CONJUNCTIVE USE OPPORTUNITIES IN SOUTHERN CALIFORNIA

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DEDICATED TO

To my beloved parents, Manuel and Ana María, and my brother, David, for their unconditional love and support.

To the memory of my cousin Pablo Pulido, and my grandfather Antonio Pulido, who will always be missed.

To my girlfriend, Olga, for her love, encouragement, and patience.

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ABSTRACT

Groundwater is a critical component of Southern California's water supply. This thesis explores the potential and limitations of conjunctive use of surface and groundwater for Southern California’s water supply system. The economic-engineering network flow optimization model CALVIN is used to analyze and compare the economic and reliability benefits from different conjunctive use alternatives. Results from CALVIN suggest that flexible management of additional conjunctive use facilities and groundwater storage capacity under flexible water allocation can generate substantial economic benefits to the region. Conjunctive use adds operational flexibility needed to take full advantage of water transfers, and transfers provide the allocation flexibility needed to take better advantage of conjunctive use. The value of projected conjunctive use facilities and groundwater storage along the Colorado River Aqueduct, in Coachella Valley, and north of the Tehachapi mountains under economically optimized operation of the system is examined. The results reveal reduction of the demand for increased imports into Southern California, and suggest some promising changes in the operation of the system.

I. INTRODUCTION

More than 70% of California's 71 million acre-feet (maf) annual average runoff originates in the northern third of the State (north of Sacramento), while about 75% of the State's urban and agricultural demands for water are south of Sacramento (DWR 1998). In response to the uneven geographic and temporal distribution of the water resource, an extensive and complex infrastructure for water storage and conveyance has been developed to match supply and demand. An integrated water system with federal, state and local participation conveys about 50% of the State's surface water distances up to hundreds of miles (WEF 1997). Meanwhile, a complex web of institutional arrangements determines when and where the water is delivered.

Southern California’s water system (California south of the Tehachapi Mountains) imports up to 70% to meet its 10 MAF demand (DWR 1998). Fig. 1 shows the study area, with the major water projects and the water users included in the study. In addition to the reliance on imported water, Southern California relies on extensive groundwater supplies (1.2 maf) and a limited amount of natural runoff (DWR 1998). The main urban demands are located in the western part of the region, and major agricultural areas in the east. The South Coast, including Los Angeles and San Diego metropolitan areas, is California’s most urbanized hydrologic region. Also it covers only about 7 percent of the State’s total land area, it is home to about 54% of the State’s population, i.e. about 18 million people (DWR 1998). The sources of imported water are the State Water Project (SWP), the Los Angeles Aqueduct (LAA) and the Colorado River (CR).

Water Users Included in Study:
Antelope Valley (AV)
Castaic Lake urban area (Castaic)
Central MWD of Southern California (CMWD)
Coachella Valley urban area (Coachella)
Coachella Valley Water District (CVWD)
Eastern and Western MWD (EW MWD)
Imperial Irrigation District (IID)
Mojave urban area (Mojave)
Palo Verde Irrigation District (PVID)
San Bernardino Valley urban area (SBV)
San Diego County Water Authority (SDCWA)

Fig. 1. Southern California Water System and Water Users (after Newlin 2000)

SWP water reaches Southern California via the California Aqueduct, with a capacity of 4,480 cfs. The Aqueduct bifurcates into the West Brach and the East Branch. The East Branch carry water through Antelope Valley, the San Bernardino Mountains and terminates at Lake Perris near the city of Riverside. An East Branch extension will convey water to the east side of San Bernardino County. On the West Branch, water flows mainly within Los Angeles National Forest, and terminates at Castaic Lake. The SWP is operated and managed by the California's Department of Water Resources (DWR). The ability of the SWP to deliver full supply requested by its contractors depends on the regulatory and physical constraints on its operation. Water export from the Sacramento-San Joaquin Delta (Delta) now depends on the ongoing CALFED Bay-Delta planning process, with the mission of developing and implementing a long-term comprehensive plan for water management in the Delta that preserves the ecosystems and water quality. As specific directives from the CALFED process remain uncertain, the water supply reliability of the SWP remains also uncertain. 29 water agencies, of which Metropolitan Water District of Southern California (MWDSC) is the largest, have contracts with DWR for SWP water (state water contractors). Most of them reached an agreement in 1994, the Monterey Agreement, which made several comprehensive changes to the SWP allocation system. For this study, SWP water deliveries are represented as a single source from north of the Tehachapi Mountains.

The Los Angeles Department of Water and Power (LADWP) owns and operates the LAA, which diverts both surface and groundwater from the Owens Valley and surface water from the Mono Basin. Although a second pipeline increased in 1970 the aqueduct's annual delivery capacity from 350 to 550 taf/yr, restrictions on Mono Basin diversions and Owens Lake withdrawals (to prevent dust storms) have substantially reduced LAA deliveries.

California is entitled of 4.4 million acre-ft per year (maf/yr) from the Lower Colorado River. The Secretary of Interior may also authorize the use of one-half of surplus flow unused by the other Lowe Basin states (Arizona and Nevada). The "Law of the River" is a body of law regulating California's allocation and the quality of Colorado River water. For many years, California has used 5.2 maf annually on average of Colorado River water, far exceeding the allocate share of 4.4 maf. However, with the completion of the Central Arizona Project and the fast growth of Southern Nevada, the 4.4 maf limitation is slowly becoming a reality (the 4.4. Plan). Three major facilities - USBR's All American Canal (AAC), MWDSC's Colorado River Aqueduct (CRA), and Palo Verde Irrigation District's main canal- convey water from the Colorado River to Califonia's users. MWDSC has received Colorado River water since 1941 under contracts with USBR. Water from the Colorado River is delivered to the Metropolitan's service area via the CRA, which conveys water from Lake Havasu (impounded by the Parker Dam) to Metropolitan's reservoirs (which include Lake Mathews and Diamonds Valley Lake). Water imported via the CRA has high level of salinity, averaging around 700 mg/L during normal water years (DWR 1998). MWDSC has historically received SWP water in exchange for relinquishing CRA water to Coachella Valley Water District (CVWD) and Desert Water Agency (DWA). The San Diego Aqueduct delivers water from the CRA to San Diego County since 1947. The Seven Party Agreement (1931) defined California's Colorado River use priorities. The first 3.85 maf of CR water is allocated to agricultural uses and the remaining 0.55 maf belongs to MWDSC. Major agricultural uses in Southern California draw water from the Colorado River, and include Imperial Irrigation District (IID), Coachella Valley Water District (CVWD), and Palo Verde Irrigation District (PVID). IID is supplied via the AAC, which diverts water from the Imperial Dam in the CR. CVWD water deliveries come from the Coachella branch of the AAC (Coachella Canal), and Palo Verde takes its water supply from stream diversions in the Colorado River.

Groundwater

Groundwater plays a crucial role in Southern California water management, not only quantitatively (providing about one-third of the deliveries in normal years) but also because of its strategic value. Some zones depend on groundwater almost completely (e.g., groundwater provides roughly 90% of the supply for the more than a million residents of the San Gabriel Valley in LA County), and groundwater storage has a significant contribution in buffering surface supply reductions during droughts. Despite its value to the region's water supply, California has not any comprehensive statute or program for managing and regulating groundwater. Much of California's groundwater production is self-supplied, and is not managed or quantified by local agencies (DWR 1998). Because California has treated groundwater management as primarily a local function, a great variety of local governance structures have been created. The institutional arrangements for governing and managing groundwater in California have emerged in reaction to local problems (Blomquist 1992).

Water Crisis?

California population is expected to increase significantly during next decades. The 1995 population was 32 million, and it is projected to reach 47.5 million people in 2020 (DWR 1998, based on DOF1997). Half of this growth (about 7 million) is expected to occur in Southern California. Urban water demand, despite water conservation and recycling efforts, continues to grow. Statewide urban use at the 1995 base level is 8.8 maf in average water years. Forecasted 2020 use increases to 12.0 maf in average years (DWR 1998). Meanwhile, the projected agricultural water reduction for 2020 is, according to DWR, about 800 taf. The short-term changes in forecasted agricultural acreage are a small percentage of the State's total irrigated area.

On the supply side, traditional imports from the Colorado River and the Owens and Mono Basins are being curtailed. The Colorado River Board's 4.4 Plan is intended to reduce California's annual diversion of Colorado River water. California's diversion must be reduced about 800 taf/yr to be adjusted to achieve the stipulated 4.4 maf. Meanwhile, court decisions to provide additional water to benefit the environment in Mono Basin and Owens Valley have substantially limited the deliveries via the LAA. Moreover, the supply from the SWP is uncertain, depending on the results of the CALFED planning process.

Actions

The 1998 California Water Plan (DWR 1998) estimated the year 2020 difference between demand and supply in California from 2 to 6 maf year. Although these projected values can be argued, it is clear that actions must be taken to avoid large differences in the future (Chung et al. 2002). The negative predictions about the growing demand for water and the unpredictable and diminishing supply have forced water managers to look at water less traditional options. This includes water transfers and markets, water conservation, wastewater reclamation and reuse, seawater desalting, water banking and conjunctive use.

Results from a previous study with CALVIN suggest substantial economic and reliability benefits from implementing *water market or other transfer mechanisms,* benefits that could be achieved with relatively little reallocation of agricultural water to urban demands with higher economic value (Newlin 2000, Newlin et al. 2002). This study also finds that substantial economic benefits could be accrued from expanding some conveyance and storage facilities, particularly the Colorado River Aqueduct and conjunctive use storage capacity.

Regarding demand reduction by *water conservation measures*, many agencies in California have implemented programs to increase water use efficiency. It is expected that these measures would yield a reduction in demand of about 2 maf from implementation of Best Management Practices (BMPs) by urban demands, and Efficient Water Management Practices (EWMPs) by the agricultural demands (DWR 1998). The urban demands used in this model are calculated based on DWR 2020 projections on per capita water use (DWR 1998), projections that include the expected effect of BMPs.

Wastewater reclamation and reuse is been increasingly applied to agricultural and landscape irrigation, industrial recycling, groundwater recharge and water for aesthetic and environmental purposes. Reclaimed water provides a dependable source of water even in droughts year because the generation of urban wastewater is affected little by drought (Asano 1998). CALVIN considers the possibility of reuse of return flows from agricultural and urban facilities (Jenkins et al. 2002). Reuse capabilities are incorporated in this Southern California model in agricultural and urban demands, according to the existing infrastructure and their capacities.

Water desalting is still considered a costly alternative (due to high energy requirements), but might be economically efficient in some coastal communities not connected to the statewide water distribution infrastructure and with very limited supply.

This thesis explores the benefits, potential and constraints (physical, environmental and institutional) for *integrated conjunctive use of surface and groundwater in Southern California.*

Conjunctive Use in Southern California: Current Operation, Promising Alternatives

Conjunctive use is a strategic element of California's water management challenge of matching an increasingly scarce resource with a continually growing population.

The Association of Groundwater Agencies of California, AGWA, has documented that over 21.5 maf of additional groundwater storage is still available in Southern California Groundwater basins, assuming resolution of institutional, water quality and other issues. Existing conjunctive use programs in Southern California provide an estimated 2.5 maf of water per year (AGWA 2000).

Conjunctive use programs include both dry-year (longer-term storage) and short-term programs (such as seasonal storage operations) to store surface water surplus underground to provide reliability during seasonal or drought periods.

Metropolitan Water District is conducting technical studies and negotiating agreements with local agencies to increase the yield and reliability of available water supplies through conjunctive use programs, both in-basin storage programs and storage in groundwater basins along the Colorado River Aqueduct and SWP (MWDSC 2000, MWDSC 2002).

The 1996 MWDSC's Integrated Resources Plan (IRP) set a resource objective to develop about 175 taf/yr of dry-year supply from in-basin groundwater storage by 2010 and 300 taf/yr by 2020. The main programs are (MWDSC 2002):

- Long-term Seasonal Storage Program. This is a pricing program providing supplies in excess of the amount needed to meet the consumptive municipal and industrial demands available to the member agencies at a discount rate for local storage.

- North Las Posadas Groundwater Storage Program. An agreement between Metropolitan and Calleguas Municipal Water District provides an extra storage capacity, which is expected to be 210 taf/yr by 2020.

- Diverse groundwater storage programs expected to be operational by 2006 (Raymond Basin, City of Pasadena, Foothill MWDSC among others).

Several technical studies and agreements have been released between Metropolitan and agencies that have Colorado River entitlements or are in proximity to the CRA. The most important of these projects are presented next (MWDSC 2002).

Groundwater Storage Program in Coachella Valley

Almost all of the Coachella Valley lies within Riverside County. The Desert Water Agency (DWA) and Coachella Valley Water District (CVWD), both in Riverside County, have entitlements to State Water Project (SWP) water (totaling 61.2 taf/yr), but they have no physical connection to SWP facilities. However, both agencies, are adjacent to the CRA. Since 1973, Metropolitan has been exchanging an equal quantity of its CRA water for their SWP water, by recharging Coachella Upper Valley groundwater supplies at the White Spreading Facility. The facility has a recharge capacity of at least 300 taf/yr. An agreement in 1984 allows Metropolitan to store additional SWP water in wet years. Part of the municipal water from wastewater treatment plants in the Upper Valley is also disposed into percolation ponds.

Metropolitan has also identified the feasibility of developing conjunctive use storage in the Lower Basin, currently in overdrafting condition. MWDSC is expecting the program to reach up to 500 taf of storage capacity. A facility capable of recharging about 100 taf/yr from the Coachella Canal could be constructed for this purpose (MWDSC 2002, CVWD 2000).

Groundwater Storage Program in Central Arizona

There is also a program to store potential unused Colorado River water in Central Arizona aquifers, capturing water that otherwise would have been released for flood control from Lake Mead. The Arizona Water Banking Authority was created in 1996 with that objective. This area is out of the scope of this study, but this program offers promising possibilities for interstate banking.

Groundwater Storage Program in Cadiz

The Cadiz Groundwater Storage Project is a $150 million, 50-year groundwater storage and transfer program, result of an agreement between MWDSC and Cadiz Inc., an agricultural company that owns 27,000 acres in the Cadiz and Fenner Valleys of eastern San Bernardino County (Mojave Desert), approximately 35 miles north of Metropolitan's Colorado River Aqueduct. The program is proposed to serve 3 functions:

- Store surplus water from the Colorado River Aqueduct (groundwater bank for MWDSC), which will be conveyed by a new water pipeline to spreading basis that will be constructed on the Cadiz property. Program facilities would be able to deliver 200 cfs of water (nearly 150 taf/yr) to the spreading basins.
- Pump the water stored in dry seasons or years
- Pump indigenous groundwater from the Cadiz and Fenner Valleys when Colorado River water in insufficient, in accordance with the terms and conditions of a comprehensive Groundwater Monitoring and Management Plan, designed to protect surrounding natural resources (MWDSC and BLM 2001). The possibility of pumping of water from the reserve of the aquifer is the most controversial aspect of the project, since there are discrepancies about the natural recharge to the aquifer (Bredehoeft 2001, USGS 2001), and possible environmental impacts if the aquifer is mined.

The water pumped will be returned to the Colorado River Aqueduct via the transmission pipeline, for ultimate delivery to Southern California urban demands.

Groundwater Storage Program in Hayfield and Upper Chuckwalla

Metropolitan is now implementing a groundwater storage program in the Hayfield basin, and conducting a feasibility study in the Upper Chuckwalla basin for a similar program, with the purpose to store available surplus from the CRA for its use during dry years conditions (MWDSC 2002). These two valleys are also located in the Mojave Desert, near Metropolitan’s Julian Hind and Eagle Mountain Pumping Plants.

Groundwater Storage Program in Kern-Delta, Semitropic and Arvin-Edison

The dry-year supply program between Kern Delta and Metropolitan will allow Metropolitan to store water in Kern Delta’s groundwater basin, either through direct spreading operations, or through deliveries to farmers in Kern Delta’s service area (in the San Joaquin Valley portion of southern Kern County). Metropolitan will have the capacity to store up to 250 taf of water, and can recover this stored water, either through direct pumping or exchange, at a rate of 50 taf/yr (MWDSC 2002).

The contract between Semitropic Water Storage District and Metropolitan allows the latter to use a groundwater capacity of 350 taf. During dry years, Metropolian can recover its stored water through a combination of direct pumping of groundwater and the release of Semitropic's SWP entitlement. The return of water to Metropolitan ranges from 31 taf to 170 taf/yr, depending on groundwater conditions, water supply hydrology and banking partners usage. This program has been operational since 1994 (MWDSC 2002).

Finally, the Arvin-Edison (Kern County) - Metropolitan program provides Metropolitan with the capacity to store up to 250 taf under the current agreement. The water can be recovered at a rate from 40 to 75 taf/yr. This program has been operational since 1997 (MWDSC 2002).

Structure of the Thesis

Following this Introduction, Chapters 2 reviews ideas regarding the potential of conjunctive use and constraints to its implementation, followed by a review of techniques to incorporate groundwater flow in system models, and the state-of-art in simulation and optimization conjunctive use models for regional water supplies. Chapter 3 examines the economic potential of conjunctive use strategies, and presents a review of the evolution and tendencies for economically driven conjunctive use optimization models. Chapter 4 provides an overview of the CALVIN model, and a description of the model developed for Southern California's water system. Selected policy results are presented in Chapters 5, 6 and 7. Finally, conclusions and limitations of this work are summarized in Chapter 8.

II. CONJUNCTIVE USE OF SURFACE AND GROUNDWATER

Conjunctive use is the coordinated management of surface and groundwater resources, taking advantage of their complementary properties. Both surface and groundwater storage are used to redistribute water in time to match supply and demands. However, surface and groundwater storage differ in storage capacity, recharge and depletion rates, capital and operation costs and constraints. Jointly operating all manageable water resources in a region can increase the yield, efficiency, supply reliability and cost-effectiveness for a system.

Compared with surface storage, groundwater storage offers vast storage reserves, usually orders of magnitude larger than the available surface storage in most watersheds. These reserves can be used as a reliable source to reduce or eliminate surface water shortages. Moreover, the great natural storage capacity of the aquifers can be utilized to store excess surface water in wet periods, increasing ground water levels for use in subsequent dry periods.

The potential for conjunctive use of surface and groundwater has not been fully developed and implemented in many real water systems. Traditionally, groundwater has been used only as a backup supply for times of shortage. Perhaps reflecting the bygone eras of their design, most large water supply systems continue to depend exclusively on surface water (van der Leeden et al.1990). Some physical, institutional and legal constraints make implementation of efficient conjunctive use management difficult.

Planning and managing a complex water system with groundwater and surface water components entails considering many aspects (hydrological, operational, economic, legal, social, etc.). Over the past 30 years, a variety of simulation, optimization and linked simulation-optimization models have been applied widely to find operating strategies for conjunctive use. Simulation models approximate the behavior of the system combining mathematical equations for physical processes with predefined operation rules. Simulation allows representing the physical system in greater detail, and is mainly useful to refine and test alternatives.

The conjunctive use can also be formulated as an optimization model in which the decision variables are the groundwater and surface water allocation in each planning period. The optimal decision maximizes the objectives of the water resources system while satisfying the hydraulic equations of the surface and groundwater systems and any imposed operational constraints. Objectives may be system yield, system reliability or economic performance (maximize the net economic benefit).

Potential of Conjunctive Use

Groundwater can provides additional resources, as well as the means for water storage, distribution and treatment, which can be combined advantageously with surface water resources and facilities.

Hall and Dracup (1970) consider six different manageable resources in a groundwater basin: the safe yield, the volume of reserves (water capable of being mined), the long-term storage capacity, the transmission system, the water quality and the energy resource, represented by modified pumping lifts as the water levels fluctuate.

Aquifers provide a natural long-term water storage reservoir, without evaporation losses (excepts in very shallow aquifers). Efficient conjunctive operation leads to an increase in yield, which results from a reduction in loss from the freshwater system in the form of reduced flow to the ocean or salt sink and reduced evaporation from surface reservoirs (Coe 1990).

Water can be stored in aquifers directly through *active recharge or through in-lieu techniques*. A variety of artificial recharge methods are available (Todd 1980, Asano 1985). The United States has been traditionally the country with greatest development of artificial recharge techniques. California artificially recharges 1400 million cubic meters per year (CDWR 1998). The most common technique of artificial recharge involves infiltration from *spreading basins*, infiltration pits or ponding, into high-permeability, unconfined, alluvial aquifers. *Injection or recharge wells* are more expensive to build and operate. Another mechanism is *induced infiltration:* by pumping from a series of wells installed along side the stream channel, streamflow is induced into the groundwater body under the influence of the gradients set up by the well. In-lieu techniques involve the substitution of surface water for groundwater in wet years in areas that traditionally rely on supplemental groundwater pumping.

In low-flow periods, groundwater supplies can supplant surface water shortages, increasing the reliability of supply. Moreover, excess surface water in wet periods can be stored in groundwater reservoirs for use in later dry periods. By *alternating use* of surface and ground water, using more surface water in wet periods and more groundwater in dry periods, we can increase significantly the ability to store groundwater.

An example of alternating use is the one applied in the Mijares - Plana de Castellon water system, on Spanish Mediterranean coast (MMA 2000). La Plana is a littoral plain whose surface is 450 km^2, constituting the lower basin of the Mijares river and its tributary, the “Rambla de la Viuda”, a dry ravine. There are three surface reservoirs of 130, 52 and 38 millions of cubic meters (MCM) of capacity. Beneath the plain there is a heavily exploited unconfined aquifer with about the same surface area as the plain itself. Two of the reservoirs have important seepages into the ground, with contributing to the aquifer recharge. Likewise, the Mijares river has substantial seepage into the groundwater reservoir since piezometric heads are under streambed. Groundwater withdrawal increases in the driest years, while in wet years irrigation uses surface water for areas accesible by canals and ditches. The variation of water stored in the La Plana aquifer, between the end of a wet period and the end of a dry period of several years of duration, has reached about 700 MCM. This aquifer storage provides a high supply reliability. Two optimization models using linear and dynamic programming were used as screening tools for operation policies, and the selected alternatives were tested and refined with a more detailed simulation model (Andreu and Sahuquillo 1987).

Another kind of conjunctive use technique is to increase the yield by taking advantage of the lag between the pumping in an aquifer and the decrease in streamflow in the draining river. If the pumping is intermittent in the driest months, when water demand is higher and streamflow lower, part of the pumping effect takes places when the streamflow is higher. In this type of conjunctive use, knowledge of stream – aquifer interaction is essential to assess the water exchanges with accuracy.

The aquifer is also a natural distribution system, reducing need for artificial conveyance facilities. It is possible to recharge in a place above the aquifer and to use water from the aquifer in a well far from the recharge point.

