge occurs compared with the base study in which artificial recharge is compounded with natural recharge.

Although NDGS takes longer to fill without natural recharge, NDGS eventually does fill and remains full until the second critical period. Since NDGS remains full during all times except the critical periods, it can be determined that pumping only occurs during the most dry years, meaning NDGS would only be exercised in droughts. This type of operation is considered conservative because it saves the stored water in NDGS for long-term use instead of annually gaining a benefit.

Table 3 compares the total SWP and CVP average annual deliveries over the long-term and during the critical periods for each study with and without natural recharge. As shown in Table 3, deliveries generally decrease due to the removal of natural recharge. This is expected since an inflow to the system is being removed and no change in system operations to account for the removal of the inflow is made.

Table 3. Final average total SWP and CVP deliveries (TAF) for the base study with natural recharge and a study without natural recharge.

	Base w/ Natural Recharge		Without Natural Recharge		Change	
	Long Term	Critical Period	Long Term	Critical Period	Long Term	Critical Period
1A	5508	4077	5503	4069	-5	-8
1B	5279	3952	5281	3956	2	4
2A	5945	4264	5940	4249	-5	-15
2B	5491	4007	5488	3985	-3	-22

The only exception to this expected result is case 1B, which has slightly increased long term and critical period deliveries. This is due to a slight increase in SWP deliveries and interruptible deliveries with no corresponding decrease in CVP deliveries. This relationship is an unexpected result, but may be due to a reduction in SWP spills. In this particular case, since this study has low demands and high pumping restrictions, more water is available in the system and is sometimes spilled. This excess water spilled from SWP in the base case is being stored via artificial recharge, resulting in more supply available for delivery. All other cases have higher demands and/or pumping restrictions, resulting in less water available to the system and less spill. Therefore, the other three studies are negatively impacted by the removal of natural recharge.

Figures 3 (a) through (d) and Table 3 reveal important information regarding system response to environmental restrictions. Figures 3(a) through (d) show that studies 1A and 1B do not empty as quickly and do not remain empty as long during the critical periods when compared with studies 2A and 2B. This shows that increased demands result in increased reliance on groundwater supplies. Also, study 2A does not empty as quickly or remain empty as long as study 2B. This shows that increased Delta pumping restrictions result in an increased reliance on groundwater supplies. The same comparison cannot be made between studies 1A and 1B due to the special case discussed above with regard to SWP spills. Table 3 shows the same relationships quantitatively. Study 2B has the greatest impacts regarding the removal of natural recharge because it has the heaviest reliance on groundwater. Study 1A has the least impact because it has the least reliance on groundwater recharge.

As will be shown later in this chapter, shortages, Shasta violations, and interruptible deliveries remained relatively constant between studies. The only change is found between CVP and SWP deliveries. Table 3 values are the sum of the CVP, SWP and Interruptible deliveries from this table.

4.4.2 Modified NDGS Operation Trigger Values

As removing natural recharge resulted in a general decrease in system deliveries, to gain more benefit on a long-term basis, additional experiments were performed to operate NDGS more aggressively. This is done by varying the SWP delivery trigger value, which results in more frequent pumping of NDGS.

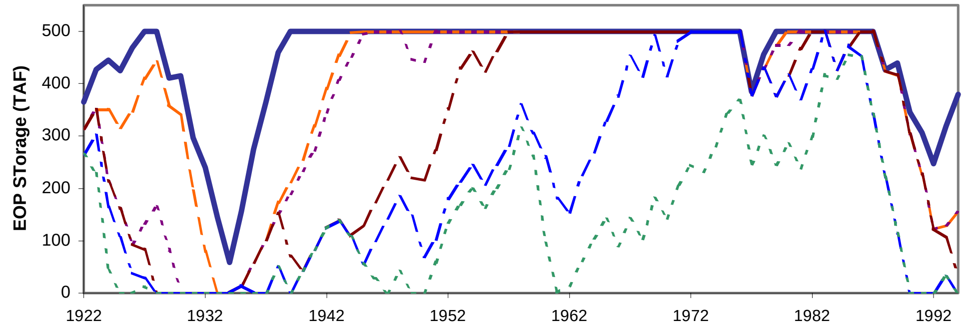
Figures 4 (a) through (d) show graphical results of modifying NDGS operations through varying the SWP delivery trigger value. As may be seen, generally, as the trigger was increased from 70% to 100%, the groundwater bank was pumped more of the time, took longer to fill, and remained full a smaller fraction of the overall time. The differences in pumping, recharge, and fraction of time full between 70%, 85%, and 90% trigger values increased between studies for studies 1A, 1B, 2A, and 2B corresponding to increased demands and Delta pumping restrictions. Like the results from the first step, these results indicate that higher demands and Delta pumping restrictions result in an increased reliance on groundwater supplies.