Groundwater recharge can be used for treatment, because of the chemical and biological purification afforded by the passage of stream water through the unsaturated and saturated zones (Freeze and Cherry 1979). Another possible use of conjunctive operation is to improve final water quality by blending surface and ground waters of different qualities. Groundwater maintains relatively constant temperature and chemical quality, but contamination would be difficult to control and to correct.

Operational, Financial, Institutional and Legal Constraints

Coe (1990) summarizes some constraints in implementing conjunctive use programs, and describes four areas in California with groundwater basin overdraft and increasing water demands where conjunctive operations have been implemented (Santa Clara Valley, Los Angeles County coastal plain, and Orange and Kern Counties).

Llamas et al. (1992) identify some obstacles to effective management of groundwater:

- Lack of knowledge of basic principles of groundwater science among water planners

- Often, ownership and control of groundwater is in the private domain, so that codependence is unrecognized.

- Misunderstanding of the concept of overexploitation and conjunctive use.

Groundwater management practice has been developed under two distinct categories, based on the concepts of *safe-yield* and *mining* (Hall and Dracup 1970). Behind the safe-yield concept, annual groundwater withdrawals are limited to the quantity that keeps the basin essentially in equilibrium with the long-term natural recharge. On the other hand, the advocates of groundwater mining believe that groundwater usage should be initially maximized to build up a broad regional economic base. Once this regional economic base is established, larger facilities for importing surface water can be constructed to take advantage of economies of scale. However, these two concepts ignore the dynamic of the system, and result in water policies that underutilize or overutilize groundwater resources (Margat 1992, Sophocleuous 1997, Bredehoeft 1997). Some authors have encouraged consideration of the yield concept in a socioeconomic sense, introducing the concept of *optimal yield* within the overall framework of optimization theory (Freeze and Cherry 1979).

Some problems associated with overdrafting groundwater basins are land subsidence, seawater intrusion into coastal aquifer, deteriorating groundwater quality, and undesired environmental side effects. Land subsidence by compaction of clay layers or consolidation of unstructured sand and gravel formations (Freeze and Cherry 1979) can result in structural damage, drainage problems, increasing flooding and reduction of the aquifer storage capacity. Undesired effects are also the contravention of existing water rights and the deterioration of the economic advantages of pumping (Domenico 1972).

The inscrutable physical and legal nature of groundwater makes central planning difficult (Draper 2001). Groundwater basins have ill-defined extent, natural recharge cannot be measured directly and records of groundwater use are seldom complete. Most groundwater is extracted by individuals and is not regulated or managed by local agencies.

In most countries, the surface water infrastructure, groundwater and agriculture (the main water use) are under the jurisdiction of different departments/ministries. Also funding, design, construction and operation may be the responsibility of different agencies. Inadequate coordination and cooperation among governmental agencies may hinder implementation of conjunctive groundwater programs (Coe 1990).

There are also some *financial constraints*. Public funds are usually used for surface facilities while individual users finance groundwater facilities and pumping costs (Coe 1990).

Legal constraints can hinder implementation of conjunctive use management. Law governing groundwater is less advanced than law for surface water because of the complexity and lack of understanding of the mechanics of groundwater flow, and the private nature of groundwater development and ownership in many countries (Hall and Dracup 1970, Fredericks et al. 1998). In the United States, traditional doctrines are often criticized as being inadequate in light of current and anticipated management problems (Cox 1982).

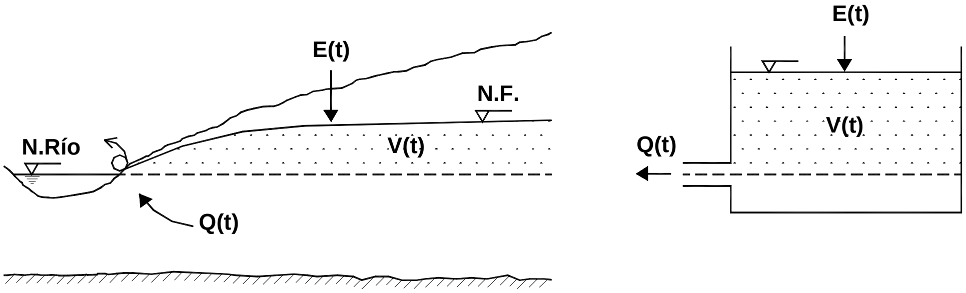
Although legal constraints to conjunctive use management could be difficult to overcome, appropriately adjusted economic prices and incentives may help to self-regulate groundwater and surface water use to mach conjunctive use objectives (Jenkins 1992). The relative prices of surface and groundwater can be adjusted so that water users should pay lower electricity rates for groundwater pumping in drought year periods and higher rates in dry periods (Basagaoglu et al. 1999, after Boyd 1991).

Aquifer Simulation in Water Management Models

In conjunctive use models, either optimization or simulation, surface and subsurface systems must be simulated simultaneously, due to hydraulic interactions between them and the combined operating rules inherent in such schemes. This has important computational implications. Thus, to derive optimal management alternatives or to evaluate many alternatives for global management over long periods of time, an efficient tool for aquifer simulation is needed (Andreu and Sahuquillo 1987).

Two types of models have been used to quantify stream-aquifer interaction, depending on the spatial detail and distribution of stresses considered: distributed and lumped models.

Lumped parameter models are mainly concern with the temporal allocation of water. They use a few parameters to represent the behavior of the system. The Unicellular Model (Fig. 2) is the simplest model that considers hydraulic stream-aquifer connection. It considers the aquifer as a reservoir with outflow proportional to the volume stored over the outlet. It is very simple, but it has been used in simulation and optimization models to indicate promising alternatives at an initial planning stage. Buras (1963) and Buras and Bear (1964) use this model in some of the earliest studies of optimization of conjunctive use of surface and groundwater, applying dynamic programming.



E(t): external stress; Q(t): aquifer discharge; V(t): water stored above the spring level

Fig. 2. Conceptualization of the Unicellular Model

Birtles and Reeves (1977) use a more complex model with a few cells, considering the system as “quasi-lumped”. Flow exchange among the cells depends on their piezometric heads, geometry and permeability, applying mass balance. Keating (1982) uses a unicellular model with non-linear relationships to consider the behavior of the Chalk in England, where the hydraulic conductivity and the storability decrease with the saturated thickness.

Lumped parameter groundwater models have also been used in economic models, typically to analyze the economic impacts of groundwater extraction on agricultural production (Provencher and Burt 1994).

To analyze a groundwater system with greater accuracy requires a distributed model, so that the spatial distribution of the aquifer and its hydrodynamic properties, the boundary conditions and the situation of external stresses, located in a point or distributed over a certain surface can be considered. Analytical, numerical and analog models have been used.

Analytical models estimate the system’s response explicitly. However, analytical models are only available for very simple cases, for homogeneous and isotropic aquifers; therefore, they are only useful for very preliminary studies, or where aquifer properties are not well known. Theis (1941) and Glover and Balmer (1954) develop an analytical solution for the case of a river perfectly connected and a fully penetrating homogeneous, isotropic and limitless aquifer, and determine the streamflow depletion by a constant pumping as a function of distance from the well to the river, duration of pumping, time of pumping and hydrodynamic properties of the aquifer. Jenkins (1968a) propones the use of a descriptor parameter of the system, which he calls SDF (Stream Depletion Factor), equivalent to the necessary time for continuous pumping to withdrawn from the river a water volume equal to the 28% of the pumped volume. The effect of pumping over the streamflow is given as a function of the pumping time divided by the SDF Jenkins (1968b) used an analog electric model of the alluvial of the Arkansas River, to estimate the effective values of the SDF parameter for each well. With the values obtained it is possible to prepare a map of the aquifer with lines of equal SDF that allows determining the effect of any pump over the streamflow. This approach has been applied to modeling conjunctive use, including influence function into optimization models by linear programming (Taylor 1974) and dynamic programming (Andreu 1982). The Glover-Jenkins model is a simple model easy to apply, but it has the disadvantage that the boundary conditions of the theoretical development imply an excessive simplification of the real conditions. Sophocleous (1995) compares the Glover analytical solution with the results obtained by a finite difference model, MODFLOW (McDonald and Harbough 1988), to assess the important of Glover´s assumptions.

When geometry and/or boundaries conditions are complex, or if the aquifer is non-homogenous, numerical models are needed. Distributed parameter groundwater models are predominantly simulations models that solve the governing partial differential equation of groundwater flow using finite element (FE) or finite difference (FD) techniques. By FE or FD, the spatial and time domain of the aquifer are discretized, and the groundwater flow equation is approximated by a system of linear equations to be solved sequentially in an iterative process with a given time step.

Two main techniques have been used to incorporate a distributed parameter groundwater in a management model: the “embedding method” and the “response matrix” method (Gorelick 1983).

In the “embedding method” the FD or FE approximations of the governing groundwater flow equation are embedded within the optimization model as part of the constraint set. The technique was described by Aguado and Remson (1974). Hydraulic heads at each cell (or node) at each time step are treated as decision variables, in addition to the stresses over the aquifer. This approach results in a very large constraint set with all the associated numerical solution difficulties, especially for large aquifer systems or for transient problems. Examples of the application of these techniques can be found in Aguado and Remson (1980), Willis and Liu (1984) or Peralta et al. (1995).

When linearity of a system can be accepted, the principles of superposition and translation in time are applicable. This allows use of influence functions or response matrixes as with other physical linear problems. The basic procedure consists on using the response functions of the physical components of the system to simulate the behavior of the whole system when it is subjected to different unit stresses. This is presented under different names by different authors. The response matrix method was proposed by Lee and Aronofsky (1958) and Aronofsky and Williams (1962) for petroleum-prospecting. However, it is not until the work of Chun et al. (1964) that it is used in groundwater hydrology for modeling the coastal aquifer of Los Angeles. Schwarz (1976) introduces the discrete form of the response function under the name of “influence coefficients”. Maddock (1972), using the Green function, defines an “algebraic technological function” that determines the drawdown at a point due to pumping in others and the latter pumping in those same points. Morel-Seytoux and Daly (1975) calls the method “discrete kernels” because the theoretical development of the expression is a convolution integral. They propose use of a finite-difference model, which they referred to as a discrete kernel generator, to develop the response matrix that generates the streamflow depletion in a river due to pumping in the aquifer. The model has been used in cases of conjunctive use of surface and groundwater (Illangasakare and Morel-Seytoux 1982, Frederiks et al. 1998).

The advantage of the influence functions or response matrix approach is that it uses the results from an external simulation model as a condensed tool in studies of other level s of detail. Unnecessary constraints or decision variables are not incorporated into the simulation – optimization conjunctive use model (Gorelick 1983). However, the use of influence functions implies consideration and storage in memory of all the influence functions and previous stresses. The number of influenced function to be stored is equal to the product of the number of excitations by the number of responses of interest. When the system is complex and the horizon time is long, this implies a great deal of computer memory and computation time. The latter can be avoided by applying a state equation that gives us the solution in an explicit way; this can be obtained by the Eigenvalue Method (Sahuquillo 1983a). In the *Eigenvalue Method*, contrary to the FD or FE methods, only space is discretized, and the linear differential groundwater flow equation is solved explicitly and continuously in time. Piezometric heads in the aquifer are expressed in a basis of orthogonal vectors, which are the eigenvectors of an algebraic eigenproblem, posed in terms of the aquifer properties, its spatial discretization and boundary conditions. The eigenproblem only needs to be solved once. External stresses and the previous state vector are explicitly transformed into a new state vector, through which piezometric heads and flux vectors can be obtained in the points/boundaries of interest, as well as surface and ground water interactions. This transformation is computed by a simple explicit state equation. Hence, there is no need for storing the influence functions and previous stresses over the aquifer. The method efficiently integrates aquifers in management models of complex water resources systems in which it is necessary to analyze several alternatives through important horizon times (Andreu and Sahuquillo 1987, Sahuquillo and Andreu 1988). This approach has been integrated in AQUATOOL (Andreu et al. 1996), a Decision Support System for water resources planning and management, used for the design of operational policies in complex systems as those of the Segura and Jucar river basins, in the southeast of Spain, with significant problem of water scarcities and important surface-groundwater interaction (Andreu et al., 1994).

In many cases, it is necessary to simplify models and adapt them to the level of available data. Frequently there is not enough hydrological information (either of surface water or ground water), neither operational, economical, or about the future demand evolution. In many cases it is possible to quantify stream-aquifer interaction by simple and operational expressions that yield adequately accurate results. The *Embedded Pluricellular Model* (Sahuquillo and Andreu 1988, Pulido et al. 2001) is a versatile conceptual model based on a semi-analytical solution of the differential groundwater flow equation for linear systems, as presented in the Eigenvalue Method, and on its analogy with the state equation of the Unicellular Model. This approach gives the solution to the problem of determining the stream-aquifer interaction in terms of a state vector. The interaction between surface and groundwater in any aquifer that can be assumed linear is analogous to the drainage of an infinite series of virtual cells or deposits with drainage coefficients α_i , among which the external stresses (pumping or recharge) are distributed proportionally to the allotment factors b_i. These coefficients can be calculated analytically in certain cases, or can be calibrated in others, as for kart aquifers (Estrela and Sahuquillo 1997). Then, it can be applied the same calculation process as in the unicellular case, just aggregating the results. For most practical cases, only a few cells are required to obtain satisfactory results.

Conjunctive Use Models

Gorelick (1983) distinguishes two categories of combined management models with distributed aquifer simulation: hydraulic management models and policy evaluation and allocation models. Hydraulic management models are principally concerned with managing flow, heads and mass transport in the aquifer. In contrast, policy evaluation and allocation models are mainly concerned with the economically efficient allocation of surface and groundwater resources.

A great variety of conjunctive use optimization models are available in the literature. Such models typically use linear, non-linear or dynamic techniques with a dynamic balance of relevant quantities (e.g. water flow, contaminant mass), appropriate constraints, and a single (usually economic) or a multiple (e.g. economic, social, target demand) objective (Lall 1995).

Linear programming has been the most widely used technique in conjunctive use optimization models. However, nonlinearities may arise due to the physical representation of the system or the cost structure for surface and groundwater use. Some important nonlinearities are:

- For a confined aquifer system, the confining equation is linear; hence, the resulting set of Finite Difference (or Finite Element) equations is also linear. For unconfined aquifers the relation between pumping and drawdown is nonlinear. However, we can assume linear behavior of the system when transmissivity and storage coefficients and the boundary conditions remain constant in time.

- Stream-aquifer interaction can be represented by a linear function of stream stage and groundwater elevation where groundwater level is at or above the streambed. However, the stream stage is a nonlinear function of discharge or reservoir release. Basagaoglu and Mariño (1999a, 1999b) uses time-variant reponse equations to incorporate stream stage variations into the management model, using a linear approximation of Manning´s equation.

- Economics-driven conjunctive use optimization models have to face the nonlinearity of the pumping costs, which is a function of the product of pumping head and pumping rate at the production well. The traditional approach is to express the drawdowns in terms of pumping rates using the response coefficients so as to express the objective function in a quadratic form. However, drawdowns are a function of not only well pumping rate but also the recharge to the aquifer, which depends on other variables (reservoir releases, percolation rates, infiltration from the recharge basin, etc). Basagaoglu and Mariño (1999b) eliminate this nonlinearity by using a polygonal approximation (δ-form approximating model).

- Stream-aquifer interaction is a linear function of stream stage and groundwater elevation provided that groundwater levels are at or above the streambed. If not, a nonlinear process takes place (shower effect).

- Nonlinearities in groundwater quality management are reviewed by Gorelick (1983).

For nonlinear systems, nonlinear programming (NLP) and differential DP (dynamic programming) have been applied (Yeh 1992). Alternatively separable programming techniques may lead to solutions using quadratic programming or by LP using piecewise approximations of the resulting quadratic functions. Application of classical DP to groundwater management problems is usually restricted to lumped parameter models, due to the constraints imposed by the “curse of the dimensionality” (Bellman 1957). Jones et al. (1987) developed a differential DP algorithm to overcome the dimensionality problem for solving a large scale, nonlinear optimization models.

Complex and detailed groundwater management decisions require groundwater to be represented at a level of detail afforded only by simulation models. In coupled simulation-optimization models, a simulation model reproduces the response of the aquifer and this information is used by the optimization model, usually and economic management model. The models either exchange data at each time step being the simulation model external or the response characteristic of the aquifer are incorporated into the surface water model using the response matrix approach.

Despite the many different optimization models and techniques that have been applied, most conjunctive use optimization work reported in the literature deal with hypothetical problems, simple cases or steady state problems. The lack of large-scale complex real-world conjunctive use optimization studies is probably due to the great size of the problem resulting when many nodes-cells and long time periods are under consideration for modeling groundwater flow and the interaction between surface and groundwater. Most conjunctive use models reported are created “ad hoc” for a particular problem. Only a few examples of generalized simulation models (in the way of a Decision Support System) for conjunctive use management including groundwater flow and surface and groundwater interaction have been reported (Andreu et al. 1996; Labadie et al., 1998). Generally, the models that can reproduce more detailed surface and groundwater interaction do not account for economic aspects of water allocation. Lastly, there is an absolute absence of generalized large-scale optimization models for conjunctive use in which the surface and groundwater interaction is included with significant detail.

Conclusion and Promising Areas of Research

Full development and implementation of conjunctive use of surface and groundwater must overcome operational, institutional, physical and legal constraints. Simulation and optimization models are being used to assess the benefits of conjunctive use management and to identify “optimal” operation policies or the capacity expansion of the system. Despite the proliferation of conjunctive use models with different system analysis techniques, efficient large-scale optimization models are missing. One of the most difficult problems to overcome is the efficient integration of simulation models of aquifers in large-scale optimization models.

Some of the promising areas of research are:

- Development of an efficient large scale generalized optimization model with an economics-driven objective function.

- The use of lumped parameter aquifer models as an initial approximation to identify alternatives of water allocation with economic efficiency.

- To find the optimal operation of the system, taking in account the effects of exploitation of the system, stream-aquifer interaction, the possibility of imposing constraints to groundwater exploitation for water quality, environmental or operational reasons, etc. is indispensable to couple the optimization model with a distributed simulation of the groundwater flow. This is indispensable also for making an accurate economic optimization (the pumping cost depends on the groundwater drawdown). For an efficient integration of aquifers in complex systems, the eigenvalue technique provides important advantages when incorporated in a simulation model (Andreu and Sahuquillo 1987). For its computational advantages and the structure of the explicit solution obtained, it seems to be a promising approach to couple an efficient aquifer simulation model in a large-scale conjunctive optimization model.

- Investigation of the importance of storage and deep percolation through the unsaturated zone in conjunctive use (Basagaoglu and Marino 1999b).

- Study of the ways of handle uncertainties associated with the random nature of streamflow and their influence on the derivate reservoir operation rules. Explicitly stochastic (e.g., Philbrick and Kitanidis 1998) and implicit stochastic models have been used (Lall 1995, Basagaoglu and Marino 1999a, Belaineh et al. 1999) to solve the stochastic control problem. However, these models use simplified reservoir operating rules, either linear decision rules or standard releases rules such as the standard linear operating policy. Draper (2001) presents a modification to the traditional implicit stochastic model that overcomes the problem of perfect foresight and incorporate consideration of risk in the prescribed reservoir operation.

- Integration of water quality constraints.

- Investigation of the importance of nonlinearities in conjunctive use (Basagaoglu and Marino 1999b). Important advances have been made in non-linear optimization techniques, which have evolved from the classical gradient-based methods (e.g., Bertsekas 1995), to non-gradient solution methods, such as the Simulated Annealing or Genetic Algorithms (Goldberg 1989). Some of these approaches, as well as the Artificial Neural Networks technique (Simpson 1990), have been recently applied to groundwater management for aquifer remediation (see review by Wagner 1995, and by Ahlfeld and Mulligan 2000), as well as to other fields of water resources analysis. How to employ the advances in non-linear optimization to couple distributed groundwater simulation models with the optimization formulation of a complex real-world conjunctive use seems to be a promising field to be explored for a more accurate estimation of the most economically efficient conjunctive use strategy in complex systems. The optimal strategy involves not only water quantity but also water quality considerations under an economic objective function.

- Due to the plateau in the objective function near the optimum, multiobjective programming can be useful in including another measures for the final decision (Cohon and Marks 1975, Yazicigil and Rasheeduddin 1987, Hippel 1992).

- Inclusion legal and institutional constraints in the model, and assessment of their cost and benefit. Analyze the externalities of conjunctive use policies.

III. ECONOMICS OF CONJUNCTIVE USE

Economic Valuation of Ground Water and Efficient Exploitation

Groundwater is a traditionally underpriced resource. A recent study by a committee of economists and ground water experts on ground water valuation (NRC 1997) suggests that such undervaluation has lead to misallocation of the resource in two ways: groundwater is not efficiently allocated relative to alternative current and future uses, and authorities responsible for resource management and protection devote inadequate attention and funding to maintaining ground water quality. As a result, pollution and depletion of aquifers largely continues. It is essential to study the total economic value of the resource for assessing the net benefits of management actions.

Following the categories established in NRC (1997), the Total Economic Value of groundwater is the sum of its *extractive values* and *in situ* values. Extractive values occur as a result of the extraction of groundwater and subsequent consumptive use. The *in situ* values are a consequence of leaving the water in the aquifer. The *extractive services* consist of municipal, agricultural and industrial uses. The efficient allocation of water to alternative uses requires information on relative values in these uses. Water is efficiently allocated when the marginal value of water is the same across all the uses. The optimal policy pursues to maximize net benefits (revenues minus costs) over time. The economic benefits from the allocation of groundwater and surface water can be expressed as the willingness of users to pay for the water or the area beneath the demand function for each water user. Costs include the cost of extracting and delivering ground water, and the opportunity or user cost. *In situ values* include ecological values, buffer values, values associated with the avoidance of subsidence, recreational values, existence values and bequest values (NRC 1997).

Since surface flows are stochastic, groundwater acts as important insurance to mitigate undesired fluctuations in the supply. Tsur and Graham-Tomasi (1991) define the *buffer value* of groundwater to be the difference between the maximal value of a stock of groundwater under uncertainty and its maximal value under certainty where the supply of surface water is stabilized in its mean. They have found that this buffer value can be significant. Using a dynamic model for fossil groundwater extraction in the Negev desert (Israel) they show that the buffer value can exceed 50% of the total value of the water stock, depending on the degree of surface water availability and the size of the groundwater stock; if it were ignored, groundwater would be seriously undervalued. Tsur (1990) states that, in general, the investment in groundwater should increase with the variability in the supply of surface water.

Environmental and recreational values also are becoming more widely recognized. Since 1960s economics have developed a variety of techniques for assessing the values of non-market good and services like natural resources or environmental attributes. These techniques are based on stated-preferences (direct methods) or on indirect methods that infer values from observed behavior of producers and consumers. The value measures are commonly expressed in terms of willingness to pay (WTP) or willingness to accept compensation for giving it up (WTA). A detailed discussion of some of these methods can be found in Freeman (1993). NRC (1997) explores several ground water valuation methods and the application of these techniques to a range of ground water services.

Increased withdrawals are causing problems such as *subsidence, salt water intrusion, and destruction of wildlife habitats.* Tsur and Zemel (1995) offer an economic analysis of optimal exploitation when extraction affects the probability of occurrence of an irreversible event, after which the resource can no longer be used (e.g., salt water intrusion). They conclude that uncertainty concerning the event occurrence has an important effect on optimal exploitation policies, given that exploitation policies under uncertainty are more conservative.

Groundwater use has some peculiarities that hinder its economically efficient exploitation. Groundwater resources typically are used by independent users pumping from a *common pool*; ground water is treated as an open access resource in which ownership is according to a rule of capture, with analogous problems to other nonexclusive resources as fisheries, common land for pasture or pollution. Such problems reflect what have been called the “tragedy of the commons” (Hardin, 1968). Pumpers have no incentive to conserve water in the aquifer. Competitive pumpers usually ignore opportunity or user costs, executing myopic pumping decisions: instead of maximizing the present value of all future net benefits, farmers simply pump water each year until the marginal cost of pumping equals the marginal physical product of water. Provencher and Burt (1993) identify three externalities under the common property arrangement that prevent the efficient exploitation of the resource. The pumping cost externality is a function of the piezometric head, the stocks externality exists where groundwater may be physically depleted, and the risk externality arises when a firm is risk averse. The risk externality would be unknown to a central control agency. Provencher and Burt (1993) suggest a creative and decentralized form of ground water management, where a private property rights regime may eliminate the stock externality (replacing the “rule of capture” by the law of supply and demand) and substantially reduce the cost of the risk externality. Young (1992) discusses possible “institutional arrangements” to coordinate the activities of individual users and how rules for limiting pumping can be monitored and enforced (taxes, subsidies, pumping permits, etc.).

Economic Aspects of the Conjunctive Use of Surface and Groundwater

Different kinds of operating strategies exist to accomplish effective conjunctive use of surface and ground water sources (some were reviewed in the previous chapter).

Some of the general economic advantages of conjunctive use were review by Todd (1956) and summarized by Maknoon and Burges (1978), including greater water conservation, smaller water storage and distribution system, better flood control, ready integration with existing development, less danger from dam failure, and better timing of availability of water for distribution. Conjunctive use schemes can provide other advantages, such as its adaptability to a progressive increase in water demand at a low cost, and the possibility of temporal overexploitation of aquifers to defer costly construction projects, mitigate the effects of droughts, or alleviate drainage problems (Sahuquillo 1985).

One form of conjunctive use that is becoming very important, especially in California, is groundwater banking. One example is the Kern Water Bank in Kern County of the San Joaquin Valley (California), a conjunctive water management program developed by the California Department of Water Resources, the Kern County Water Agency and several local water districts, to augment the reliability of the State Water Project (SWP) supply. SWP water will be released and stored underground in years of abundant supply. This is expected to increase ground water storage by up to one million acre-feet (WEF 1990). When surface water is scarce, the banked water will be pumped and used by SWP contractors. A simulation model based on network flow programming was developed to assist in the Kern Water Bank planning process (Andrews et al. 1992). Groundwater banking is a cost-effective method for increasing supply in some areas without constructing costly new facilities.

The main economic difference between ground and surface water projects is that, in general, initial investments are much lower for ground water, but operation and maintenance costs are higher. In surface water the initial investment is usually high and the operation and maintenance costs are small. An exception is that surface water treatment for urban uses usually requires higher energy and chemical costs (Sahuquillo 1989).

The traditional criterion for economically efficient allocation of a resource over time is to summarize benefits and costs to a present value through a discount factor. The decision of what discount rate to use is controversial (e.g., Howe 1971, Howe 1990, Zerbe and Dively 1994). The higher the discount rate, the greater the amount of the resource that will be allocated to earlier periods. However, a lower rate favors investment in projects involving a greater component of surface water, where groundwater projects are economically preferable for cases with limited capital and a high interest rate. The costs of transport, distribution and treatment should also be considered, which often tend to favor ground water (Sahuquillo 1989).

There are two main groundwater management objectives: maximization of net revenue and minimization of the cost of achieving some goal. Bredehoeft et al. (1995) analyze the differences between both approaches. In maximizing net benefits, demands are not fixed and the quantity to pump is one of the decisions. In minimizing the cost, the water demand is assumed to be fixed. Usually, the first approach is used in regional agricultural-management problems, while minimizing costs in the small scale, design problems.

For large agricultural areas, where the net benefit relates directly to the cost of obtaining the water and revenues come from irrigated crop, the objective function (net revenue) near the point of optimality may be nonunique. Instead, there is often a broad plateau where several solutions provide nearly equal benefits. Optimization models can suggests alternate near optimal policies and include other social or environmental benefits at a small cost. The shape of the net revenue function depends on the relative shape of the agricultural revenue function, generally concave (diminishing marginal returns), and the pumping cost function. The pumping cost function is a quadratic function of the pumping lift and the quantity of water pumped. As one uses more water, both pumping rate and pumping lift increase. Therefore, the pumping cost function will be convex. The resulting net benefit function will be concave or convex depending upon their relative magnitudes (see Ahlfeld and Mulligan, 2000 – pp.149–152, for a mathematical analysis on the convexity of the quadratic pumping cost function by analyzing the Hessian terms of its first-order Taylor approximation).

Cost Structure of Surface and Groundwater Exploitation

Pumping cost

Given that the demand for irrigation water can be significantly elastic in the price of water (Howitt et al. 1980), the cost of ground water pumping can be a key factor in water decisions.

Fixed costs include the capital cost for installing and developing a well field (which becomes sunk cost once the infrastructure is ready), the depreciation of investments, staff expenditure and fixed maintenance costs (Sanchez 1989). The variable costs correspond to the energy used in pumping and the accelerated maintenance associated with mechanical wear. The pumping cost is proportional to the total quantity pumped and the total lift. Many studies assume that total lift remains constant over all times periods, ignoring the additional expenditures necessary to overcome drawdowns, underestimating the expected cost “by a sizable margin” (Maddock 1974). The energy required for extracting water from a well has the following five components (Harter 2001): the sub-regional average depth to water, the pumping drawdown created in the aquifer formation surrounding the well, the head losses due to flow restrictions along the well borehole, well pack and well screen (well losses), the additional discharge pressure required and the pumping plant efficiency. Well losses can be evaluated by an step-drawdown test (Todd 1980, Driscoll 1986), and are usually reported as well efficiency or ratio of aquifer pumping drawdown and total drawdown. They are typically proportional to the square of the well pumping rate. Harter (2001) finds that well efficiencies for agricultural wells typically range from 30% to 70%, and suggest as a first approximation to use a well efficiency of 50% (well loss equal to pumping drawdown).

It is necessary to be cautious when estimating pumping costs from local drawdowns given by numerical simulation models. The models yield average values over discrete cells or elements, but do not account for in-well drawdowns, the interference between neighbor wells due to overlapping cones of depression, or well losses. Gorelick (1983) reported two techniques to estimate of in-well drawdowns using simulation models in conjunction with analytic solutions. In one technique hydraulic heads are computed using simulation followed by a correction based on analytic solution for radial flows conditions. In the second technique the analytic drawdown correction is added to the original finite difference or finite element formulation.

In calculating unit pumping cost, Basagaoglu et al. (1999) assume that the energy needed to lift 1 m^3/s of water vertically to a height of 1m in one second is 2.80 W-h, and then use and wire-to-wire efficiency of 0.55 and an electric cost 0.03 $ /KWH in dry and 0.09

$/KWH in wet periods. The reason for this seasonal energy cost is the strategy of imposing higher unit pumping costs and lower O&M costs in wet periods and the contrary in dry periods to encourage an alternative conjunctive use of the resources, with more surface water use in wet periods and more groundwater during droughts. Jenkins et al. (2001) apply in their economically driven optimization model CALVIN for California´s great water inter-tied system an estimate of $0.20 per acre-foot per foot of lift for operation and maintenance of groundwater pumping in the agricultural sector, including an average $0.20/KWH/af energy cost, as statewide average value from several reference sources.

Recharge cost

Recharge cost is highly variable, depending on the methods used and the site available for the recharge program. Methods may include surface spreading, injection, and enhanced natural recharge (see for example Asano 1985). The cost of artificial recharge must include the O&M cost, the water diversion cost and the opportunity cost of the water itself and of the land that is taken.

In a recent study, Philbrick and Kitanidis (1998) use a constant marginal cost of $40/ac-ft to account for the cost of water treatment (previous to recharge), maintenance of facilities (eg. resurfacing spreading ponds to reduce clogging), pumping to deliver water to the recharge sites, or water purchase. In the case of injections well, the energy cost of injection can be assumed to be negligible when upper and lower limits on drawdown are imposed to prevent pressurized injection (Basagaoglu and Mariño 1999).

Jenkins et al. (2001) apply in the CALVIN model for California´s water system two levels of operating cost for recharge facilities as a first approximation: $5/af in rural areas and in places that manage natural streambeds as recharge areas, and $10/af in urban areas and in those rural areas or managed streambeds known to have extensive recharge facilities. The higher $10/af cost reflects the higher value of urban land and higher operating cost in urban areas. Where treated wastewater is directly recharged to the aquifer, an incremental treatment cost (over the usual treatment of effluent to discharge to a water body) is assed at $33/af.

Several models have been developed to study the potential benefit from artificial recharge (eg., Botzan et al. 1999).

Water supply operating costs

The CALVIN model of California´s water system neglects variable costs for agricultural water supplied since most irrigation district surface water costs are minimal (capital, administrative and other fixed cost are excluded in and analysis of water management). Urban water variable operating cost address three components: water treatment cost, water quality damage related to salinity, and local distribution cost (estimated from USBR 1997).

Basagaoglu et al. (1999) use a linear relation between the annual OMR (Operation, Maintenance and Replacement) costs and annual target water demands, based on the assumptions of Maass et al. (1962). In other occasions, the OMR costs are assume to be a fixed percentage all the capital costs. This assumption is less tenable for channel than for reservoirs: the smaller the scale of the channel, the greater the ratio of OMR cost to capital cost (Maass et al. 1962, p.320).

Conjunctive Use Management Models

In this section, a review of some important works on conjunctive use optimization for maximizing the net revenue of water use is presented. This review focuses on quantity management. Bredehoeft et al. (1995) review models for quality management.

Castle and Lindeborg (1960) made one of the earliest studies of conjunctive use optimization applying linear programming to allocate ground water and surface water between to agricultural areas, assuming that water users in the two areas would expand their use of other inputs of production in proportion to the increases in supplied water. Buras (1963) applied dynamic programming for the conjunctive supply from a reservoir and an aquifer to two agricultural areas to find design criteria (optimum size of the dam and recharge facilities) and operation policies (reservoir releases and aquifer pumping). Burt (1964a, 1964b) use dynamic programming to maximize a net function by solving an inventory problem with two storage capacities, an aquifer and a surface reservoir. The model considers benefits derived not only from the use of water but also from its conservation. Groundwater is produced to a point where the marginal cost of pumping equals the marginal cost of storing ground water. Burt (1966) extended this work to a temporal allocation of ground water applying dynamic programming. Chun et al. (1964) introduce use of the response matrix approach in groundwater hydrology for modeling the coastal aquifer of Los Angeles to obtain the most economical combination of storage and pumping facilities operation. Dracup (1966) developed a parametric linear programming model using as decision variables the optimal quantity of four sources (surface water, pumped water, imported water, and wastewater reclamation) to be allocated to four uses (municipal and industrial demands, agricultural demand and artificial recharge to the groundwater basin), considering pumping cost as constant over time. Trade-offs between multiple objectives were examined were analyzed by changing cost coefficients.

The first work to include distributed parameter groundwater simulation in the optimization of agricultural revenues was by Bredehoeft and Young (1970) and Young and Bredehoeft (1972). They developed a simulation model incorporating stream-aquifer interaction, the stochastic properties of surface flow, and the response of water users to hydrologic, economic and institutional conditions for the South Platte system in Colorado. The economic model reflects two stages. In the planning-stage, a linear programming model determines the type of crop and the acreage planted within the constraints of expected water availability, farms programs and physical production response parameters. In the second stage a monthly operating model allocates water to crops. Bredehoeft and Young (1983) updated their 1972 model by considering the influence of uncertain surface water supplies in motivating farmers´ investment in groundwater capacity. These models, however, are simulation models and, therefore, they do not guarantee an optimal solution.

Maddock (1972) developed a quadratic programming model to minimize the present value of pumping cost in the operation of an stream-aquifer system under stochastic demand and supply. In this study he introduced the use of algebraic technological functions (response equations) to incorporate the simulation of the aquifer behavior into the optimization model. The solution provides operating rules for stream diversions, groundwater withdrawals, return flow to the stream, and spreading. The discounted expected cost and the operation rules are functions not only of the expected value of the demand, but also of its variance and persistence. Maddock (1974) derives the nonlinear response function for the unconfined case in the form of an infinite series.

Noel and Howitt (1982) formulate an optimal linear-quadratic control model for conjunctive multibasin management in Yolo County (California), comparing two methods (analytic solution and mathematical programming). A linear programming model is used to estimate the derived demand for agricultural water use through parametric analysis. In the control model, the quadratic objective function is an explicit economic measure of social welfare, including the stock opportunity cost by defining the present value of the stream of pumping costs as the user cost associated with changes in groundwater storage. The linear program is linked with the control model in two ways: the derived demands from the programming model are part of the control objective function and the control model feeds back optimal supplies of water as water constraints and their related costs to update the linear programming model. A separated finite element groundwater model calculates the subsurface flow. The authors conclude that the optimal control approach provides a more realistic specification of the hydrologic system and additional economic information over the dynamic programming technique, which severely limits the number of state and control variables that can be specified.

More recent studies have incorporated aspects of distributed parameters groundwater simulation directly into an agricultural optimization model. Some of them are commented in Bredehoeft et al. (1995), who include a summary of net benefits reported in the literature from different studies concerned with maximizing agricultural revenues by use of conjunctive use management models. Constrained equations use either response matrix or embedded approaches (Gorelick 1983).

Simplified Lumped Models for Economic Analysis

Some studies have used simplified lumped parameter systems, usually with a single-cell groundwater basin, to test how net agricultural revenues can be improved by optimizing conjunctive use of surface and ground water. These models vary considerably in sophistication. Some precedents are the works by Buras (1963) and Burt (1964a and 1964b), mentioned above. Some of these models analyze optimal withdrawals with stochastic surface supplies but do not consider the possibility of artificial recharge of surface supplies to the aquifer (Tsur and Graham-Tomasi 1991; Provencher and Burt 1993). In Knapp and Olson (1995), annual recharge and extraction volumes are the decision variables. They use a stochastic dynamic programming model for the optimal operation of the Kern County aquifer (California). The authors analyze the effect of energy cost on the withdrawal-recharge decisions as a function of the hydraulic head in the aquifer and the surface flows. Optimal withdrawals are found to be generally increasing in hydraulic head and deceasing in surface flows, although nonmonotone behavior is observed in some instances. At low head elevation it is profitable to store water by recharge, as there is insufficient stock to buffer the random surface water availability. Intermediate head levels imply enough water to buffer surface flows but pumping costs remain high so that the marginal benefits from recharge are low. At higher heads pumping cost are low and expected future withdrawals are large so that marginal benefits from recharge are again high. Another factor that influences the level of recharge is the shape of the demand curve. If demand is elastic at low prices and inelastic at high prices this would increase the recharge.

Provencher and Burt (1994) consider a three-cell model for three interrelated aquifers in Madera County (California), applying a policy iteration dynamic programming approach where the value function is estimated by Monte Carlo simulation. They compare this approach with a Taylor series approximation to the functional equation of DP (first suggested by Burt (1964b) for a single aquifer), which reduces the problem, given an observed state, to solving a system of equations once. The results include an analysis of how cropping patterns evolve in response to the availability of water.

The simplifications and assumptions inherent in treating the groundwater system as a single cell need to be considered when analyzing the results of these studies (Bredehoeft et al. 1995).

Conclusions

Conjunctive use optimization models can demonstrate the economic benefits of operating strategies that consider coordinated use of surface and ground waters. Lumped-parameter groundwater models are useful to indicate potential benefits. As it has been reported, theoretical models have been developed to study the optimal extraction of groundwater over time and to test the efficiency of proposed policy instruments to deal with the economically inefficient common property exploitation of groundwater. More detailed distributed models of groundwater are required to define complex conjunctive management decisions, while allowing quantification of the impacts of conjunctive use on the system.

IV. MODELING CONJUNCTIVE USE IN SOUTHERN CALIFORNIA

CALVIN Model Overview

CALVIN (CALifornia Value Integrated Network Model) is a network-flow based economic-engineering optimization model developed at the University of California, Davis (Howitt et al. 1999, Jenkins et al. 2001). The model explicitly integrates the operation of water facilities, resources and demands for California´s main inter-tied water system. It combines year 2020 economic values for agricultural and urban demands with year 2020 infrastructure, operating costs and hydrology to suggest economically optimal water operations and allocations. Operation and allocation decisions are made monthly over the 1992-1993 range of hydrologic events, and are limited by environmental flow requirements and facility capacities.

CALVIN uses HEC-PRM, Hydrologic Engineering Center – Prescriptive Reservoir Model (USACE 1994), a network flow optimization solver with gains and losses (generalized network-flow optimization). The solver minimizes the cost of all flows in the network each weighted by a unit cost that can vary between arcs. Mathematically the optimization problem can be expressed as:

$$\text{Min } Z = \sum_{I} \sum_{J} c_{ij} X_{ij}$$

subject to: $\sum_{i} X_{ji} = \sum_{i} a_{ij} X_{ij} + b_j$ for all nodes j (conservation of mass at each node)

$X_{ij} \leq u_{ij}$ (upper bound on arc ij) , for all arcs

$X_{ij} \leq l_{ij}$ (upper bound on arc ij), for all arcs

where Z is the total cost of flows through the network, X_{ij} is the flow leaving node i towards node j, c_{ij} = unit economic costs, b_j = external inflow to node j, a_{ij} = gain/losses coefficient on flows in arc ij.

To represent the system to be optimized, CALVIN requires a multitude of physical and economic input parameters. Physical parameters include infrastructure facilities, hydrology and environmental requirements. Economic parameters include penalty-demand functions and variable operating costs. Fig. 3 summarizes the input data requirement, as well as the output produced. Generated monthly time series of flows, storages, scarcities, scarcity costs, marginal values, and willingness-to-pay results are post-processed, providing considerable information and insight for policy and operations planning.

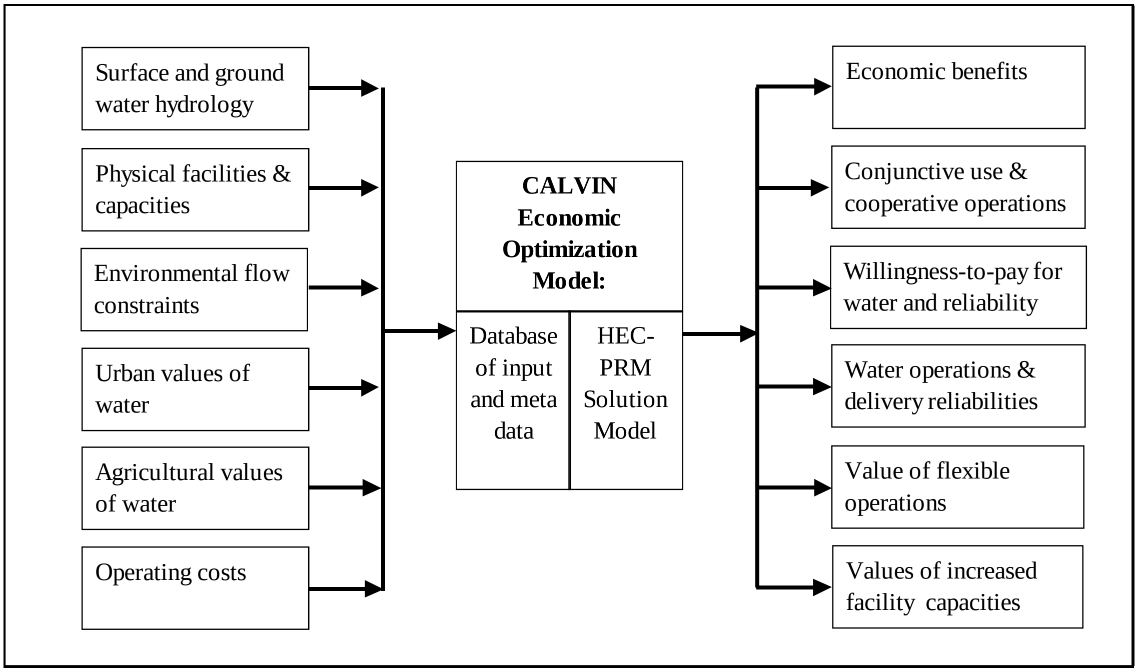


Fig. 3. CALVIN Input/Output Data flow

Fig. 4 shows an example network diagram for CALVIN. The main elements are storage nodes, junction nodes, demands and links. Storage nodes represents both surface and groundwater reservoirs. Junction nodes may be pumping plants, diversion points, confluences or forks in pipelines, channels and rivers, with only the constraint of mass balance. Demands are represented by penalty functions, which allow assigning a penalty to any delivery below a target or maximum demand. Links may represent a river, artificial channel or pipeline, and are constraints by minimum and maximum flow. Costs for pumping, treatment and delivery are placed on the arcs entering demands or on other links, as appropriate.