Although an increase in the trigger value increased pumping frequency, it did not always increase total deliveries. Each study had a unique optimal trigger value so that a lower as well as higher trigger value decreased deliveries. The optimal trigger values for 1A, 1B, 2A, and 2B were 100%, 95%, 90%, and 85% respectively. Therefore, as demands and pumping restrictions increase from studies 1A to 2B, aggressive groundwater operations became less useful due to higher system constraints. These constraints can be remedied by conjunctive use.

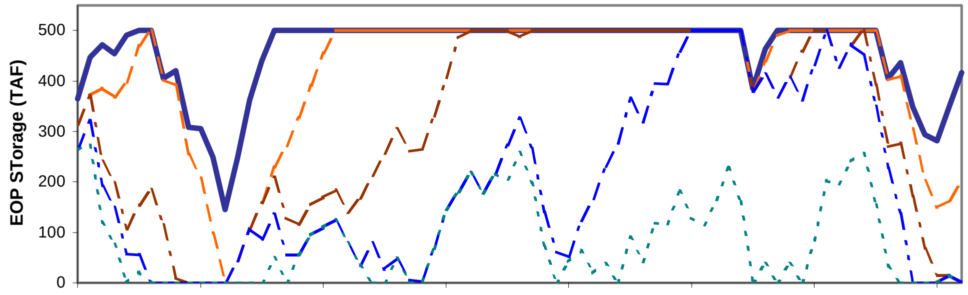
Figures 4(a-d). Comparison of NDGS at the end of the water year for several studies using different SWP delivery trigger values for pumping.

NDGS EOP Storage Comparison for SWP Delivery Trigger Values

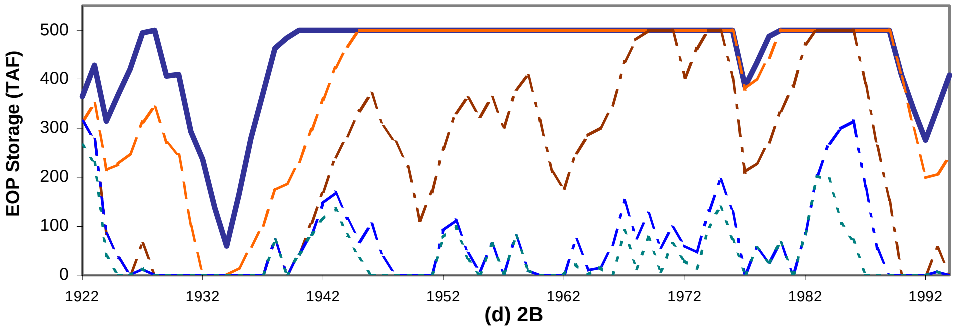
(a) 1A



(b) 1B



(c) 2A



(d) 2B

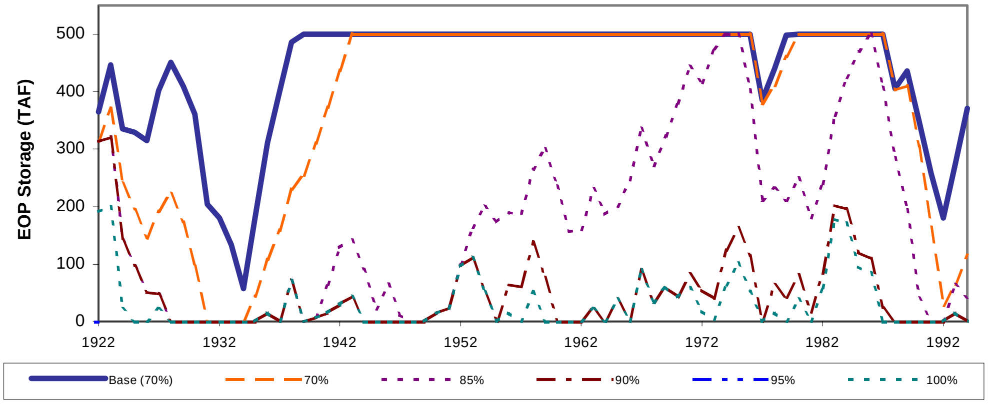


Table 4 shows the total CVP and SWP average annual system deliveries for the optimal trigger value for each study. For each study, deliveries during both the long-term and critical periods decreased. More aggressive operations affected carryover storage and deliveries but no changes were made to the operating rules for the system to take advantage of the available water from groundwater supplies. Again, as shown graphically, Table 4 shows that study 2B has the largest loss in deliveries due to higher demands and environmental pumping restrictions.