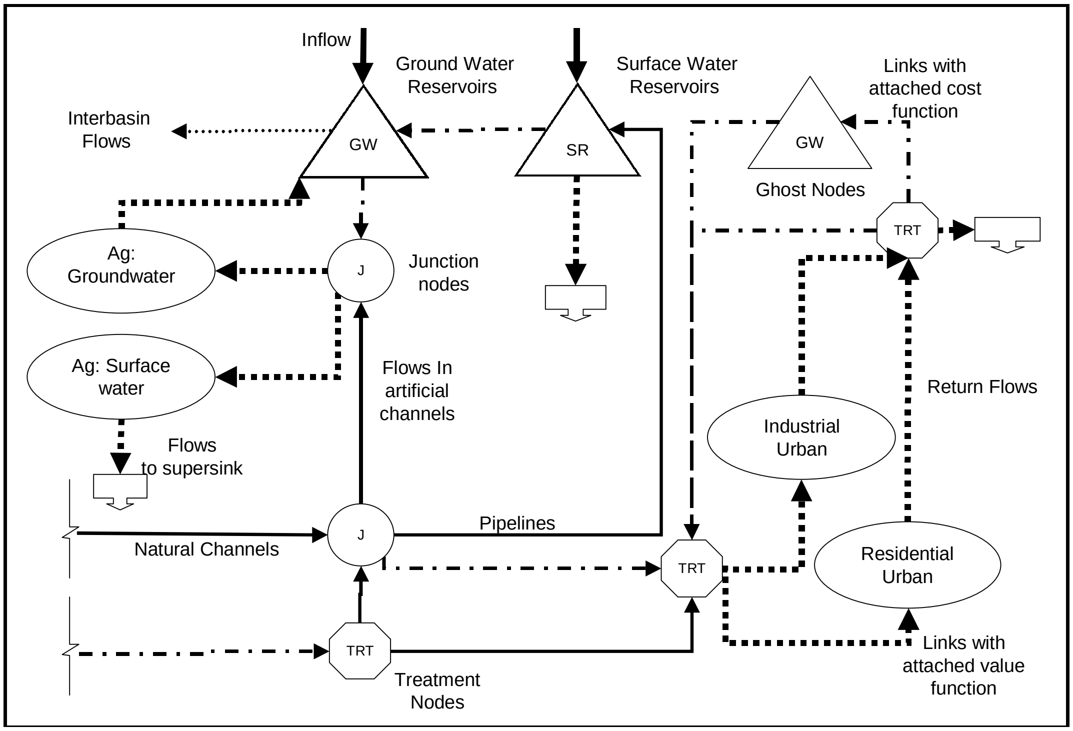


Fig. 4. Example Schematic diagram for CALVIN (after Newlin 2000)

A detailed description of CALVIN's conceptual framework, applications and limitations can be found elsewhere (Howitt et al 1999, Jenkins et a. 2001).

Optimizing Conjunctive Use in CALVIN

CALVIN automatically achieves optimal conjunctive use operation by maximizing the net economic benefits of water deliveries to agricultural and water users, within the limits of the infrastructure, and environmental and other constraints imposed to the model. The facilities represented in CALVIN include surface and groundwater reservoirs, conveyance facilities (canals and pipelines), and pumping, recycling, and recharge facilities.

CALVIN models results are idealized in the sense of perfect foresight. The model yields the optimal storages, flows and diversions over a 72-year period simultaneously. It effectively has no hydrologic uncertainties, allowing the system to operate in advance for droughts and surplus. This limitation is discussed in more detail in a later section (Chapter 8).

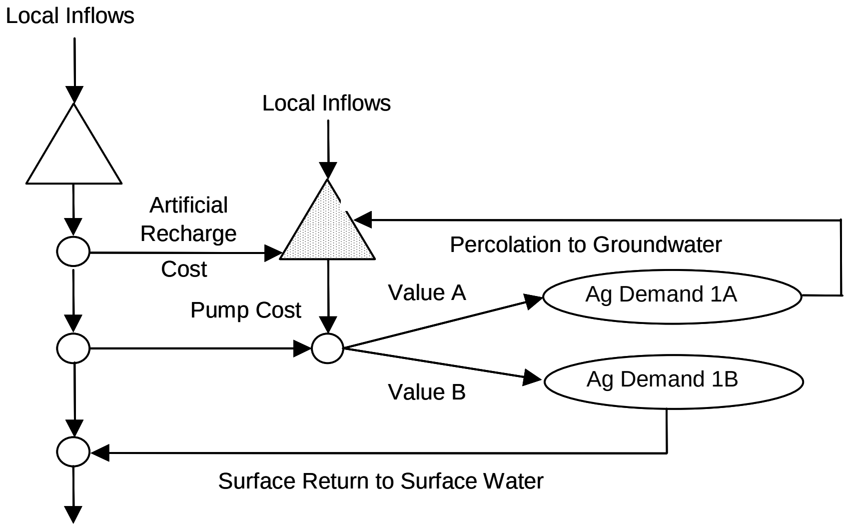
Groundwater is fully integrated with surface water and demands. Groundwater basins are represented as lumped reservoirs with a certain capacity, and treated in the same manner as surface reservoirs. The unit pumping cost is assumed to be constant (fixed head), and it is calculated for an average depth to groundwater. The model is incapable of dynamic stream-aquifer interaction and dynamic inter-basins flows. In some cases recoverable conveyance losses, inter-basin flows, streamflow exchanges and deep percolation from rainfall have been preprocessed into a fixed time series of monthly groundwater inflows.

The highly simplified representation of the aquifers is determined mainly by the limitations imposed by the network flow solver, and also the lack of data either for the groundwater hydrology or for the current exploitation and overdraft condition. This lack of information is especially significant in the Tulare Basin Region and in areas of Southern California.

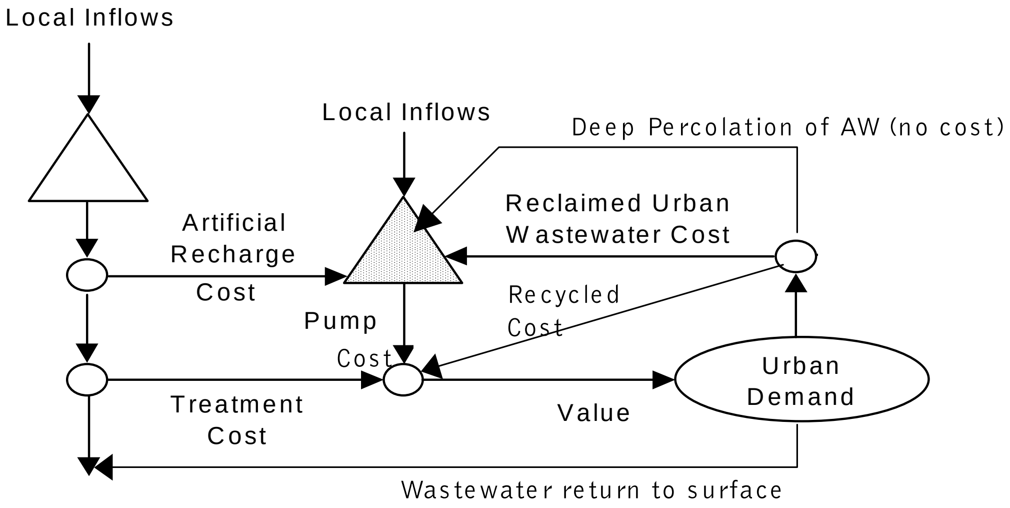
Fig. 5 shows the main elements that interact with the groundwater reservoirs. Six groundwater-related components are required to run CALVIN: storage characteristics (initial storage, storage capacity and ending storage), percolation of applied and urban agricultural water, local inflows (preprocessed fixed monthly time series of net recharge), inter-subbasin flows, artificial recharge characteristics (capacity and cost), and pumping characteristics (capacity and cost).

A fixed 5% loss has been added to all artificial recharge facilities to account for evaporation, seepage to other aquifers, and other possible losses.

Agricultural Sector



Urban Sector



Notes: 1. Triangles represent reservoirs. Groundwater reservoirs are shaded. Arrows indicate links (possible flow lines).
2. Calibration nodes are not depicted in the schematics.
3 In the current formulation of CALVIN, inter-subbasin flow between groundwater subbasins is included in the local inflows.

Fig. 5. Groundwater interaction with other elements in CALVIN (from Jenkins et al. 2001)

The inputs required to model surface reservoir operations are: maximum and minimum storage levels (usually the maximum refers to the top of the conservation pool, and the minimum to the dead storage level), initial and final storage, elevation-area-capacity relationship, and monthly evaporation rate.

Modeling Approach

The model presented here is based on a previous model of Southern California (Newlin 2000). The model has been completed with added infrastructure in a few cases (for example, the Coachella supply system has been modified to improve representation of the groundwater recharge, and use of Coachella Canal water for golf irrigation), corrections, and other improvements.

The representation of the current operation policy for the State Water Project (California Aqueduct) has been updated with new data from the CALSIM II Benchmark Study (DWR 2002) in the Base Case alternative. CALSIM is the California's DWR and Bureau of Reclamation computer simulation model for operating, planning and managing water supply and water quality in the State Water Project and Central Valley Project (DWR Web Site). Deliveries and surface water storages in the SWP are constrained to the time series obtained in the CALSIM study for year 2020 demands. This update has also redefined the SWP inflows to the system from North of the Tehachapis to Southern California. The average annual SWP inflow to Southern California is now 61 taf/yr lower than the one corresponding to the DWR Simulation Model (DWRSIM, run 514a), employed in previous CALVIN studies (Howitt et al. 1999, Jenkins et al. 2001). Table 1 displays the annual average and monthly extreme delivery values from the CALSIM and DWRSIM studies.

Table 1. CALSIM (II Benchmark Study) andd DWRSIM (run 514a) deliveries

	CALVIN ELEMENTS	**SR-25**	**SR-27**	**SR-28**	**SR-29**	**D888_C161**
		Silverwood Lake	Lake Perris	Pyramid Lake	Pyramid Lake	Castaic Lake to MWD
ANNUAL AVERAGE	DWRSIM	731.9	1,400.1	2,008.6	3,717.3	590.7
	CALSIM II	711.9	1,376.1	2,007.0	3,713.6	579.7
	difference	20.0	24.0	1.6	3.7	11.0
MONTHLY MAX	DWRSIM	73.0	127.0	170.0	324.0	86.3
	CALSIM II	73.0	127.0	170.0	324.0	91.4
	difference	0.0	0.0	0.0	0.0	-5.1
MONTHLY MIN	DWRSIM	44.0	98.0	95.0	294.0	3.5
	CALSIM II	44.0	86.0	95.0	294.0	8.4
	difference	0.0	12.0	0.0	0.0	-4.9
	CALSIM EQUIVALENT	S25	S27	S28	S29	D895

	CALVIN ELEMENTS	**C136_C145**	**D888_D889**	**SR-29_C106**	**SR-28_C106**	**DEVIL PWP_C129**
		CRA to Coachella Urban	Urban Penalty	Castaic Lk to Ventura	Pyramid Lk to Ventura	SWP East Branch
ANNUAL AVERAGE	DWRSIM	58.3	44.4	12.2	3.6	1,199.7
	CALSIM II	51.7	32.6	11.9	3.5	1,162.6
	difference	6.6	11.8	0.2	0.0	37.1
MONTHLY MAX	DWRSIM	12.2	7.4	1.9	1.6	172.8
	CALSIM II	12.3	5.3	2.1	2.0	172.8
	difference	0.0	2.1	-0.1	-0.4	0.0
MONTHLY MIN	DWRSIM	0.2	0.2	0.0	0.0	11.1
	CALSIM II	0.9	0.4	0.1	0.0	10.2
	difference	-0.7	-0.3	-0.1	0.0	0.8
	CALSIM EQUIVALENT	D883_D884	D896	D29	D28	C25

To look at the potential of conjunctive use in the region, new groundwater storage facilities have been considered, along the Colorado River (Cadiz, Upper Chuckwalla and

Hayfield) and north of the Tehachapi Mountains (aggregating Kern, Semitropic and Arvin/Edison groundwater basins). Recharge and pumping facilities have been incorporated for these new groundwater basins. Likewise, other projected future facilities have been added in the corresponding model alternatives (new recharge capabilities, recycling facilities, etc.).

Fig. 6 shows the updated CALVIN schematic corresponding to Southern California water system (base case), using a network diagram.

The region modeled comprises the main inter-tied water supply and demand system, from the Tehachapi Mountains to the Mexican border, including the State Water Project supply from above the Tehachapi's, and the Colorado River and the Eastern Sierra supplies, together with the major urban and agricultural demands.

Infrastructure

Surface reservoirs

16 surface storages nodes are included in the Southern California CALVIN representation. From these, 13 are storage reservoirs (Table 2). Owens Lake (SR-OL), Mono Lake (SR-ML), and SR-SS (Salton Sea Lake) are also represented.

Table 2. Southern California Surface Reservoirs included in CALVIN

Surface Water Reservoirs			
CALVIN name	Description	Minimum Capacity (taf)	Maximum Capacity (taf)
SR-25	Silverwood Lake	44	73
SR-27	Lake Perris	31	127
SR-28	Pyramid Lake	95	170
SR-29	Castaic Lake	294	324
SR-CR3[a]	Colorado River Storage	0	4,440
SR-ER	Diamond Valley Reservoir (Eastside Reservoir)	400	800
SR-GL	Grant Lake	5	48
SR-LA	Aggregate Los Angeles Reservoir	10	103
SR-LC	Long Valley Reservoir (Lake Crowley)	18	183
SR-LM	Lake Mathews of MWDSC	79	182
SR-LSK	Lake Skinner	34	44

The operation of the SWP reservoirs is constrained in the Base Case, according to the simulated CALSIM storage time series. The constrained Base Case end of period storage is used in these reservoirs as the ending storage condition for the unconstrained runs. In the remaining surface reservoirs the ending storage is set equal to the initial storage to avoid water depletion at the end of the optimized period. Initial storage was assumed to be 50 % of the maximum usable storage (maximum storage minus the dead pool storage). Groundwater reservoirs are discussed in groundwater representation section.

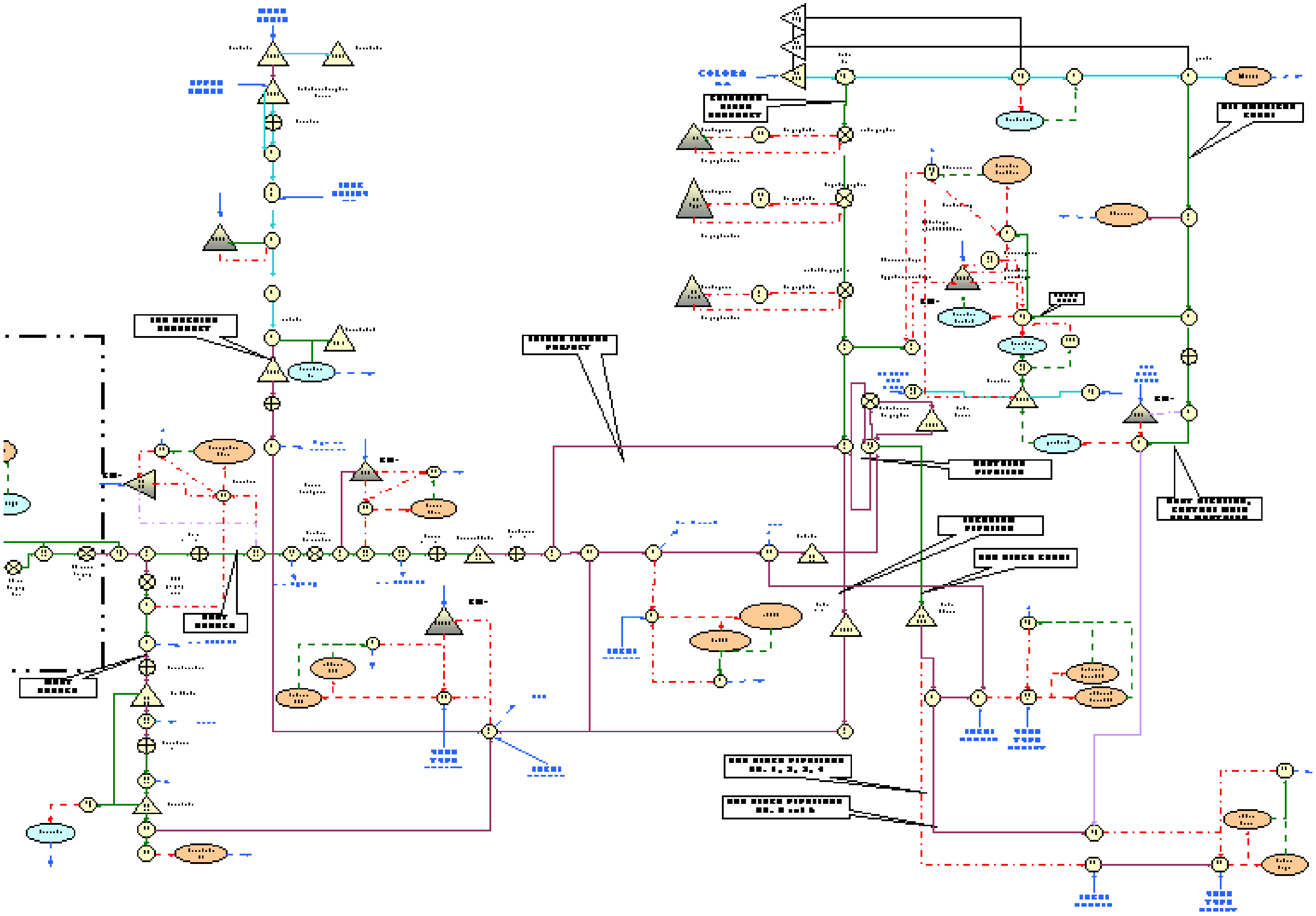


Fig. 6. CALVIN updated schematic for Southern California

Conveyance

The conveyance infrastructure in this model includes canals and pipelines, pumping and power plants, agricultural and urban diversions, recycling facilities and groundwater pumping and recharge facilities.

Hydrology inputs

CALVIN uses monthly data from 1921 to 1993 for both surface and groundwater inflows. This period includes three severe droughts: 1928-1934, 1976-1977, and 1987-1992 (DWR 1998).

Most of Southern California's water supply depends on imports (approx. 70%). Water imported to the system includes SWP, Colorado River and LA Aqueduct imports. Each of these three imported sources is allocated by different policies (Newlin 2000). The current operation and allocation policies are implicitly incorporated into the model for the constrained Base Case by constraining flows, storages and deliveries according to CALSIM results.

SWP imports are incorporated by a monthly time series inflow entering from north of the Tehachapi Mountains, which corresponds to the California Aqueduct supply. This supply is split between the East Branch and the Coastal Branch of the Aqueduct. A single inflow is also added to represent SWP Coastal Branch supply to Castaic Lake Water Agency (mainly supplied by the California Aqueduct West Branch).

Colorado River allocation to the region is represented by a single source entering at Parker Dam on the California-Arizona border. An annual 4.4 maf inflow enters California. For the constrained Base Case, this quantity is distributed throughout the year by three virtual reservoirs, used to mimic the different tiers of priorities in accordance with the Seven Party Agreement. In the constrained Base Case, 3.55 maf of Colorado River is allocated to agriculture (CVWD, PVID, and IID), and 0.85 maf is allocated to urban (MWDSC and SDCWA). In the unconstrained runs these proportions can change, allowing water transfers between agricultural and urban demands. This transfer is limited by the MWDSC Colorado Aqueduct's conveyance capacity. In any case, each annual allotment must be depleted by September.

LAA supply is aggregated in a single inflow for the constrained Base Case. A more detailed representation of the Aqueduct is included in the unconstrained case, in which the inflows from the Owens and Mono Basins are aggregated into three different inflows (Mono Basin, Upper Lowens River, and Long Valley to Haiwee).

Local surface water supplies are available only in the South Coast Hydrologic Region, where coastal range streams represent approximately six percent of supply (DWR 1998). In the model, surface local inflows are included for the three MWD demands.

Groundwater local inflows are lumped estimates of average groundwater recharge from different sources. They are discussed in the following section.

Groundwater Representation

In the Base Case, six groundwater storage basins (GWSB) are included: Mojave (GW-MJ), Coachella (GW-CH), Imperial (GW-IM), Metropolitan (GW-MWD), Owens (GW-OW), and Antelope (GW-AV). In these basins, ending storage is set equal to initial storage to prevent long-term depletion or mining.

Existing Groundwater Storage Capacity

GW-MWD represents additional empty groundwater storage capacity in MWD local area basins that could be used for additional conjunctive use operations, which is identified as 1,450 taf (MWDSC 1997). No additional local inflows are considered, since these basin's yield is already included in the preprocessed surface local supplies to each of the three MWD areas represented in CALVIN.

GW-MWD (Mojave) currently has an available storage of 1.79 maf (AGWA 2000). It is the source of supply of the Mojave urban demand. The basin is recharged from diverted water of the East Branch of the SWP (Mojave has SWP entitlement) through four recharge facilities, and also by direct streamflow percolation in the Mojave River. A single annual local recharge estimate (72 taf/yr) is monthly distributed based on precipitation as a local inflow.

GW-CH (Coachella) has 0.5 maf of potential storage capacity for MWD, according to MWDSC (2002). It is the main source of supply in the Coachella Valley. The groundwater local inflow is obtained from a single annual recharge estimate (33 taf/yr) that is distributed monthly based on precipitation. The water used for recharge comes mainly from the Colorado River Aqueduct, in exchange for SWP water with MWD. Through its recharge facility in the Upper Valley (Whitewater Spreading facility), CVWD (Coachella Valley Water District) and DWA (Desert Water Agency) are able to recharge up to 300 taf/yr (CVWD 2000). As part of the planning process, CVWD presented in its Water Management Plant (CVWD 2000) a series of planning and management alternatives, and a preferred alternative has been identified under the criteria of ability to eliminate groundwater overdraft and associated adverse impacts, ability to maximize conjunctive use opportunities, and economic and environmental impacts. The preferred alternative includes water conservation, groundwater recharge, and source substitution management elements. Based on this alternative, Fig. 7 shows the schematic developed to include the Coachella subsystem in the Southern California model.

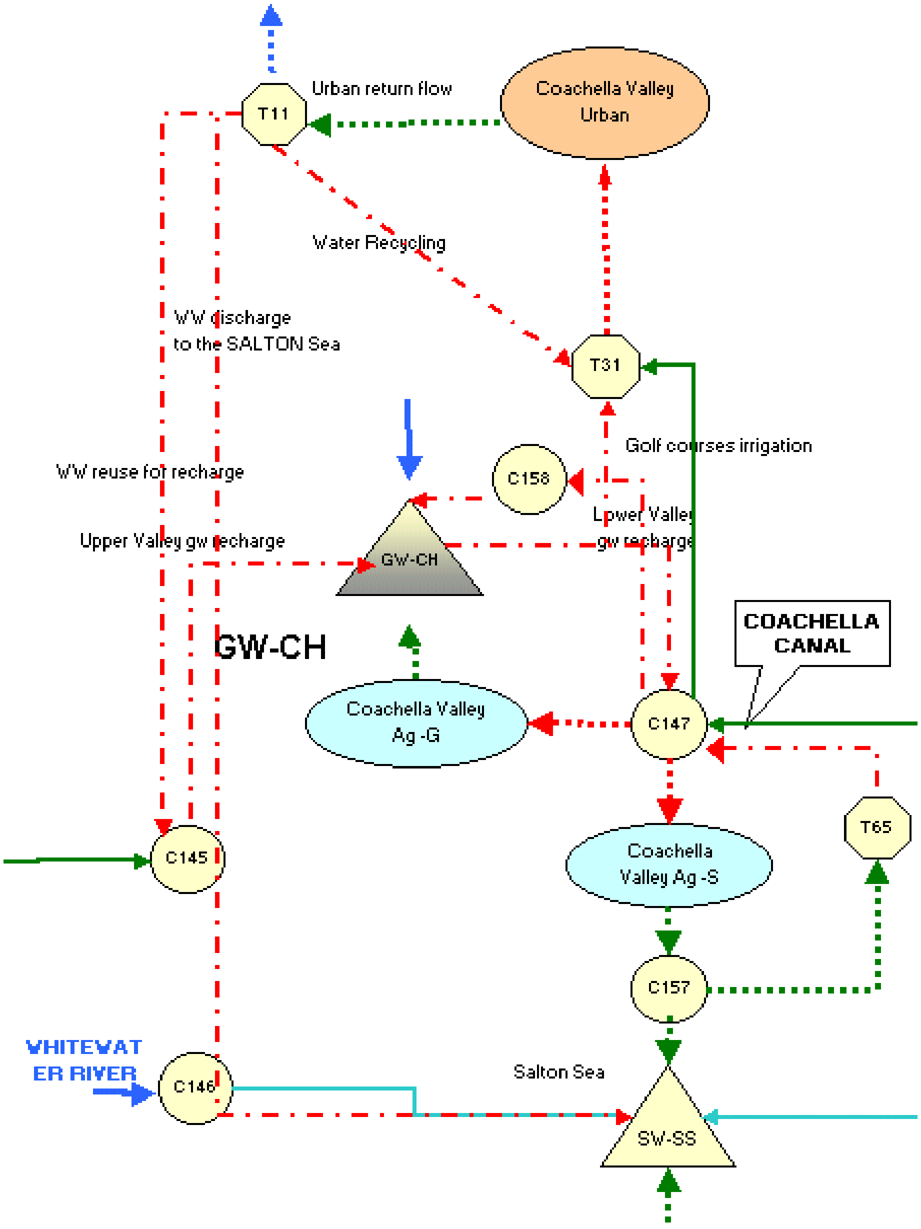


Fig. 7. Coachella's schematic

The Coachella Canal, a branch of the All American Canal, delivers water mainly to agricultural demands of the Valley. This water is also used for golf courses irrigation. The projected *source substitution* includes conversion of existing golf courses from groundwater to Canal water (in the Lower Valley) and to recycled water (in the Upper Valley), and conversion of municipal use from groundwater to treated Canal water. CVWD has also projected to desalt agricultural drain water for irrigation use (up to 11 taf/yr). The desalting facility has been incorporated to the model. This water can be delivered to golf courses, allowing the model to optimize the water allocation within the system. Finally, Metropolitan and Coachella have identified the feasibility of a conjunctive use storage program in the Lower Valley (CVWD 2000, MWDSC 2002).

The basin is currently in overdrafted condition. The capacity of the recharge facility is estimated to be around 100 taf/y. MWDSC is conducting studies to define it. It includes two sites, Dike N. 4 (range of 30-60 taf/y) and Martinez Canyon (average recharge rate 40 taf/y).

Must of the water stored in the Imperial Groundwater Basin (GW-IM) is of poor quality, not suitable for drinking water or even for irrigation, including a large proportion of groundwater underlying the Imperial Irrigation District (Montgomery Watson 1996). An average value is used for irrigation efficiency and percolation of agricultural applied water. A linear regression relationship was developed between annual precipitation and annual recharge in each area.

GW-AV (Antelope Valley) has minimal direct recharge (clay layer), and it seems that there is no artificial recharge for the area (in the model, no artificial recharge capacity has been assigned). The groundwater local inflow is obtained from a single annual recharge estimate (49 taf/yr) that is monthly distributed based on precipitation as a local inflow. The aquifer supplies the Antelope Valley urban demand, which also receives water from the SWP East Branch.

GW-OW (Owens Basin) is represented mainly to include the groundwater pumping to augment flows in the Owens River, with ultimate destination the City of Los Angeles. Local inflow is obtained from a linear regression between modified annual recharge from water budgets and annual precipitation, and is monthly distributed based on precipitation pattern.

A more detail description about the groundwater representation, local inflows and assumptions regarding pumping and recharge unit operating costs and capacities for these six groundwater basins can be found in Jenkins et al, 2001.

New Groundwater Storage Capacity

In the runs that include future facilities, several groundwater basins are added to represent additional storage along the Colorado River (GW-Cadiz, GW-Upper Chuckwalla, and GW-Hayfield) and extra storage capacity for SWP inflows north of the Tehachapis' (GW-KERN) .

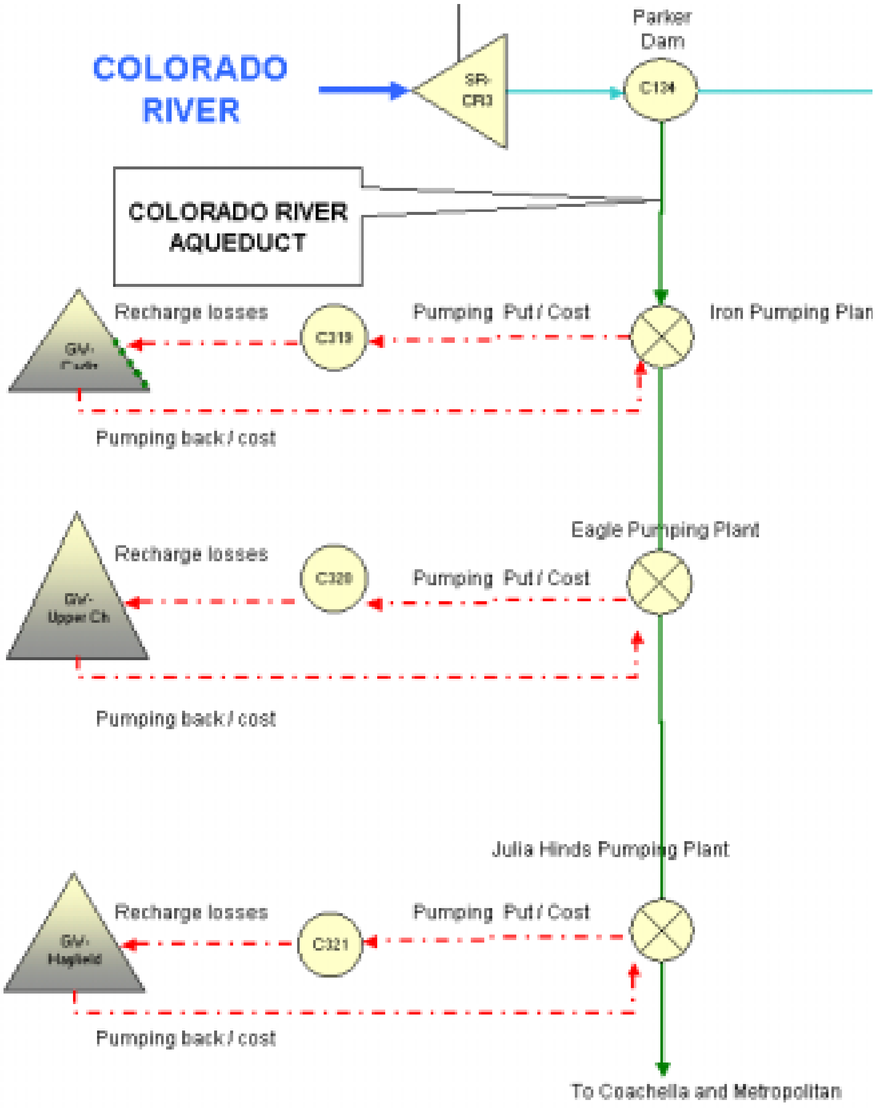


Fig. 8. Colorado River Aqueduct projected Conjunctive Use Facilities

GW-Cadiz has a potential storage capacity of 1 maf at any given time for water imported from the Colorado River Aqueduct (AGWA 2000). Project facilities would be able to deliver 200 cfs of water (MWDSC 2002) to spreading basins, with the same capacity of delivering water back to the CRA during dry periods. Initial storage is assumed to equal to 50% the total usable storage by MWD in Cadiz. A lower bound of 150 TAF/year is imposed; this is the supply capability estimated by MWD for multiple-dry years (MWDSC 2002). The recharge and pumping unit operating costs (26 and 54 $/af) are taken from a recent economic evaluation of the project (Pacific Institute 2001). Although the program contemplates the possibility of exploiting additional native water, since this aspect remains controversial due to discrepancies in the estimates of natural recharge to the aquifer (Bredehoeft 2001, USGS 2001), we have chosen not to include this possibility in the model. Only water quantities that have been recharged can be drawn for the aquifer.

GW-Upper Chuckwalla is estimated to be capable of holding up to 500 taf of CRA water, water that would be extracted at a rate of up to 150 taf/year (MWDSC 2002). It is estimated that GW-Hayfield can hold up to 800 taf of additional CRA water, at a rate up to 150 taf/year (MWDSC 2002). Pumping and recharge costs are lower than in Cadiz, due to their proximity to the CRA.

As mentioned in a previous section, Metropolitan is also implementing conjunctive use storage programs north of the Tehachapi Mountains, with the possibility of storing SWP water surplus during wet yeas, and recovering the stored water during dry periods (MWDSC 2002). The main programs include water storage in Kern Delta, Semitropic and Arvin-Edison groundwater basins. These groundwater basins have been lumped in this study as a groundwater reservoir with storage capacity equal to the extra storage that Metropolitan is expecting to be allowed to use when these programs are fully implemented, totaling 850 taf (Kern, 250 taf; Semitropic, 350 taf; Arvin/Edison, 250 taf). Metropolitan can recover the stored water at a rate of 120-300 taf/yr, according to MWD ranges for Kern-Semitropic and Arvin/Adison (MWDSC 2002).

Economic Value Functions

Economic value functions for urban and agricultural demands, and variable operating costs and benefits drive the results of the optimization model.

Urban water demands are modeled with bounded piece-wise linear economic value functions. The demands are split into three sectors (residential, industrial, and others). Annual target demands are base on the 2020 projected population levels and per capita water use. For each urban area, annual demand is disaggregated into monthly demands according to a monthly use pattern. Using 1995 observed retail water prices and estimated seasonal price elasticity of water demand, the monthly penalty functions on water deliveries for each demand are generated. Different long-term elasticities values are considered for winter, summer and intermediate months. The penalty function for industrial water demand is represented as a simple linear function of water shortages, using data for production losses for a 30% cutback in 1991 (CUWA 1991). Deliveries less than the target incur a scarcity cost (Fig. 9). A detailed description of the derivation of the urban demand penalty functions is given in Jenkins et al. 2001 (Appendix B).

The urban demands included in the Southern California model, derived from the aggregation of different smaller agencies, are: Mojave Water Agency (MWA), Antelpe Valley (AVEK), Castaic, Coachella Valley, San Bernardino Valley, Central MWD (CMWD), Eastern and Central MWD (EAMWD), and San Diego Water Agency (SDCWA). El Centro and Ventura County are modeled as fixed diversions, using fixed monthly time series of deliveries, due to the lack of data and their relatively small populations.

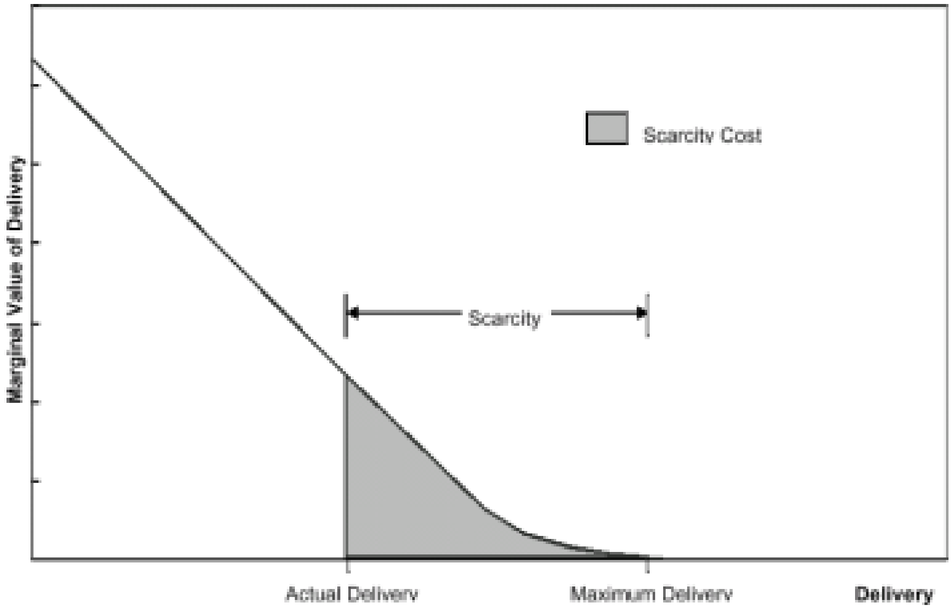


Fig. 9. Economic Value of Water

Agricultural water demands include Imperial Irrigation district (IID), Palo Verde Irrigation District (PVID), and Coachella Valley Water District (CVWD). The economic value of water for agricultural demands is derived from the Statewide Agricultural Production model, SWAP. SWAP is a quadratic optimization model that simulates an agricultural area's choice of crop, planted area and investment in irrigation to maximize farm profit, limited by water, land, technology and capital availability

Variable operating costs and benefits include fixed-head pumping cost for groundwater and surface conveyance, fixed-head hydropower benefits (for Mono Basin, Owens Valley and other locations in the East and West Branch of the SWP, and in the AAC), cost of recharge facilities, wastewater recycling cost, urban water quality for salinity and local distribution cost (Jenkins et al. 2001, Appendix G).

For Colorado River urban deliveries, an additional variable cost of $136/af is applied as an average water quality salinity damage cost. The treatment cost, with average levels of contaminant, has been estimated in about $20/af. Delta exports incur an additional $224/af treatment cost to remove bromide, with a basic treatment cost of $30/af, given the high level of contamints (TCO or other pollutants). Using pure high Sierra water, the unit treatment cost applied for LAA supply to MWD is $5/af. LAA deliveries also provide substantial benefits.

Operation Constraints

Several constraints on flow and storage limit the sytem's operation. Infrastructure and environmental constraints are always included. Institutional constraints vary between model runs. For each constraint a shadow value (Lagrange multiplier) is calculated, reflecting the economic value for the region of loosening the constraint by one acre-foot/month. This is the willingness-to-pay for changing the constraints.

Infrastructure constraints include maximum, minimum or fixed flows on particular links. Storage facilities (surface and groundwater reservoirs) have maximum and minimum storage levels.

Environmental constraints are represented as minimum instream flows at various locations. The environmental constraints explicitly included in this Southern California model are Mono Basin lake level and minimum instream flow (SWRCB Decision 1631), and Owens Lake dust mitigation deliveries, a fixed annual diversion of 51 taf (Jenkins et al. 2001, App. F).

Institutional constraints reflect current projected water allocation and operation policies for year 2020 demands. These constraints are applied in the Base Case model runs.

Model Alternatives

Three main model runs have been developed to compare different conjunctive use possibilities for Southern California water system; one is institutionally constrained and two are unconstrained:

- *Run BC* reproduces the "Base Case" with current facilities and operation constrained to the current projected water allocation policies for year 2020 levels of demand. SWP deliveries are allocated based on the deliveries simulated in the CALSIM II Benchmark Study (DWR 2002), according to each user's contractual entitlements. Colorado River allocation reflects the Seven Party Agreement, using three virtual reservoirs, as it was described in a previous section. Current LAA operation is represented as an inflow into MWD.

- *Run U* represent the "Unconstrained" case, with current facilities but with, in effect, an ideal market with flexible water allocation driven only by the economic objective function, without current water rights or operating rules. Comparison of the alternatives BC and U illustrates the economic values of changing current institutional constraints of operation and allocation in the system for a more flexible water exchange and conjunctive use operation. For this run, the new conjunctive used facilities are added with zero capacity, allowing to determination of the shadow values of these facilities.

- *Run UNF* represents the unconstrained case with new conjunctive use facilities. The additional facilities include the proposed groundwater storage facilities along the Colorado River (GW-Cadiz, GW-Upper Chuckwalla, and GW-Hayfield), the aggregated groundwater storage basin north of the Tehachapi Mountains (GW-KERN), and the new facilities projected in Coachella Valley for artificial recharge in the lower valley.

V. ECONOMIC VALUE OF CONJUNCTIVE USE IN SOUTHERN CALIFORNIA

Economic Value to the Region

Table 3 shows the average annual scarcity, scarcity cost, and operating cost from the different alternatives. Flexible water allocation and conjunctive use operation in an ideal market significantly reduce scarcity and scarcity cost (16% and 85% reduction respectively from alternative BC to alternative U). More water is allocated to urban demands (with higher marginal economic value than agricultural users), also increasing the reuse possibilities since more returns flow can be recycled. The greater flexibility and perfect foresight of the optimization procedure, allows readjusting the storage of water in the reservoirs, so that the system can be prepared against droughts (perfectly hedging storage use), reducing spills and losses in the optimal way. The high percentage of reduction in scarcity cost is due to the reduction in scarcity, but also to the reallocation of water to the demands with higher economic values of water, and to the perfect hedging of reservoirs operation, that reduces higher scarcities during droughts that would be more costly (since the scarcity cost is nonlinear with the scarcity).

Table 3. Scarcity, and Scarcity and Operating Cost

RUN	DESCRIPTION	Total Annual Average					
		Scarcity (taf)		Scarcity cost (M$/y)		Operating Cost (M$/y)	
		Average Value	Δ from current policy	Average Value	Δ from current policy	Average Value	Δ from current policy
BC	Constrained Base Case	1,179	0	1,541	0	22	0
U	Unconstr. Base Case	990	-16%	226	-85%	25	16%
UNF	Unconstr. Base Case with new CU facilities	969	-18%	127	-92%	26	17%

The results of the alternative UNF reveal the benefits of the proposed conjunctive use facilities. The change in scarcity is not very significant in comparison with alternative U, but the scarcity cost is reduced in a 44%. The additional groundwater storage capacity allows better regulation of flows in time, improving the hedging of the water available in the system, and thus, its temporal reallocation to reduce scarcity costs. The operating cost (total operating cost minus hydropower benefits) is almost equal for both alternatives. Since the aquifers along the Colorado River play no finally any role in the operation of the system (as it is discussed in a later section), the implementation of the CU program in GW-KERN, together with the artificial recharge program in Coachella’s Lower Valley, are worth 98 M$/year on average for the region (total net benefit increment from run U to run UNF).

Fig. 10 shows the stream of annual scarcity costs during the 72-years for the different alternatives. It reveals the economic differences between current operating policies and an economically-based water allocation (alternatives BC and U). Differences between the values for alternatives U and UNF correspond to the annual benefits of conjunctive use with the new facilities.

Although Fig. 10 shows that the scarcity is more or less similar in the three alternatives, except for an important reduction during the drought periods, Fig. 11 demonstrates that the scarcity cost in the Base Case run is far above the unconstrained run's annual scarcity costs during the whole period. As we discussed above, this is the result of a more flexible operation that reallocates the water to more valuable uses, and conserves the water with perfect foresight to mitigate the effects of droughts. The mitigation of scarcity cost during droughts is greater in run UNF, due to the extra storage capacity, and thus the extra capability of hedging the flows.

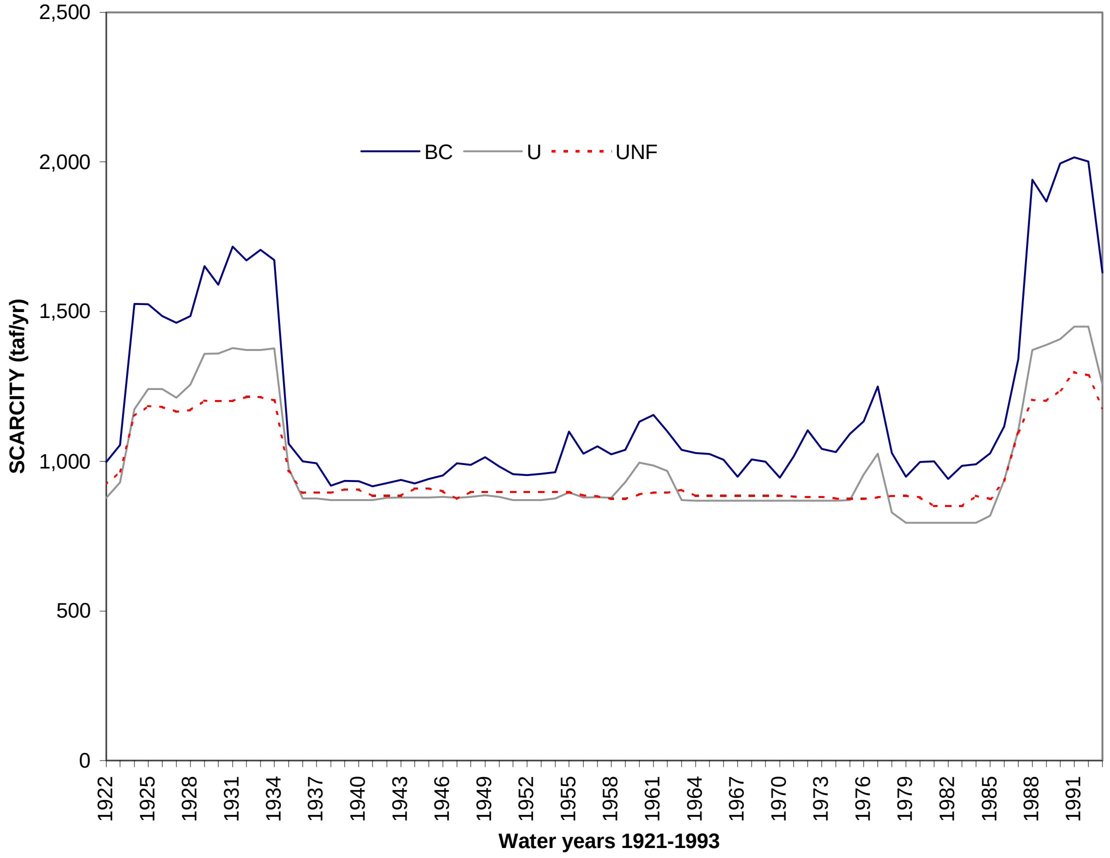


Fig. 10. Annual Scarcity (taf/yr) for Southern California. Years 1922-1993

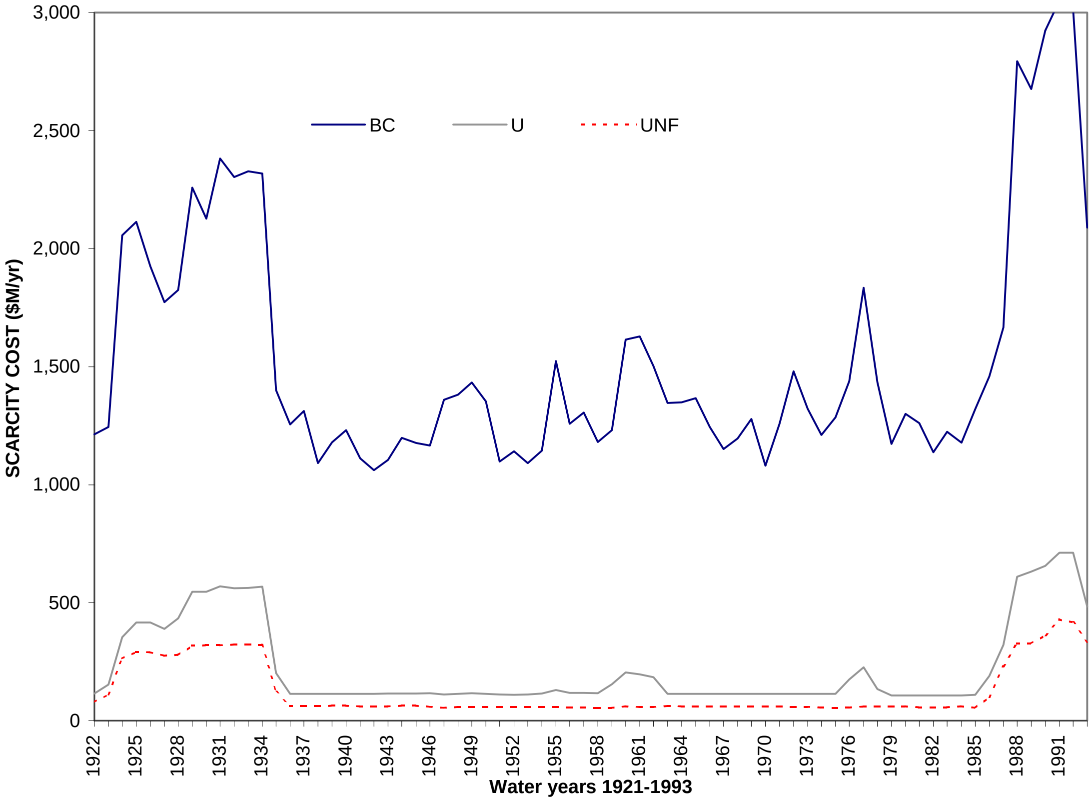


Fig. 11. Annual Scarcity Cost (M$/yr) for Southern California. Years 1922-1993

Conjunctive Use Economic Value to Water Users

Although the aggregated region gains significant benefits from a flexible conjunctive use operation and water allocation, and these benefits increase with the additional conjunctive use facilities, the overall benefits are not proportionally shared among the different economic sectors (Table 4).