Table 4. Final average total SWP and CVP deliveries (TAF) for the base studies and the studies with aggressive groundwater operations**.**

	Base w/ Natural Recharge		Modified Trigger		Change	
	Long Term	Critical Period	Long Term	Critical Period	Long Term	Critical Period
1A	5508	4077	5495	4027	-13	-50
1B	5279	3952	5276	3936	-3	-16
2A	5945	4264	5931	4225	-14	-39
2B	5491	4007	5472	3967	-19	-40

Tables 6 (a) through (d) show detailed delivery, shortage, and violation data for each study. To compare results of this study with the results of the previous removal of natural recharge step, compare columns 3 and 4 Table 6. As indicated above, the optimal trigger values for 1A, 1B, 2A, and 2B are 100%, 95%, 90%, and 85% respectively. Shortages generally decreased slightly when compared with the previous step, but remained within the same ranges for each study. Violations increased for all studies but study 1B, indicating a higher reliance on the CVP and Shasta reservoir for supplies. This is due to increased groundwater supplies and no system re-operation to take advantage of these supplies.

4.4.3 Modified SWP Operation

As just explained, although more aggressive operations of NDGS resulted in more water being pumped from groundwater, overall system deliveries did not improve. To increase deliveries, SWP operations were modified to exercise Oroville Reservoir more and reduce spills.

SWP operations are based on total SWP demands, deliveries, and carryover storage. After the optimal trigger value for NDGS pumping was identified in the previous step, the SWP “risk curve” rule for delivery versus carryover storage was modified to examine the benefits from the most aggressive NDGS operations. These modifications were made using model simulations until an acceptable rule was found. For these cases, a rule was acceptable if it resulted in the highest deliveries at a level of delivery shortage comparable with the base case.

Figures 5(a) through (d) show the magnitude of modifications to the SWP “risk curve” rule needed to improve benefits from the groundwater storage. As expected, the deliveries increased for a given carryover storage after a minimum carryover storage was reached for both the base and re-operated cases. In all cases, deliveries increased for a given level of carryover storage in the re-operated case compared with the base case. This is a respected result since more water available in the system from NDGS allows for more system flexibility. At a given level of SWP carryover storage, more deliveries can be made.

However, as Figures 5 (a) through (d) show, the magnitude of modifications allowable to gain benefits from NDGS re-operations varies between studies. Study 1A has the greatest increase in flexibility due to NDGS re-operation. This is due to the low level of demands and low level of Delta pumping restrictions. With low demands, the risk for delivery shortages is less. Therefore, the system can be operated with more flexibility. Study 2B has a high level of demands and a high level of pumping restrictions. As expected, this study has the least flexibility for SWP operations and SWP “risk curve” rule modifications. The other two studies, studies 1B and 2A, with mixtures of high and low demands and Delta pumping restrictions, have intermediate levels of SWP operation flexibility. However, since there is slightly more flexibility in study 1B, it can be determined that demand level has a greater impact on SWP operation flexibility than the level of Delta pumping restrictions.

Figures 6(a) through (d) show the impacts of modified SWP operations on NDGS storage. This figure shows the base study after natural recharge was removed, the study with re-operated NDGS at the optimal delivery trigger (called Base (trigger)), and the study with modified SWP operations at with NDGS operated at the optimal delivery trigger. For each study, as SWP operations were modified to take full advantage of aggressive NDGS operations, the overall effect was a slightly decreased reliance on NDGS. This is expected because the modifications to SWP operations resulted in better management of water throughout the system and therefore less reliance on NDGS for supplies. However, as Figures 6 (a) through (d) demonstrate, there is no difference in NDGS operations during the critical periods, indicating a heavy reliance on NDGS during these periods.

Table 5 shows total average deliveries for the base operations with natural recharge removed and the final modified operations for each study. The final modified operations were chosen based on obtaining the greatest benefits to deliveries with the least impact on shortages. As Table 5 indicates, each study experienced benefits on a long-term basis. Study 1A benefited the most from more aggressive NDGS operations. For this study, total long-term average deliveries increased by 40 TAF compared with the base study. Compared with original SWP operations at a 100% delivery trigger in Table 5, the net increase in total long-term average deliveries was 67 TAF. Study 2B also experienced a large benefit. For this study, total long-term average deliveries increased by 31 TAF compared with the base study. As shown in Table 5, study 1B benefited least, while study 2A experienced intermediate benefits on a long-term basis. This is expected, since study 1A had the most flexibility to obtain benefits from aggressive NDGS operations while study 2B had the highest stress on the system and therefore benefited from higher system flexibility.

As expected, Table 5 shows that except in the case of 1A, the critical period averages either decreased or increased slightly due to a shift from critical period benefit based operations to long-term benefit based operations. Unexpectedly, in the case of 1A, average critical period deliveries increased by 107 TAF. Increasing releases from NDGS results in an increased North of Delta CVP release during the critical period due to COA (the Coordinated Operating Agreement) regulations. This increases deliveries in the critical periods.

Table 5. Final average total SWP and CVP deliveries (TAF) for the base study and a study with modified SWP operations for aggressive NDGS operations with maximum system benefits.

	Base w/ Natural Recharge		Modified SWP Operations		Change	
	Long Term	Critical Period	Long Term	Critical Period	Long Term	Critical Period
1A	5508	4077	5548	4184	40	107
1B	5279	3952	5285	3959	6	7
2A	5945	4264	5960	4229	15	-35
2B	5491	4007	5522	3981	31	-26

Tables 6 (a-d) give detailed results for each study. As indicated, all studies were operated at the same level of SWP and CVP shortages. Modified SWP operations resulted in slightly decreased interruptible deliveries. All studies had approximately the same level of Shasta violations. As expected, CVP deliveries slightly decreased or increased little while the major delivery benefits were from SWP delivery increases. This is expected since NDGS is considered part of SWP and also because SWP was re-operated to take advantage of NDGS.

Figures 5 (a-d). Comparison of base and final modified delivery vs. carryover storage “risk curves” for each NDGS re-operation study (TAF).

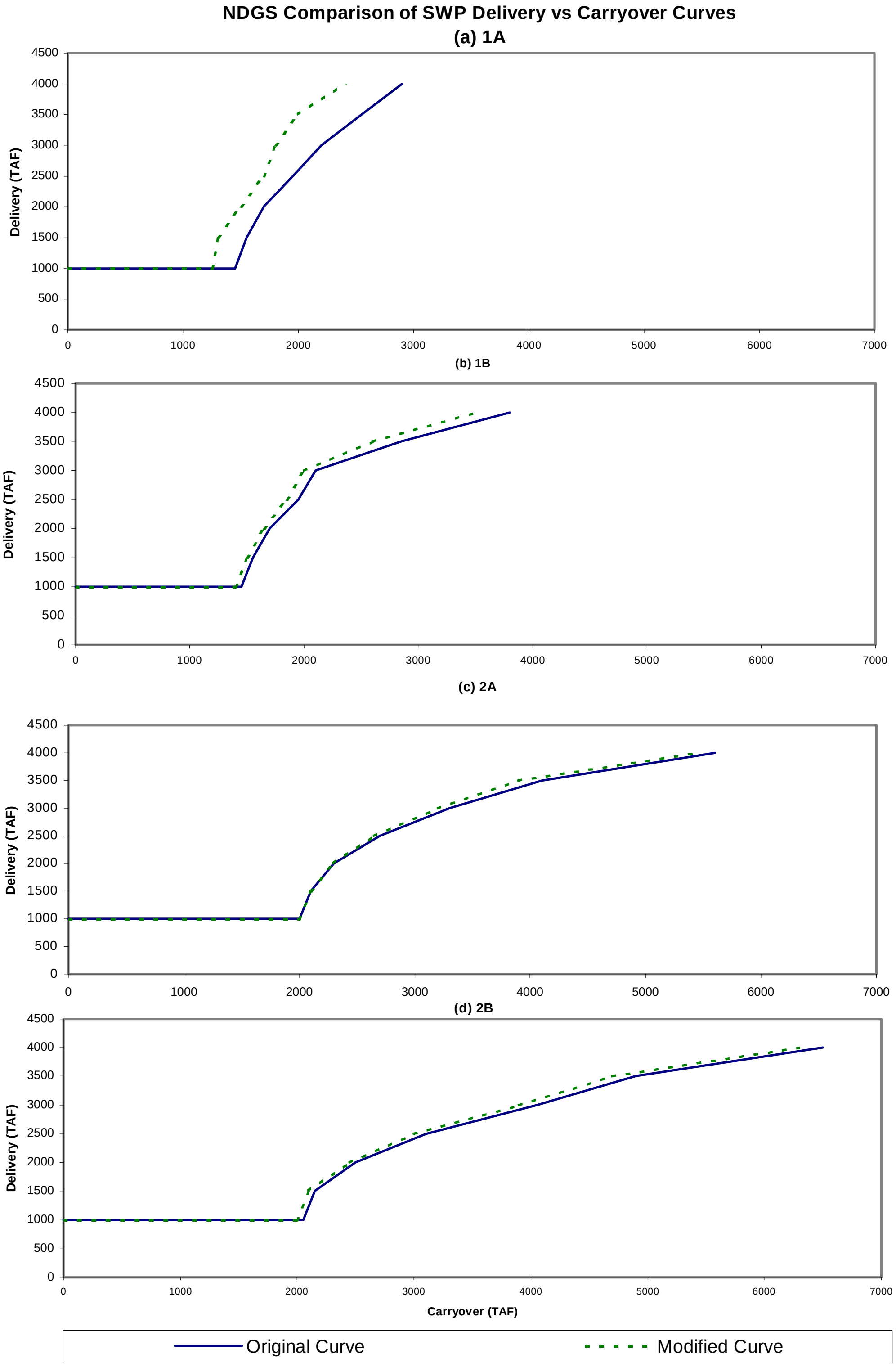


Figure 6 (a-d). Comparison of NDGS at the end of the water year for modified SWP operations at a chosen SWP delivery trigger value for pumping.