Palo Verde and especially Imperial agricultural regions see the largest decrease in deliveries from the Base Case. All the urban areas see increased deliveries (except an small reduction in San Bernardino in run U). Therefore, the most promising transfers are from agricultural areas on the Colorado River to the urban regions.

Fig.12 and Fig. 13 highlights the changes in deliveries and scarcity cost due to the new conjunctive use facilities. With the new facilities, 100 taf/yr of additional water are transferred on average from the Palo Verde and Imperial irrigation districts to Coachella via the Coachella's branch of the All American Canal. The artificial recharge facility in Coachella's Lower Valley is used at its full capacity in all years (100 taf/yr). The increase in recharge in the Lower Valley allows increased groundwater use, reducing water scarcity in Coachella (70 taf/yr less). It also allows decreased CRA diversion for recharging the Upper Valley (around 60 taf/yr less, thanks to the multiplier effect of the increase of groundwater return flows with the increase in supply). The reduction to CRA's Coachella supplies is transferred to the three MWD demands through MWD facilities, reducing their scarcity and releasing SWP water for other users. So from the 111 taf/yr of increased agricultural scarcity, urban scarcity is reduced in 132 taf/yr, due to the higher return flows from urban deliveries.

Table 4. Water Target, Deliveries, Scarcity, and Scarcity Cost by User

	Max. (taf/yr)	Delivery (taf/yr)	ΔDelivery (taf/yr)		Scarcity (taf/yr)			Scarcity Cost (M$/yr)		
Demand / Run		BC	U-BC	UNF-BC	BC	U	UNF	BC	U	UNF
Palo Verde	789	661	-148	-160	127	276	287	1	9.4	10
Coachella Ag	195	195	-14	-14	0.0	14	14	0	0.9	1
Imperial	2,732	2,513	-233	-333	219	452	552	5	21.0	32
Total Ag	3,716	3,370	-396	-507	346	742	853	7	31	43
Central MWD	3,731	3,520	126	158	211	85	54	207	75.7	44
E&W MWD	740	703	23	28	37	14	9	42	13.6	8
San Diego	988	953	20	26	35	16	10	40	15.4	9
San Bernardino	283	277	-1	1	6	8	5	5	4.7	3
Antelope Valley	277	181	87	92	96	9	5	201	8.5	4
Castaic Lake	128	41	79	82	87	8	5	528	5.8	3
Mojave	352	216	117	126	136	20	11	200	10.5	5
Coachella Urban	601	377	136	206	224	88	18	311	61.0	8
Total Urban	7,100	6,266	586	718	834	248	115	1,534	195	84
TOTAL	**10,816**	**9,636**	**190**	**211**	**1,180**	**990**	**969**	**1,541**	**226**	**127**

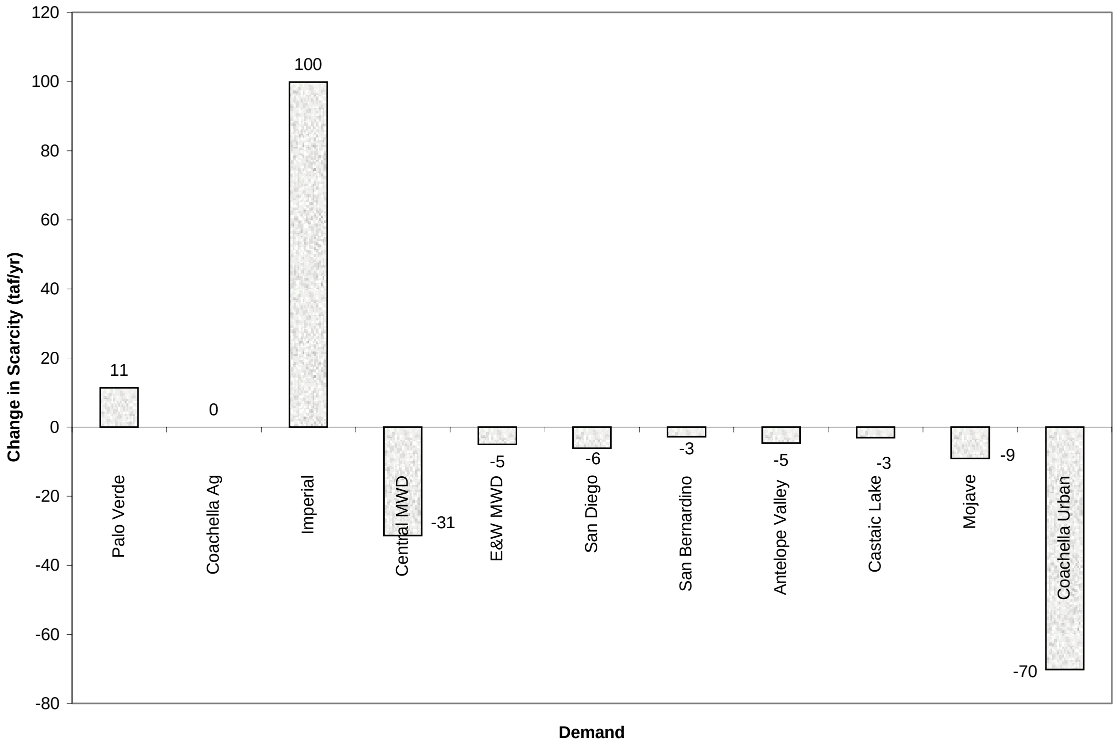


Fig. 12. Change in Annual Average Scarcity, Run UNF- Run U

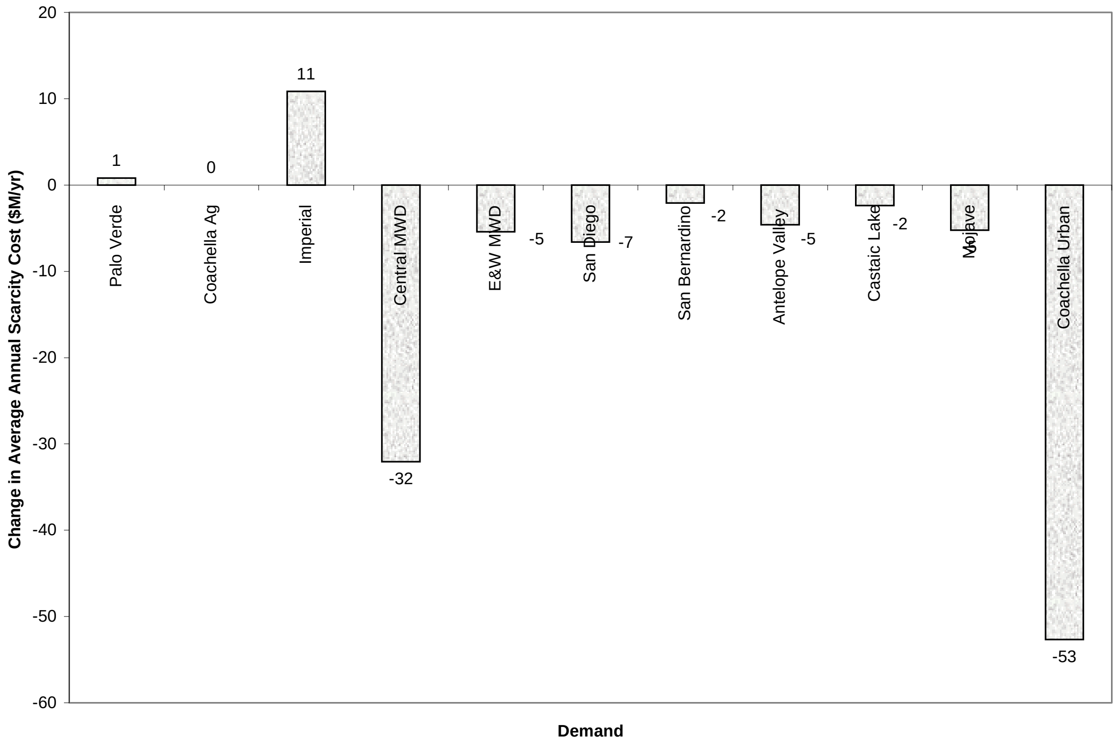


Fig. 13. Change in Annual Average Scarcity Cost, Run UNF- Run U ($M/y)

Table 5 reveals that MWD supply from the CRA increases about 60 taf/y, and its SWP supply decreases 20 taf/y. It allows MWD to reduce its scarcity in 40 taf/y, releasing about 20 taf/y of SWP water for use by other SWP users (San Bernardino, Antelope, Mojave and Castaic). The role of the groundwater storage north of the Tehachapi Mountains (GW-Kern) is mainly to redistribute this water in time to mitigate the effects of the two major droughts. Figure 14 shows a typical pattern of annual supply to the urban demands for the different runs. The substantial storage capacity in GW-Kern, allows the extra water gained from the increasing conjunctive use in Coachella to be stored for Coachella's use during the severe droughts. This higher supply during the two major droughts (in run UNF over run U) reduces scarcity cost significantly between the two runs.

Table 5. Sources of supply for each demand (runs BC, U and UNF)

Ag demands	*Supply Source*	*BC supply (TAF/yr)*	*BC%*	*U supply (TAF/yr)*	*U %*	*UNF supply (TAF/yr)*	*UNF %*
Palo Verde	CR	661	100	513	100	502	100
Coachella Ag	CR (AAC)	195	100	181	100	181	100
	GW-Coachella	0	0	0	0	0	0
Imperial	GW-Imperial	0	0	60	3	60	3
	CR (AAC)	2,513	100	2,220	97	2,120	97
TOTAL AG SUPPLY	-	**3,370**	**-**	**2,974**	**-**	**2,863**	**-**
Urban Demands	*Supply Source*	*BC supply (TAF/yr)*	*BC%*	*U supply (TAF/yr)*	*U %*	*UNF supply (TAF/yr)*	*UNF %*
MWD	LA Aqueduct	343	7	385	7	388	7
	SWP-West Branch	609	12	881	16	899	17
	SWP-East Branch	1,073	21	576	11	538	10
	CR (CRA)	798	15	1,153	22	1,211	23
	Local supply	1,774	34	1,774	33	1,774	33
	Year type correction in demanc	591	11	591	11	591	11
	Internal losses	-13	-	-15	-	-14	-
San Bernardino	SWP-East Branch	277	100	275	100	278	100
Antelope Valley	GW-Antelope	49	27	49	18	49	18
	Urban water recycling	6	3	6	2	5	2
	SWP-East Branch	126	70	213	79	218	80
Castaic Lake	SWP-West Branch	41	100	120	100	123	100
Mojave	GW-Mojave (SWP recharged)	216	100	332	100	341	100
Coachella Urban	GW-Coachella (CR recharged)	343	91	448	87	528*	90
	Urban water recycling	0	0	32	6	22	4
	CR (Coachella Canal)	34	9	34	7	34	6
TOTAL URBAN SUPPLY	-	**6,266**	**-**	**6,853**	**-**	**6,985**	**-**

* Includes Lower Valley recharge as new source for groundwater

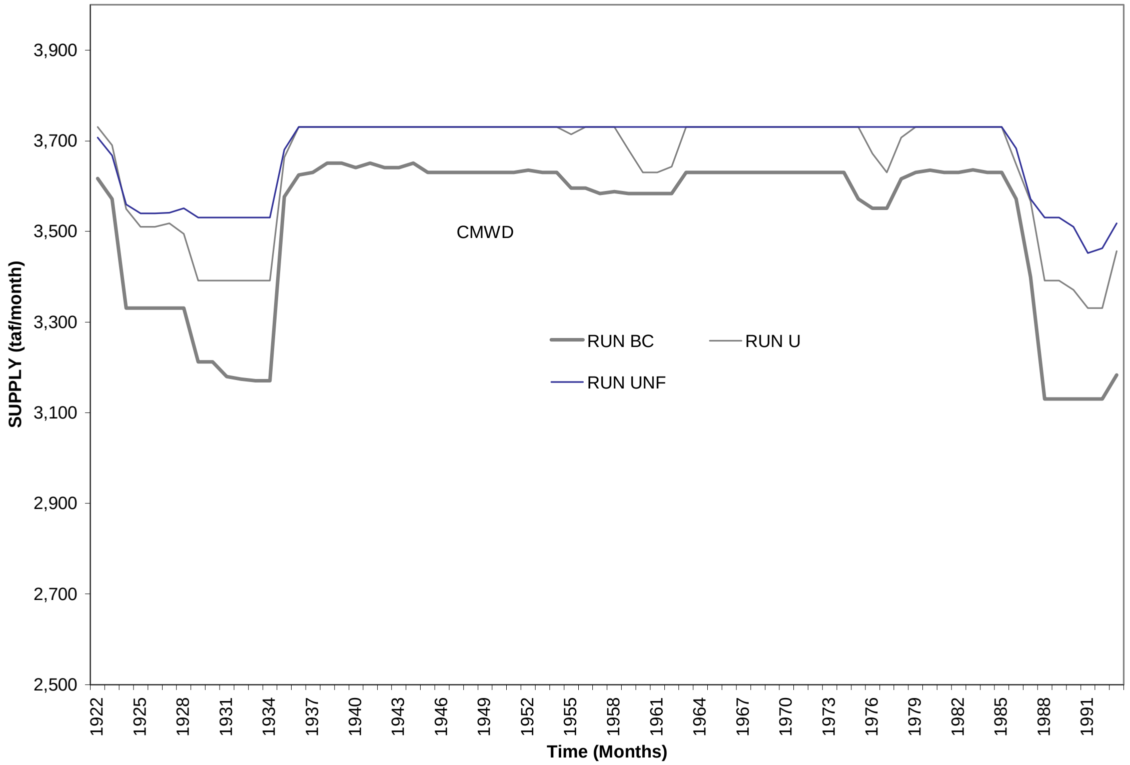


Fig. 14. Monthly supply to Central MWD

Users’ Marginal Willingness-To-Pay for additional water

In the demands with scarcity, there is an economic value to additional supplies. CALVIN reports the marginal value (net benefit to the modeled region) at any time and location in the system of an additional unit of water from an external source. This value, also called the marginal willingness-to-pay (MWTP) at the point in consideration, is a useful indicator of where and when there is a potential economic value for inter- and intra-regional transfers. For each demand, the MWTP in each time step is driven by the slope of the demands economic function at the delivered quantity of water. Table 6 shows the marginal willingness to pay for an additional unit of water for each run at each demand area.

Since all demands experience scarcities, all of them remain with MWTP. As expected, urban users have much higher MWTP than agricultural users. Agriculture experiences increased MWTP in the unconstrained runs, due to their increased scarcities resulting from transfers to the urban demands. On the other hand, all urban users see decreases in MWTP compared to the Base Case, reflecting decreased urban scarcities. The most significant reductions take place in Antelope and Castaic Lake, in which the huge MWTP under the current operation policy reflects the high marginal value of water in these areas under current high scarcities, according to their demand curves. The optimal operation of the new conjunctive use facilities reduces the MWTP for all urban demands, especially in Coachella, which has a very steep demand function (due to the presence of high-valued recreation resorts and golf courses). In economic theory, economically optimal allocation is reached when all the demands have the same marginal net return (equimarginal principle). In this case the allocation is constrained by the physical capacity of the infrastructure, and we have to consider also the operating cost that implies any additional unit delivered to come up with the marginal net return. The return flow percentage and reuse cost also has to be considered, since future reuse affects the value of additional water.

Table 6. Users' MWTP for additional water

Ag Demands	Average WTP ($/af)			Maximum WTP ($/af)		
	BC	U	UNF	BC	U	UNF
Palo Verde	18	67	71	21	71	71
Coachella	0	61	61	0	62	62
Imperial	24	72	90	24	109	109
Urban Demands	Average WTP ($/af)			Maximum WTP ($/af)		
	BC	U	UNF	BC	U	UNF
Castaic Lake	10,496	441	250	20,473	1,322	1,039
San Bernardino	401	205	155	3,323	911	753
E & W MWD	838	293	229	4,078	1,364	1,020
Central MWD	924	324	238	2,194	1,326	1,095
Antelope Valley	2,611	441	250	3,136	1,322	1,039
San Diego	571	271	220	2,483	1,240	1,060
Coachella	1,499	895	367	1,953	1,060	593
Mojave	1,552	572	496	2,066	620	507

Inter-Regional Boundary Economic Values

The dual values at the boundary regions represent the marginal willingness-to-pay for increasing deliveries from each imported source, indicating which source of imported supply has the highest marginal value for the whole region. It can be used to indicate the economic desirability of inter-regional water transfers (Jenkins et al. 2001).

Table 7. Boundary Marginal Economic Value of Water

	Positive Average Bound.Value ($/af)			Max Boundary Value ($/af)			Min Boundary Value ($/af)		
	BC	U	UNF	BC	U	UNF	BC	U	UNF
SWP	2,267	183	109	2,794	782	534	1,246	-226	-219
LAA (Mono-Owens)	964	585	477	2,383	1,245	998	249	276	283
Colorado River	785	109	111	2,211	111	111	486	104	111

(Note: The table does not include hydropower benefit associated with the LAA, since the LAA is incorporated as an inflow in the Base Case, and it would not be comparable for the different runs)

A flexible water market and conjunctive use operation (run U) reduces significantly the MWTP from all the imported sources with respect to the current operation (Table 7). The run with new conjunctive use facilities (run UNF) also reduce the MWTP for LAA and SWP water. The LAA average boundary value is the highest in the unconstrained runs, reflecting better water quality (LAA has the lowest quality cost of the imported sources) and lower operating cost (there is no pumping cost). If hydropower benefit in the LAA were included (estimated in $298/af between Mono Lake and Los Angeles), the differences would have been much higher. Fig. 15 displays for each run the time series of marginal economic values of additional LAA water. LAA water is especially valuable during the two major droughts. Flexible allocation and flexible conjunctive use in runs U and UNF reduce significantly the demand for increased LAA imports, especially during the major droughts.

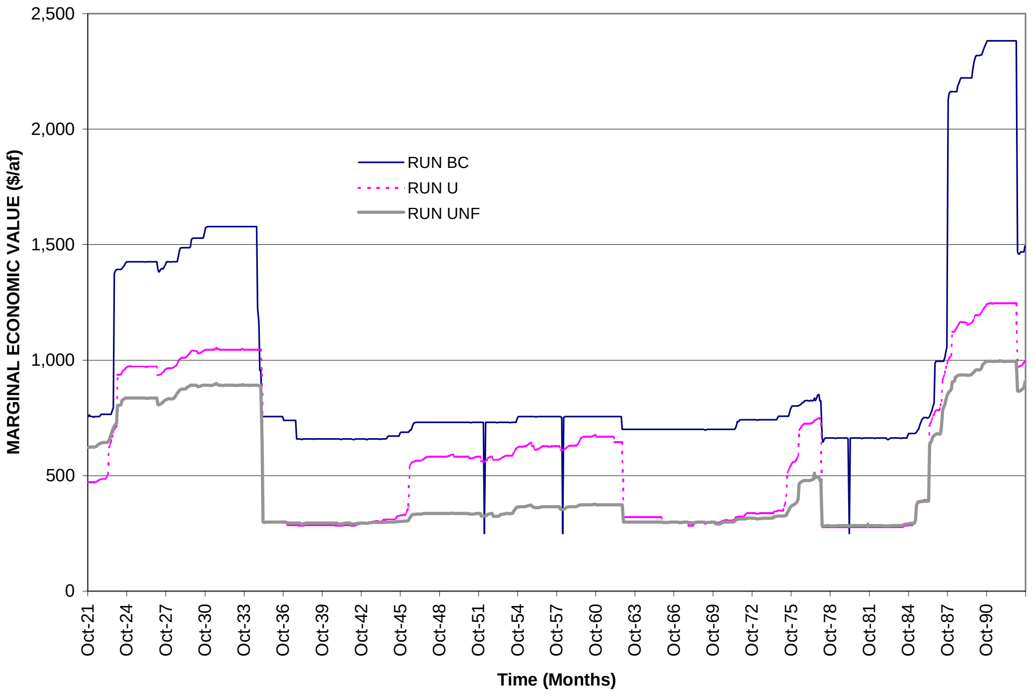


Fig. 15. Marginal Economic Value of LAA water

Fig. 16 displays the marginal economic value of additional SWP water in runs U and UNF. The economic value of an additional unit of SWP water becomes negative during most of the period (from 1935 to 1976, and from 1977 to 1985), except for the storage refill and supply times corresponding to three major droughts. During that time, Mojave and Antelope supply pipelines are binding (comments on Mojave pipeline capacity constraint appear in chapter VII). Moreover, at that time Castaic Lake scarcity is zero (Fig. 17). Therefore, there is no value for additional SWP water during that time.

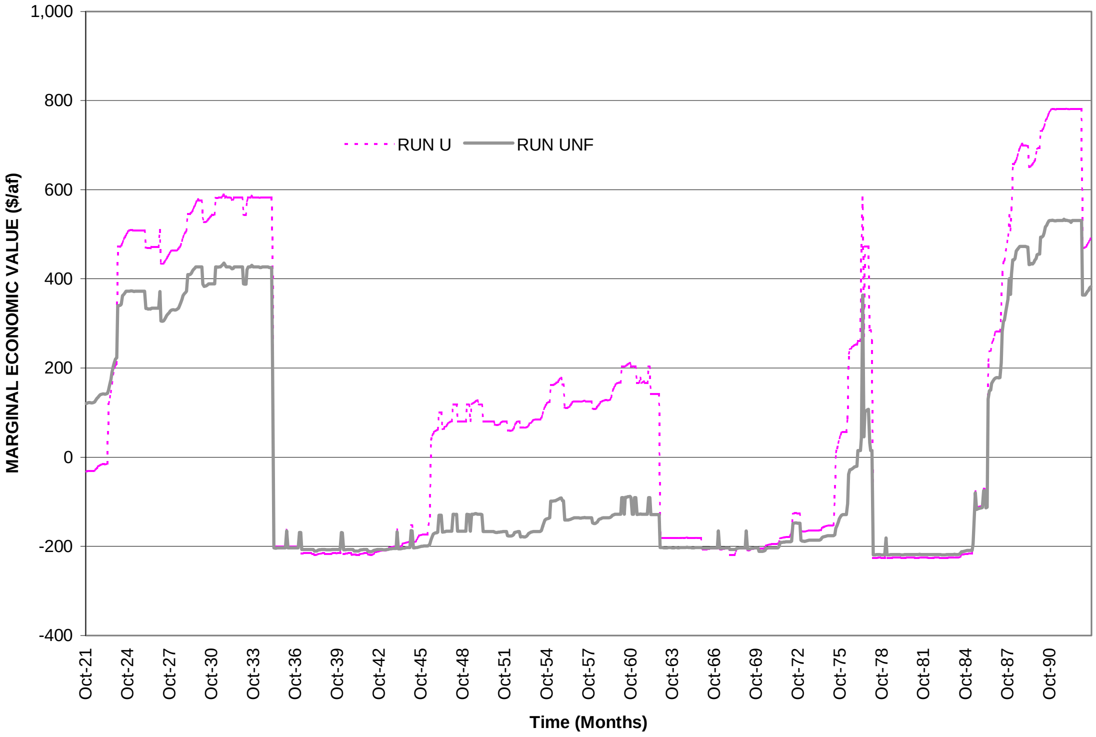


Fig. 16. Marginal Economic Value of SWP water

In run BC, Colorado River water is allocated according to the *Law of the River* to urban demands (through the CRA) and agricultural contractors. Additional water yields a very high benefit, since it can be allocated to Coachella or the MWD urban demands, which have a high MWTP (high scarcities). The average marginal value ($785/af) is far from the willingness-to-pay for additional water in Coachella ($1,499/af) and Central MWD ($924/af), due mainly to the CRA physical constraint, when it binds. In runs U and UNF (Fig. 18), since the CRA capacity is binding most of the time for the supply to the urban demands, the marginal value of additional water in the Colorado River (about $110/af) is practically equal on average to the marginal-willingness-to-pay of the agricultural demands supplied by Colorado River water, Palo Verde and Imperial (minus losses and operating cost). CRA capacity binds most of the time in the unconstrained runs. Fig. 19 and Fig. 20 depict the marginal economic value of the CRA water at the Coachella diversion node, and after that point, at the beginning of Metropolitan’s Valverde Tunnel. In both locations, downstream of binding CRA capacity constraints, the marginal economic value in these runs increase considerably.

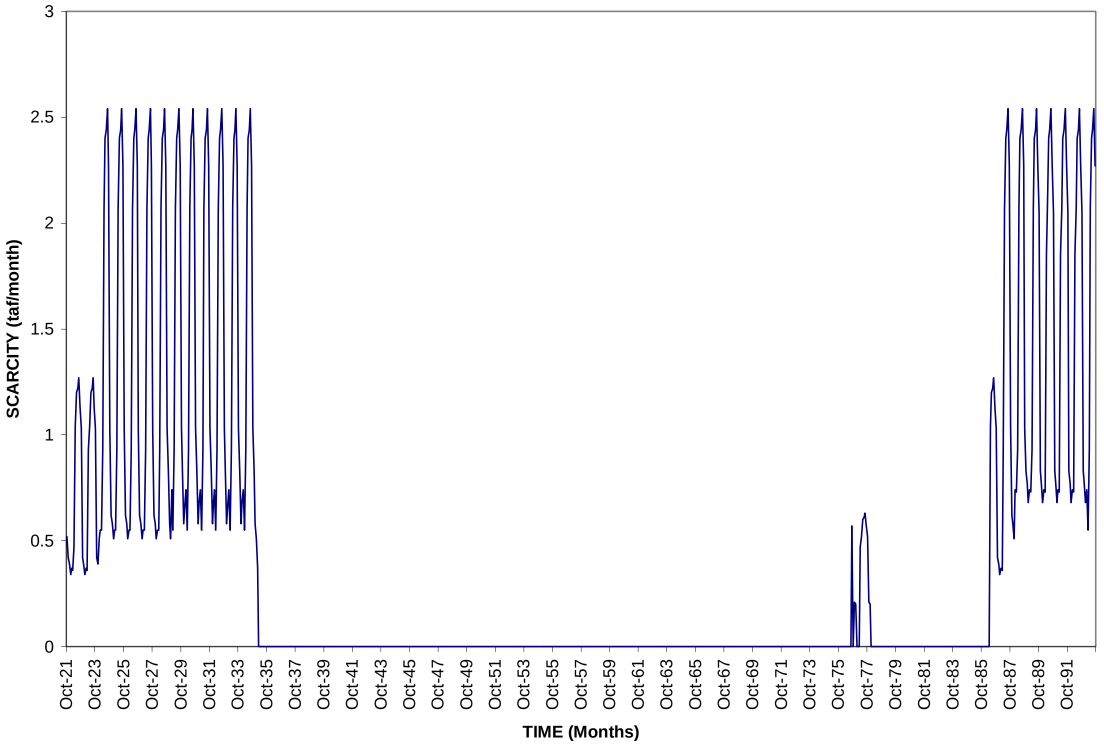


Fig. 17. Scarcity in Castaic Lake Urban Demand

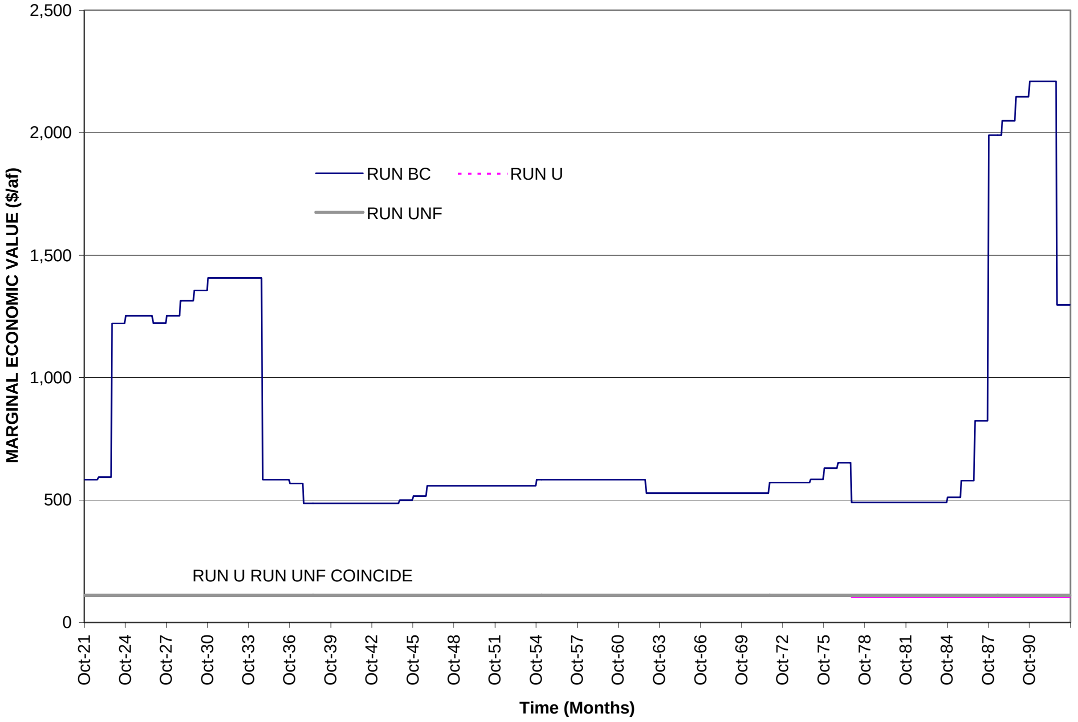


Fig. 18. Marginal Economic Value of Colorado River water (including cost of pumping above the Tehachapi Mountains)

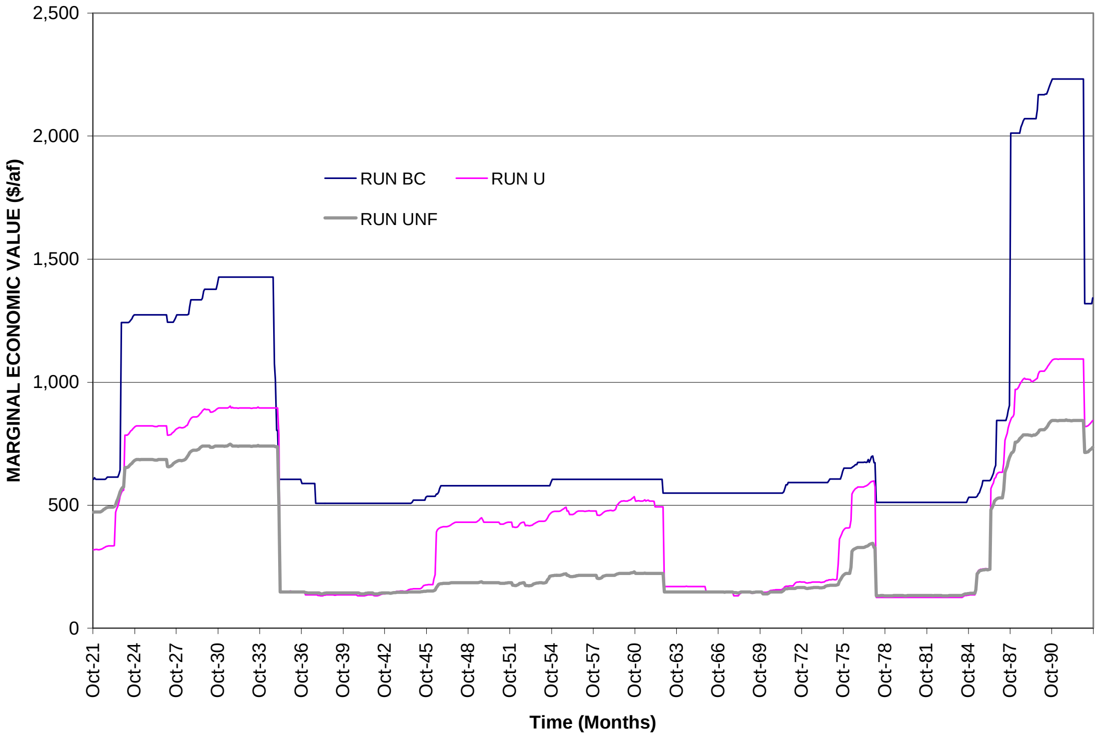


Fig. 19. Marginal Economic Value of CRA water at Coachella's diversion

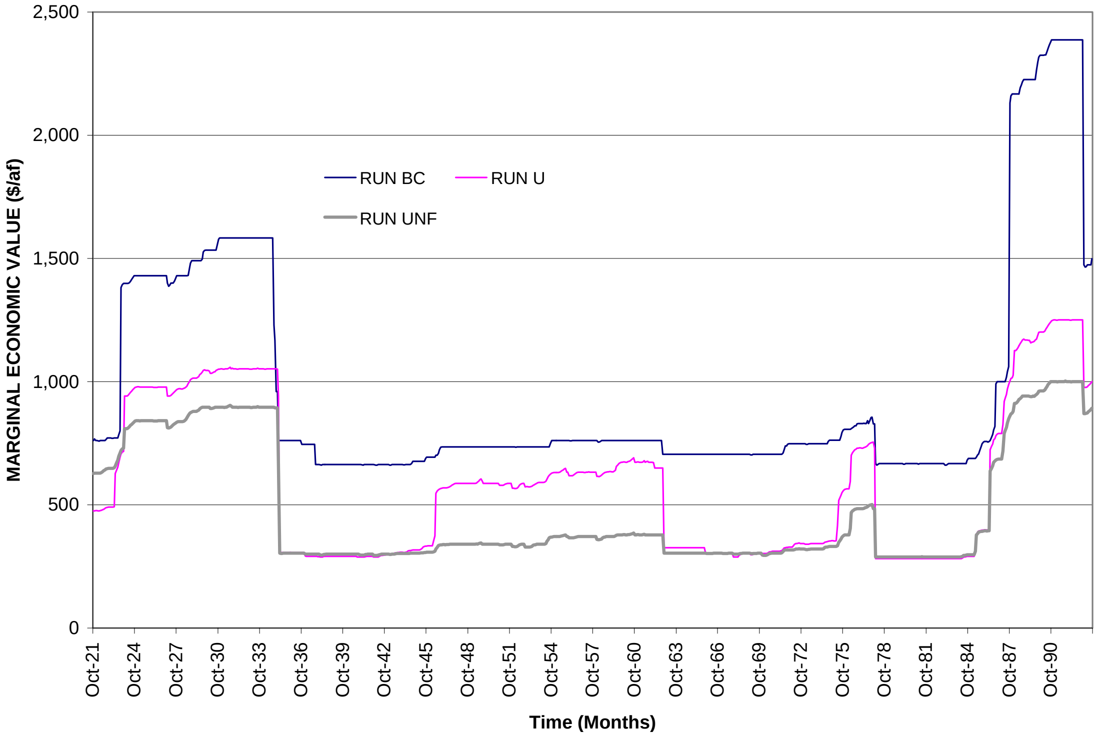


Fig. 20. Marginal Economic Value of CRA water at Metropolitan's diversion

Environmental Flow Shadow Values

In CALVIN environmental demands are modeled as constraints (lower bounds for minimum streamflow requirements or minimum storage). When the lower bound is binding, the shadow values that CALVIN reports for the links with environmental constraints indicate the marginal opportunity costs of environmental requirements on agricultural and urban water users (and lost hydropower generation in some cases).

In this Southern California model, the environmental constraints represent the minimum Mono Lake instream flows and minimum lake level (Decision-1631), and Owens Lake diversion for dust mitigation. The constraint on Mono Lake level does not limit the water flowing to Los Angeles, assuming initial Mono Lake storage is above or at required minimum elevation.

Table 8. Shadow Values on Environmental Flows

	Annual Req. (taf/y)	Average Boundary Value ($/af)		Max. Boundary Value ($/af)	
		U	UNF	U	UNF
Mono Lake inflows	74	912	804	1,997	1,696
Owens Lake dust mitigation	40	703	600	1,425	1,168

The high shadow values for Mono Lake inflows and Owens Lake diversions (Table 8) reflects the scarcity cost in Central MWD, but also the higher cost of substitute water from SWP (with high pumping cost, high quality cost, and also high opportunity cost, since it is the main source of supply for Antelope, Mojave and Castaic). The shadow values for Mono Lake inflows are higher, since the marginal opportunity cost of Mono Lake diversions is higher because of the lost hydropower benefits ($161/af between Mono Lake and Owens Lake diversion, and $298/af in total between Mono Lake and Los Angeles). In run UNF the shadow values decrease, due to the important reduction in scarcity, and therefore, in the marginal value of water for the agricultural and water demands.

VI. PROMISING OPERATING RULES FOR CONJUNCTIVE USE

Preliminary system operating rules for a large multipurpose multireservoir system can be inferred from deterministic optimization results based on a long hydrologic record (applied in this study) or synthetic streamflow time series. Advantages of the implicit stochastic optimization over the explicit stochastic approaches have been analyzed elsewhere (Karamouz and Houck 1987, Lund 1992, Lund and Ferreira 1996, Lund and Guzman 1999, Draper 2100, Sanchez-Quispe et al. 2001). A variety of approaches are available for discerning reservoir operation rules from optimization results (Young 1967, Lund 1992 and 1995, Lund and Ferreira 1996). The main difficulty in detecting rule patterns in long-term optimization results is the amount of results available, and the high number of interrelated variables (storages, releases, upstream inflows, demands, etc.). Lund (1992) summarizes some of the classical approaches: intuition (engineering expertise and knowledge of the system, aided by graphical and statistical tools), regression techniques, reservoir operation theory (space rules, hedge rules, and so on) and mixed simulation-optimization approaches. None of these techniques are perfect, and it is normally necessary to combine them in an iterative process to come up with derived preliminary policy rules. Also different desaggregation techniques and heuristic optimization procedures have been applied for developing operating rules for multireservoirs systems, like artificial neural networks (Saad et al. 1994), genetic algorithms (Oliveira and Loucks 1997) and fuzzy programming (Russel and Campbell 1996, Shrestha et al. 1996, Tilmant 2002). In any case, the preliminary patterns suggested by the optimization results have to be tested and refine using a more detail simulation modeling, without perfect foresight, to better assess the performance of the system under these rules.

As stated in the introduction, it is not the goal of this thesis to derive operating rules for the complex system under analysis, but to discuss the economic advantages of an optimal conjunctive use operation under flexible water allocations for Southern California, and the added value of new CU infrastructure. However, since flexible conjunctive use operation implies a substantial change in management of the system, some general ideas of the operational implications of this change are presented in this section.

Surface and groundwater storage

CALVIN operates the system to achieve the maximum benefit with ideal perfect foresight. The resulting optimal operation of the system is more flexible than in real systems, being constrained only by the physical limitations of the infrastructure and environmental constraints. Because of the perfect foresight, it is also less risk averse than water managers would be. The optimal conjunctive operation of surface and groundwater reservoirs suggests changes in the current operating policy that would improve significantly the overall performance of the system.

Fig. 21 displays the changes in the aggregated surface storage. Run U presents more inter-year storage than run UNF, where this mission is mainly accomplished by GW-Kern. Fig. 22 displays the aggregated groundwater storage. It shows clearly the effect of perfect foresight in the derivation of the optimal operation of the system. For the unconstrained runs, CALVIN suggests more aggressive pumping during the 1929-34 drought, after which the average storage level is recovered, and a more intensive recharge in preparation for the 1987-92 drought. Fig. 23 shows for the groundwater basin in Coachella that the groundwater operation is even more aggressive with additional recharge capacity (recharge in the Lower Valley for run UNF). Comparing Fig. 21 and Fig. 22 it can be noticed that most storage for Southern California is groundwater.