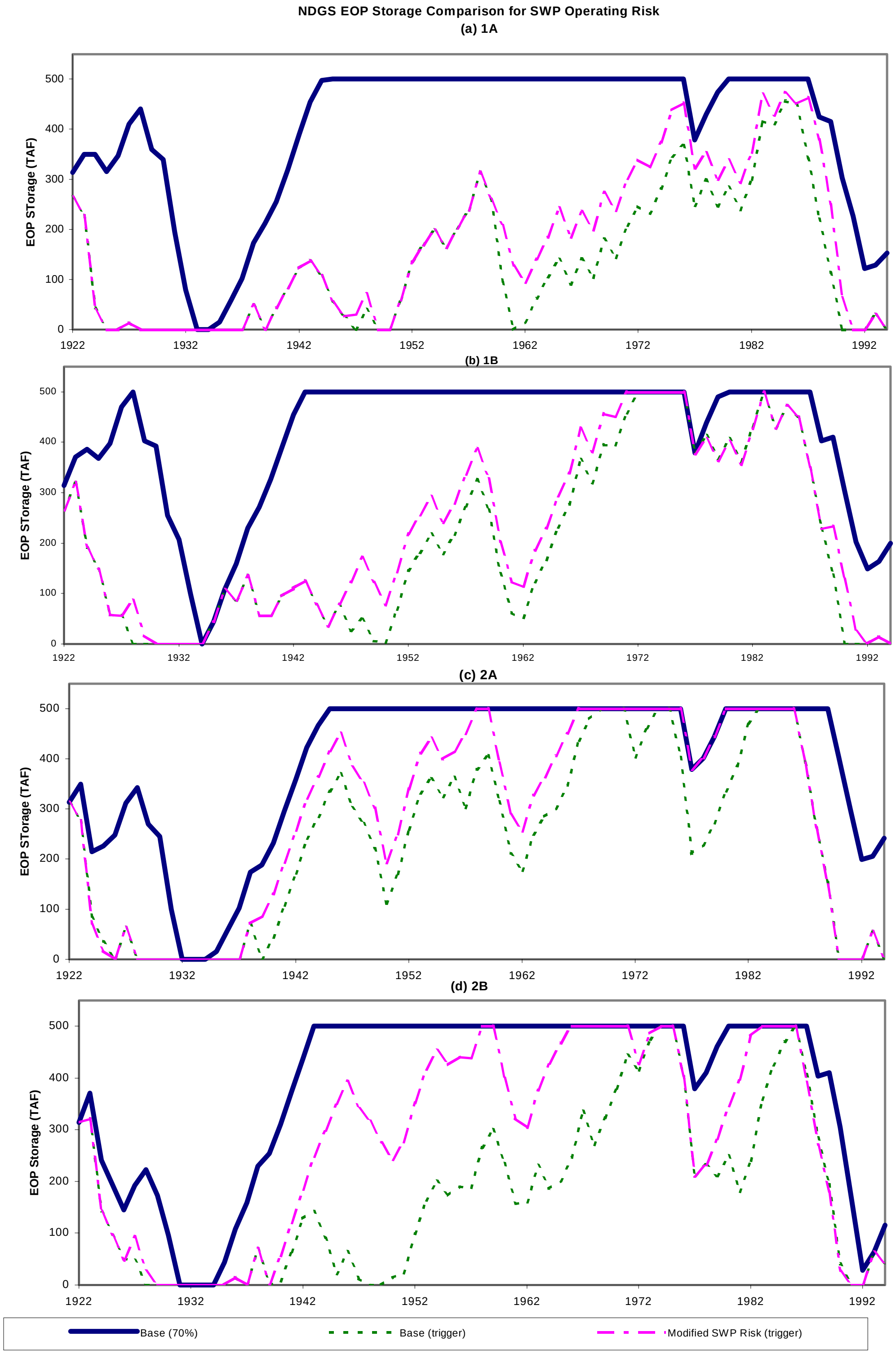


Table 6 (a-d). Project performance for base, removal of natural recharge, aggressive groundwater operations, and modified SWP Operations (TAF or number of occurrences).

Tabel 6(a). Study 1A

		Base, With Natural Recharge	Without Natural Recharge	Modified GW Operations	Modified SWP Operations
		Base(70%)	**70% Trigger**	**100% Trigger**	**100%**
Long Term Average	CVP Deliveries	2327	2322	2311	2316
	SWP Deliveries	3031	3031	3032	3084
	Interruptible	150	150	152	148
	Shasta Violations	11	12	12	12
	SWP Shortages	24	24	20	32
	CVP Shortages	17	17	16	15
Critical Period Average	SWP Deliveries	1678	1671	1615	1613
	CVP Deliveries	2342	2344	2360	2511
	Interruptible	57	54	52	60

Table 6(b). Study 1B

		Base, With Natural Recharge	Without Natural Recharge	Modified GW Operations	Modified SWP Operations
		Base(70%)	**70% Trigger**	**95% Trigger**	**95% Trigger**
Long Term Average	CVP Deliveries	2217	2217	2207	2209
	SWP Deliveries	2955	2956	2961	2969
	Interruptible	107	108	108	107
	Shasta Violations	10	10	11	11
	SWP Shortages	78	76	71	79
	CVP Shortages	44	44	42	42
Critical Period Average	SWP Deliveries	1652	1652	1603	1617
	CVP Deliveries	2274	2277	2309	2318
	Interruptible	26	27	24	24

Table 6(c). Study 2A

		Base, With Natural Recharge	Without Natural Recharge	Modified GW Operations	Modified SWP Operations
		Base(70%)	**70% Trigger**	**90% Trigger**	**90% Trigger**
Long Term Average	CVP Deliveries	2320	2314	2306	2306
	SWP Deliveries	3485	3485	3480	3520
	Interruptible	140	141	145	134
	Shasta Violations	11	13	11	11
	SWP Shortages	34	33	32	40
	CVP Shortages	22	22	21	21
Critical Period Average	SWP Deliveries	1633	1609	1535	1534
	CVP Deliveries	2620	2626	2655	2667
	Interruptible	11	14	35	28

Table 6(d). Study 2B

		Base, With Natural Recharge	Without Natural Recharge	Modified GW Operations	Modified SWP Operations
		Base(70%)	**70% Trigger**	**85% Trigger**	**85% Trigger**
Long Term Average	CVP Deliveries	2171	2167	2165	2163
	SWP Deliveries	3202	3201	3186	3245
	Interruptible	118	120	121	114
	Shasta Violations	11	12	13	11
	SWP Shortages	49	48	43	57
	CVP Shortages	33	30	28	28
Critical Period Average	SWP Deliveries	1591	1561	1541	1534
	CVP Deliveries	2377	2383	2384	2408
	Interruptible	39	41	42	39

4.5 Review

Based on long-term average deliveries, critical period average deliveries, and delivery shortages, elimination of natural recharge has been shown to negatively impact system deliveries. To compensate, NDGS was operated more aggressively to increase long term average deliveries with the same level of risk accepted in the base studies (same number of delivery shortages). Since NDGS operations affect operations of the entire system, SWP was re-operated to take full advantage of aggressive NDGS operations. This resulted in increased long-term average project deliveries under the same level of risk. Without re-operation of other SWP facilities, more aggressive operation of NDGS reduced project deliveries.

Study 1A experienced both long-term and critical-period benefits from more aggressive NDGS operations. This is due to low demands and low Delta pumping restrictions. Alternatively, study 2B also benefited from aggressive NDGS operations, but only on a long-term basis. High demands and high Delta pumping restrictions result in a heavier reliance on NDGS supplies. Since the base case was operated to only supply critical-period benefits, the shift from critical period based operations to long-term based operations resulted in more water available over the long-term, but less water available during the critical period. Studies 1B and 2A have intermediate combinations of demands and Delta pumping restrictions, resulting in less potential for benefits from aggressive NDGS operations.

5 SOUTH OF DELTA GROUNDWATER STORAGE RE-OPERATION

The next experiment was to determine the impacts of more aggressive SDGS operations. To do this, South of Delta Groundwater Storage (SDGS) was operated conjunctively with San Luis Reservoir instead of, as in previous studies, operated independently of San Luis Reservoir but depending on SWP deliveries. By making this change, each time San Luis Reservoir releases for deliveries, SDGS also releases. The motivation behind this experiment was to determine if more aggressive SDGS operations would also affect system yield.

5.1 Assumptions

Table 7 is a summary of the major assumptions made in this experiment. The assumptions are based on current and/or expected physical and operational aspects of the system. The study was performed based on assumptions from CALFED's Comprehensive Analysis with Delta pumping restrictions occurring 48 days of the year in the months of April to June (CALFED, 1999). SDGS storage capacity is assumed to be 1800 TAF, the recharge capacity is 1200 cfs October through April and 1500 cfs May through September with a 15% loss, and the withdrawal capacity is 800 cfs throughout the year. The base study withdrawals at a SWP delivery trigger of 70% while the experimental study withdrawals are in conjunction with San Luis withdrawals.

5.2 Methods

To operate SDGS jointly with San Luis Reservoir, several modifications to the model and model inputs were made. First, operations of Kern Water Bank (SDGS) were turned off using the Kern Water Bank switch in the "jobcon.dat" file. Second, the

Table 7. Modeling assumptions for SDGS re-operation.

Characteristic	**Assumption**
Hydrology	2020
Demands	2020
Surrogate	Cap @ 500 TAF
Interruptible	Max 134 TAF/Mon
Trinity	815 TAF
ERPP	Yes
Upstream AFRP	Yes
Delta b (2)	Yes
EBMUD American River Diversion	No
SWP Wheeling for CVP	Joint Point Type Unlimited
South Delta Improvements	10,300 CFS Banks
Dec 15 – Mar 15 Corp Banks Limit	8500 CFS
NOD Land Fallow	5% @ 70% all DA's (300 TAF)
SOD Land Fallow	500 TAF Total
Shasta Enlargement	none
NDGS Storage	788 TAF
NDGS Withdrawal Capacity	200 CFS Oct-Sep @ 70 %
NDGS Active Recharge Capacity	150 CFS Oct-Apr 250 CFS May–Sep 15% Loss
NDSS Cap	Sites @ 1200 TAF, Shasta @ 0 TAF
NDSS Fill Cap	5000 CFS
NDSS Release Cap	5000 CFS
Sac Flow before NDGS Fill	0 CFS
Sac Flow before NDSS Fill	10,000 CFS
SDGS Storage	1800 TAF
SDGS Recharge Capacity	1200 CFS Oct-Apr 1500 CFS May-Sep, 15% Loss
SDGS Withdrawal Capacity	800 CFS Oct-Sep @ 70 %
SDSS Storage, LBG	none
Transfer Benefit	Dry to Urban, then AG
Facility Benefit Allocation	Dry to Urban, then AG
Environmental Flexibility	Level 12 all years
E/I relaxation	75% Aug-Sep

DWRSIM nodes for Los Banos Grandes, a reservoir already programmed to operate in conjunction with San Luis in DWRSIM, were relocated to the SDGS position in the DWRSIM schematic using the “main.dat” input file. Finally, an evaporation rate of 15% of inflow to the reservoir was imposed to simulate the 15% recharge loss for groundwater. Due to modeling constraints, the 15% loss for a particular month was accounted for in the following month. This does not affect the final outcome of total storage or diversions and therefore does not affect average deliveries or shortages. In this case, to take full advantage of the aggressive SDGS operations, modifications to SWP and CVP operations were made by modifying both risk curves (see section 4.3 for description of “risk curve”).

5.3 Results

As expected, operating groundwater and San Luis Reservoir conjunctively enables more aggressive operations of groundwater. Figure 7 shows SDGS end-of-period storage over the entire period of record. As shown in Figure 7, conjunctive operations increase the frequency of recharge (represented by the frequent oscillation of storage), resulting in more supplies available for later delivery. Also, conjunctive operations result in a higher frequency of withdrawal. Instead of being full most of the time as in the case of the base study (see Figure 7), the bank never fills in the experimental study, creating more available space in the groundwater bank to store excess water. These results show that conjunctive use operations of SDGS is a type of “space rule”. Space rules are operating rules applied to reservoirs in parallel with the purpose of balancing storage between reservoirs to increase supplies and consequently deliveries. Conjunctive operations of SDGS result in more storage as well as more system deliveries.

Table 8 shows detailed aspects of this study. As this table indicates, CVP deliveries were slightly decreased by 20 TAF while SWP deliveries were substantially increased by 282 TAF. However, since interruptible deliveries decreased by 147 TAF, the net increase in total long-term average deliveries was 114 TAF. Total average critical period deliveries also increased, but only by 11 TAF. This is due to changing from critical period benefit based operations to long-term benefit based operations.

Table 8 indicates that SWP and CVP shortages decreased due to conjunctive use operations. Although these studies would ideally operate the projects under the same acceptable level of project delivery shortages, further modifications to the risk curve than made in this study resulted in unacceptable increases in Shasta violations. (Shasta violations are any instance when the storage in Shasta reservoir falls below 1900 or 1200 TAF. See section 2.3 for a more detailed description.) Therefore, total shortages are less than in the base study.

Overall, conjunctive operations increase project deliveries, decrease interruptible deliveries, increase total deliveries, and decrease diversion shortages for both long-term and the critical period of 1928 to 1934 (see Table 8).

Due to the higher frequency of recharge and withdrawal, the operating costs of conjunctive operations would probably be higher than independent operations due to energy costs. A remaining question is whether the rapid increases and decreases in storage seen in the experimental study are hydrogeologically feasible given constraints of the groundwater bank media.

Figure 7. Comparison of SDGS EOP storage between independent and conjunctive operations with respect to San Luis Reservoir.

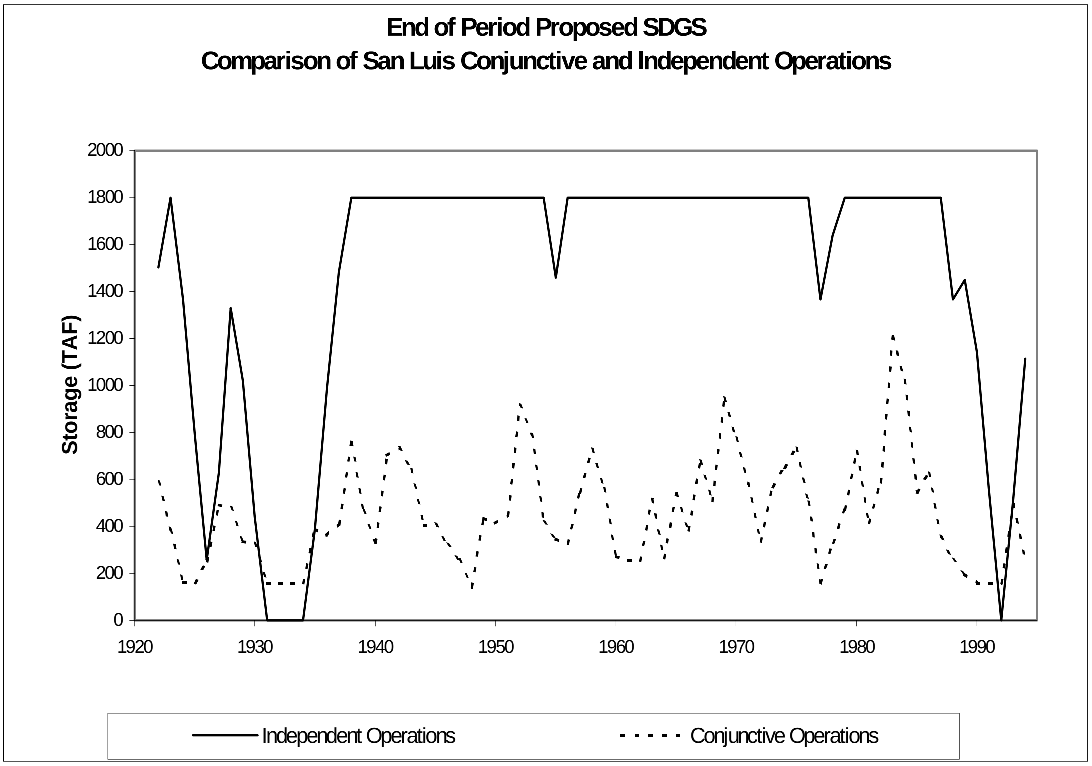


Table 8. Comparison of project characteristics for independent and conjunctive groundwater operations with relation to San Luis Reservoir (Deliveries in TAF).

		Independent Operations	Conjunctive Operations	Difference
		Base	**Experiment**	
Long Term Average	CVP Deliveries	2344	2323	-20
	SWP Deliveries	3331	3613	282
	Interruptible	161	14	-147
	Total Deliveries	5836	5950	114
	Shasta Violations (1900)	12	12	0
	SWP Shortages	18	14	-4
	CVP Shortages	24	14	-10
Critical Period Average	SWP Deliveries	1640	1612	-28
	CVP Deliveries	2464	2557	93
	Interruptible	55	0	-55
	Total Deliveries	4159	4169	11

CONCLUSIONS

California's water supply system is stressed due to increasing demands as well as increasing environmental restrictions. New water management alternatives are needed to increase available supplies without further harmful effects to fisheries and the environment. This project suggests that conjunctive use and aggressive operations of groundwater are management alternatives that can increase supplies using the system already in place.

In this project, experiments to assess effects of aggressive and conjunctive operations of groundwater banks were performed to determine the effects on California water supply. These experiments show that aggressive re-operation of groundwater storage, both north and south of the Delta, can increase long-term average project deliveries under all levels of environmental constraints. However, to obtain these benefits, the entire system (including surface reservoir storage) must be re-operated to take advantage of increased groundwater storage flexibility. This project shows that increased benefits from groundwater can be obtained through management of reservoir operating rules such as the "risk curve" rule and the space rule.

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