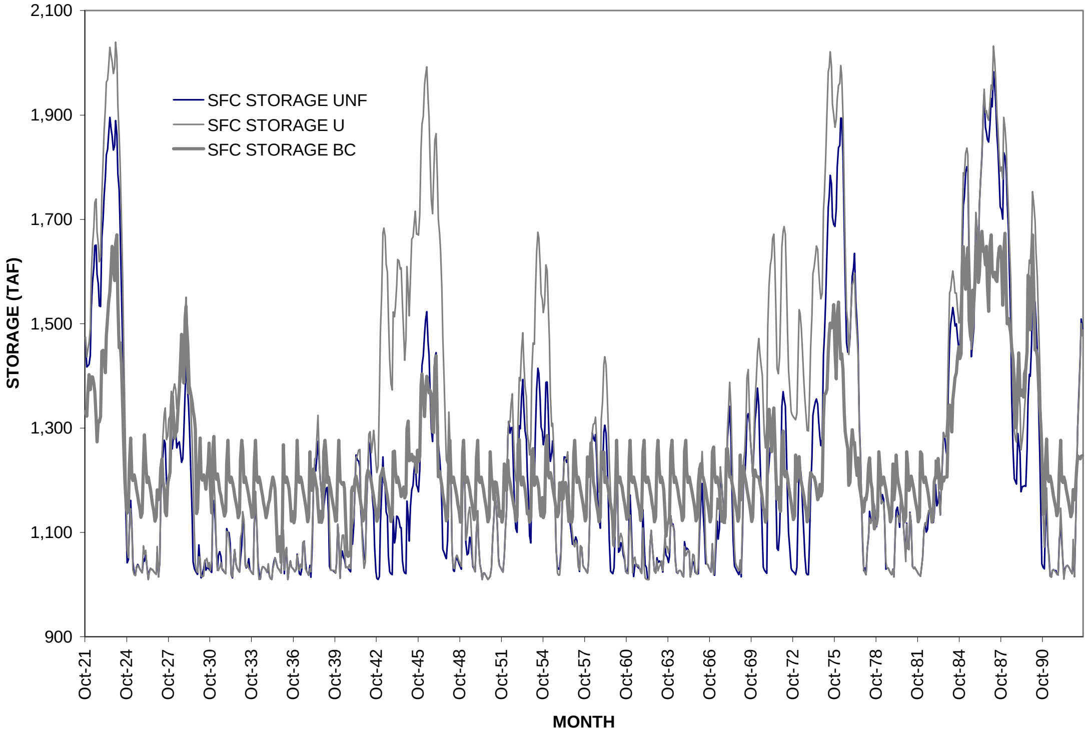


Fig. 21. Southern California Total Monthly Surface Storage

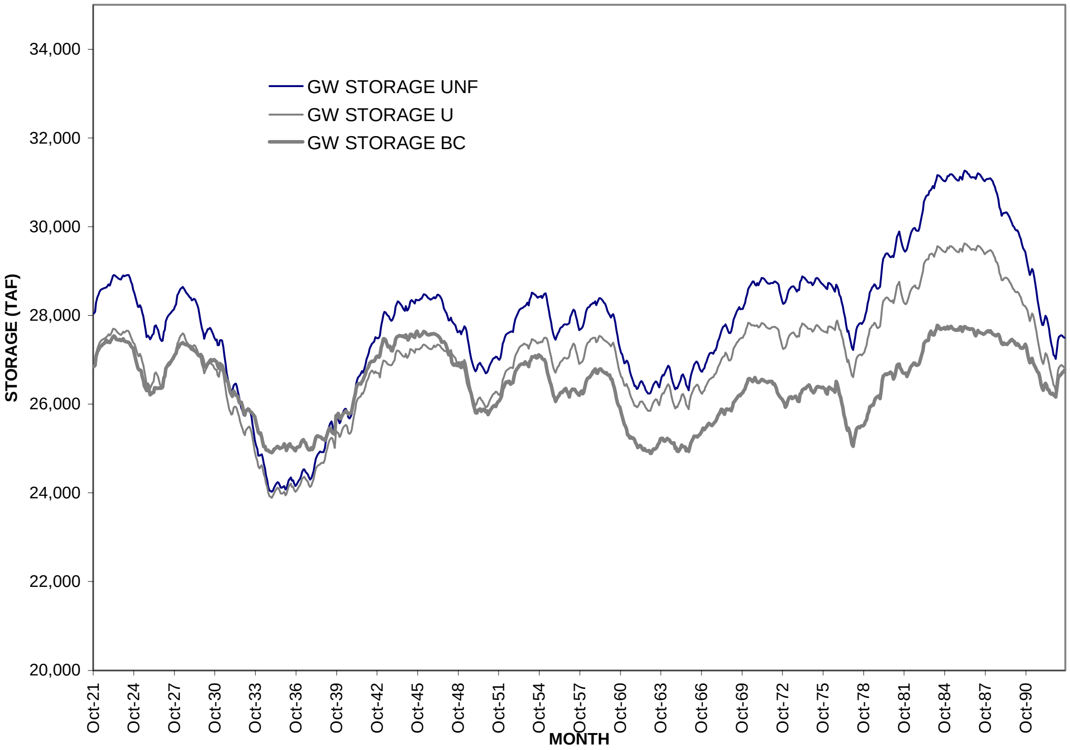


Fig. 22. Southern California Total Monthly Groundwater Storage

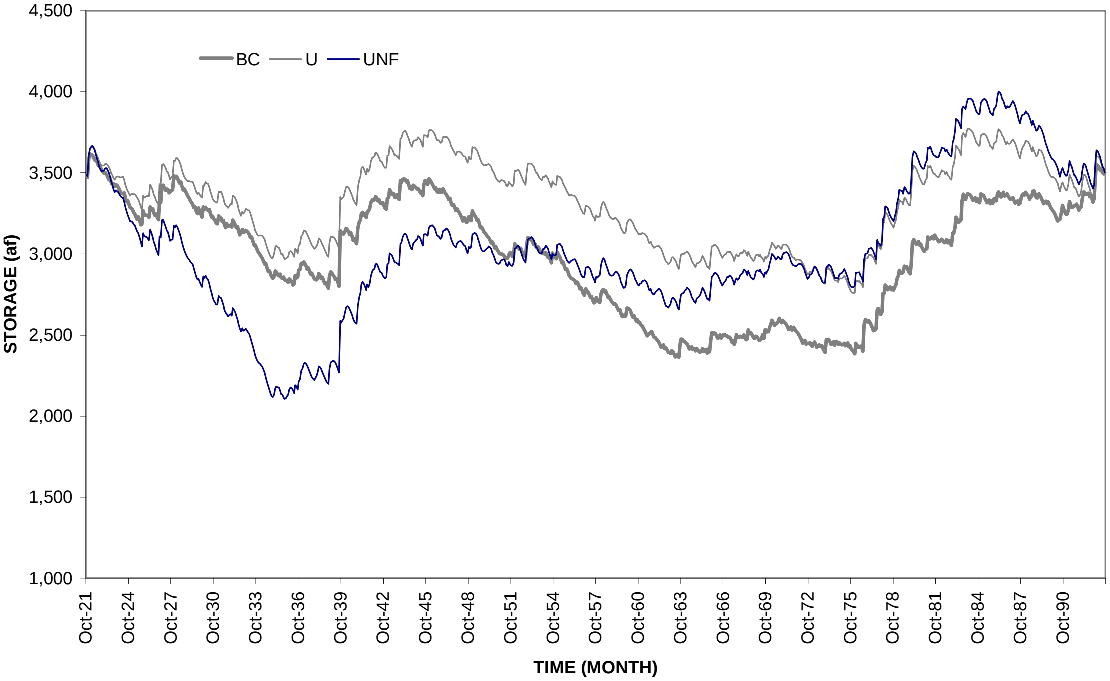


Fig. 23. Coachella Monthly Groundwater Storage Level

Conjunctive Use in Coachella Subsystem

Fig. 24 shows the time series of annual groundwater recharge in the Coachella subsystem with CRA water. In run UNF, the artificial recharge facility in Coachella's Lower Valley is always used at its full capacity (100 taf/yr), since the CRA is full and the urban demand has a much higher marginal willingness-to-pay than the agricultural demands, Imperial and Palo Verde. The increase in recharge in the Lower Valley allows increasing groundwater utilization, obtaining a substantial reduction of water scarcity in Coachella (70 taf/yr less), and allowing a decrease in the CRA diversion for recharging the Upper Valley (around 60 taf/yr less). The multiplier effect of the increase of groundwater return flows with the increase in supply allows increasing water reuse through groundwater recharge and pumping, and also through direct reuse (recycling). CRA deliveries to Coachella for recharge in the Upper Valley are eliminated during the two major droughts (1928-1934 and 1987-1992), given the high willingness to pay in Central MWD during those periods. During these droughts Coachella urban demand is served by resorting to intensive use of groundwater (Fig. 23 in section above), previously accumulated in the groundwater basin during the refill period. The reduction in CRA's Urban Coachella supplies is transferred to the three MWD demands, releasing 20 taf/yr of SWP water for other users.

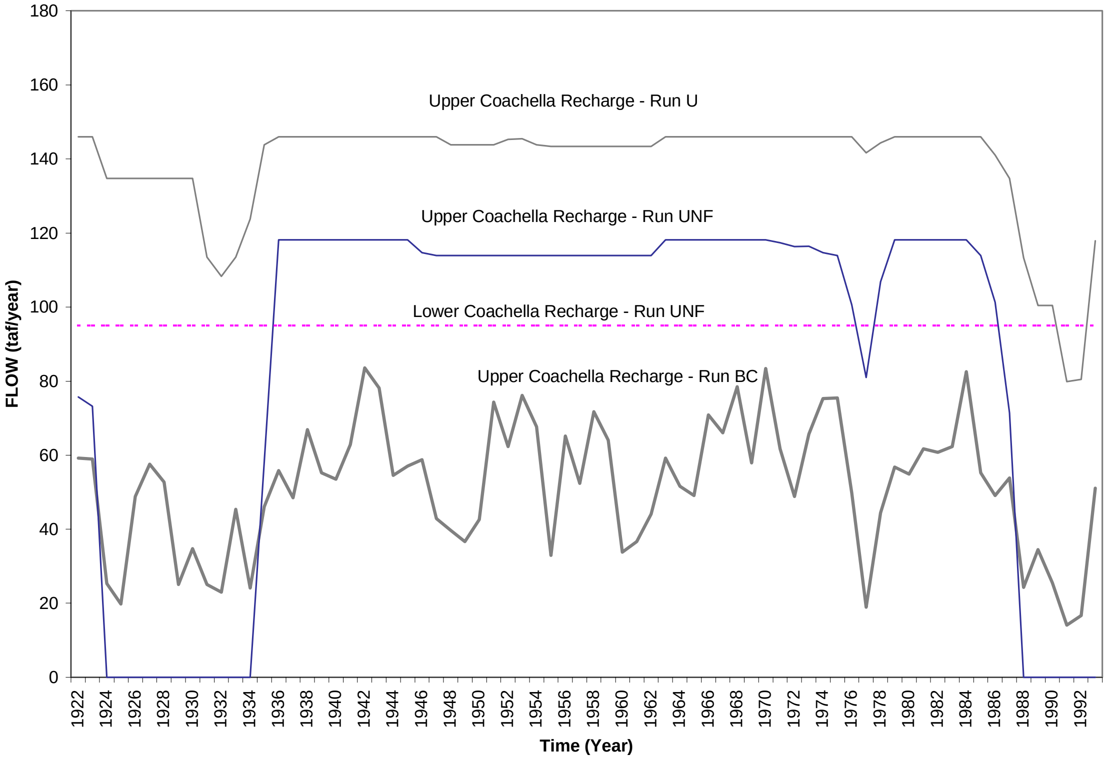


Fig. 24. Coachella Annual Groundwater Recharge

Conjunctive Use along the Colorado River Aqueduct

In both unconstrained operation runs, U and UNF, the additional groundwater storage along the Colorado River is not used. The reason is that Metropolitan can store Colorado River water surplus in its Diamond Valley Reservoir, and Coachella Urban does not need additional storage capacity, since it can recharge the aquifer in advance with foreknowledge of the water it will need. Therefore, we can conclude that with foresight, flexible water exchange, Coachella conjunctive use facilities, and the additional groundwater storage capacity in GW-Kern, there is no benefit from implementing the Cadiz, Upper Chuckwalla or Hayfield conjunctive use projects.

Reservoirs Operation

Diamond Valley Reservoir (Eastside Reservoir)

The Metropolitan's off-stream Diamond Lake Reservoir is, with difference, the main surface storage in the system (800 taf of storage capacity). As Fig. 25 shows, in run UNF Diamond Valley reservoir's role is reduced to store extra water in the 3-5 years before the three more severe droughts (carryover storage), maintaining the rest of the years an almost inactive constant level, which coincides with the prescribe minimum emergency storage in the reservoir. Although the Diamond Valley Reservoir carries out the main carryover storage in the system in runs BC and U, in run UNF carryover storage is moved to GW-Kern. Long-term groundwater storage prevents evaporation losses, which are significant in Diamond Valley Reservoir for high storage levels (higher than evaporation and filtration losses in the aquifer, since they are happening only once during the recharge, while evaporation in surface reservoirs is depleting their storage month by month).

Comparison of the monthly storage upper quartiles (Fig. 26) reveals that the monthly operation of the reservoir in run UNF is surprising closer to the current operation than in run U. The increased conjunctive use storage in run UNF diminishes the importance of long-term storage in Diamond Valley Reservoir, for storing SWP and CRA water prior to the major droughts.

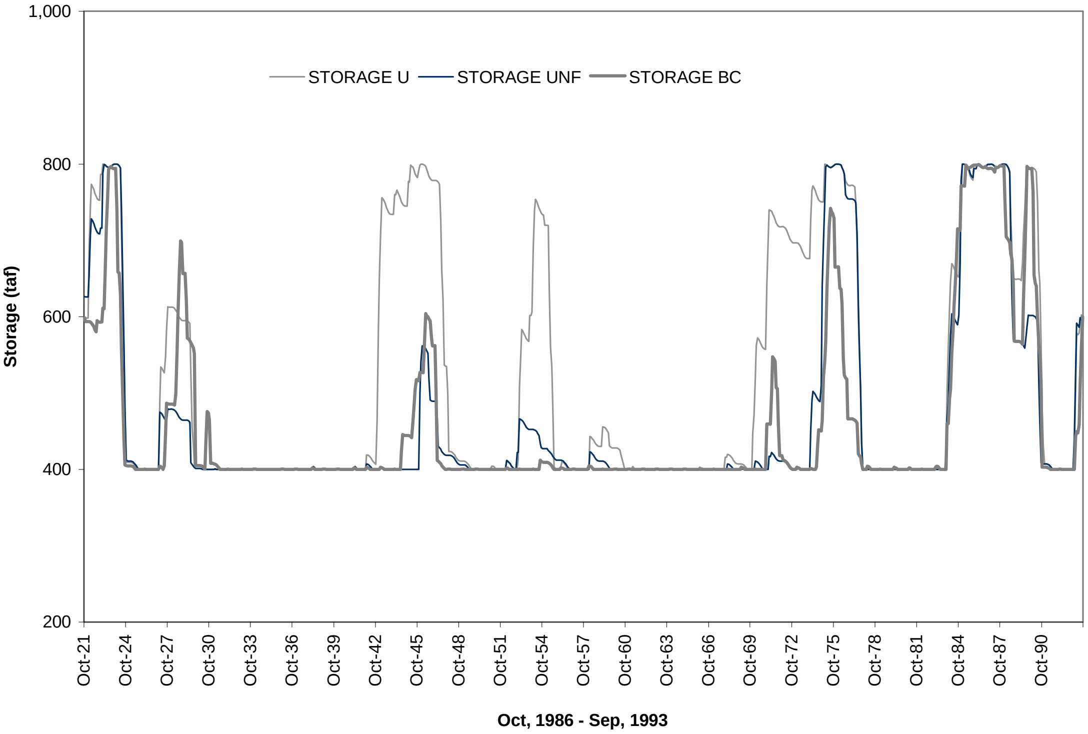


Fig. 25. Diamond Lake Reservoir Monthly Storage

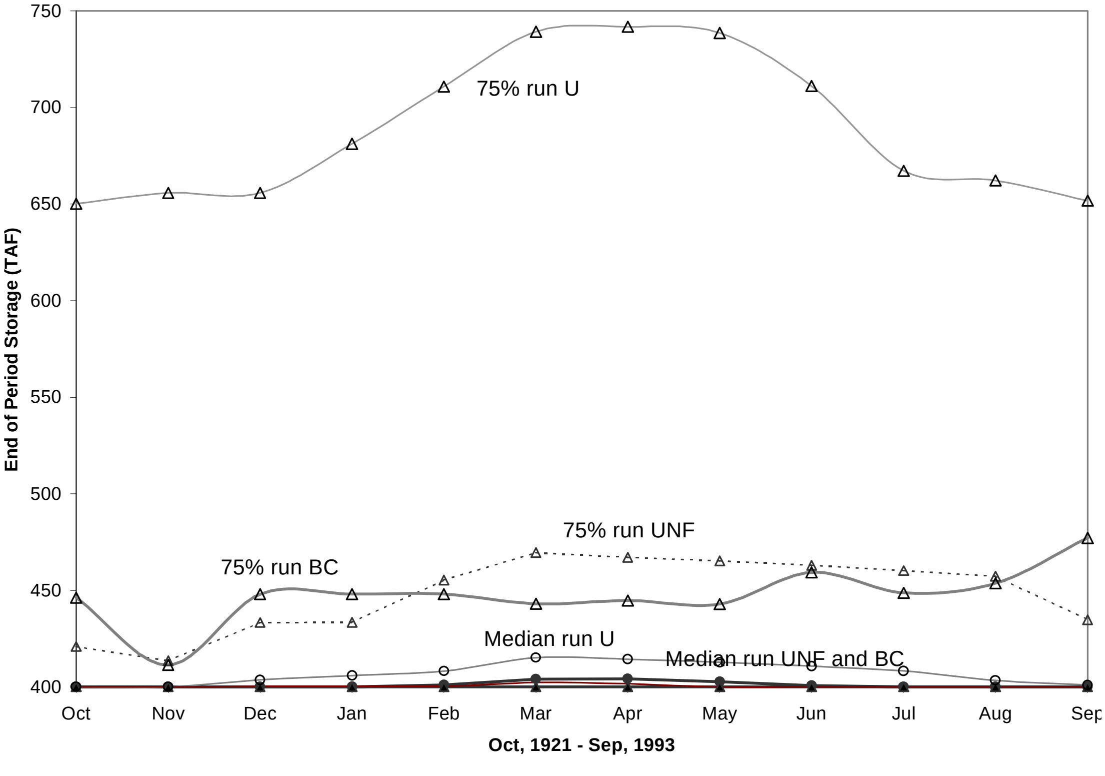


Fig. 26. Diamond Valley Reservoir. Monthly Storage Upper Quartiles

GW-Kern (run UNF)

Under alternative UNF, the two main reservoirs of the system, Kern Groundwater Basin (north of the Tehachapi Mountains) and Diamond Valley Reservoir, act complementarily. The storage in Kern is totally driven by drought storage value. Since there is no lower bound imposed to the groundwater storage there is no permanent pool, and all the storage is long-term carryover storage to mitigate the droughts of the system (Fig. 27). During the main droughts the storage is driven to empty, after of which the fulfill cycle starts again. Meanwhile, Diamond Valley Reservoir captures part of the CRA flow released before the droughts thank to Coachella conjunctive use, and this extra storage is used to supply the three MWD demands, with very high willingness-to-pay in those periods. It would be easy to develop an operating rule that would give similar Kern groundwater operations without perfect foresight.

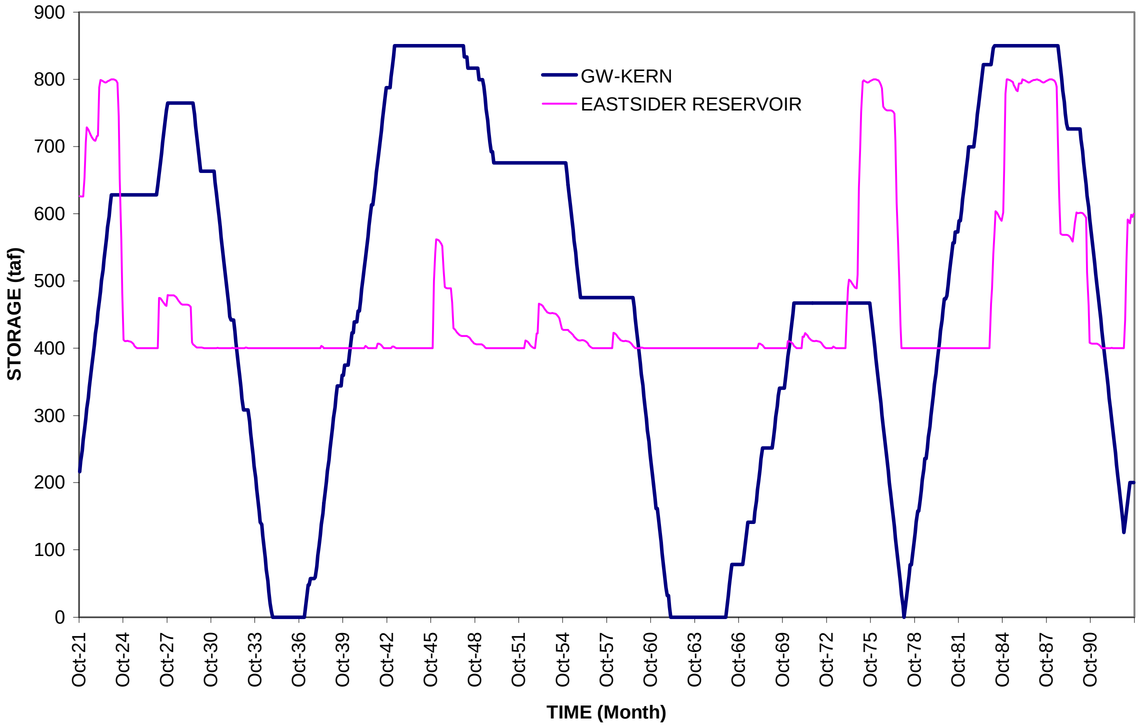


Fig. 27. Diamond Valley Reservoir and Groundwater-Kern Monthly Storage

Distribution of Storage Among Reservoirs

Storage allocation rules based on balancing total storage of the system among some of the reservoirs can be useful in some cases, if some patterns can be identified (Lund 1992, Lund and Ferreira 1996). In this study, the optimization results appear to present a pattern in balancing the total storage between the two main storages in the system, Kern Groundwater Basin and Diamond Valley Reservoir, in runs U and UNF (Fig. 28 and Fig. 29). In run UNF, maximum storage levels correspond to the situation prior to the severe droughts. The initial reductions in total system storage from maximum levels come from the storage in the other surface and groundwater reservoirs. GW-Kern (run UNF) storage is decreased as the total storage is reduced below 1,900 taf. After that, there is a dominant linear pattern of decreasing the storage in GW-Kern when the total storage is reduced. The groundwater basin becomes “empty” (empty according to storage capacity defined as the empty storage currently available in the groundwater basin for conjunctive use) at the end of severe droughts (Fig. 27), as the total storage becomes less than or equal to 1,100–1,000 taf.

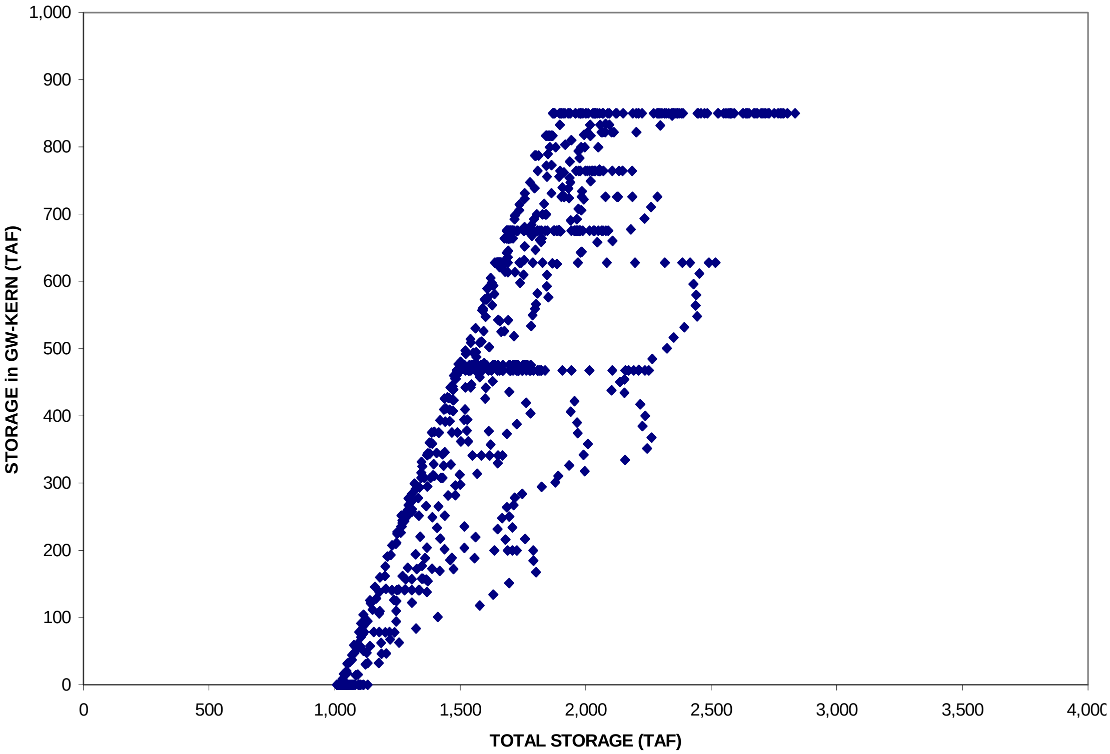


Fig. 28. Monthly Storage in GW-Kern vs. Total Storage (run UNF)

In run U, the pattern of the balancing rule for the Diamond Valley Reservoir storage approaches a piecewise linear allocation (Fig. 29). It is retained as full or nearly full at the earliest reductions in total system storage. As total storage is reduced below 3,000 taf., the storage in the reservoir is decreased until the minimum storage pool is reached. Refill storage allocation follows this rule in reverse.

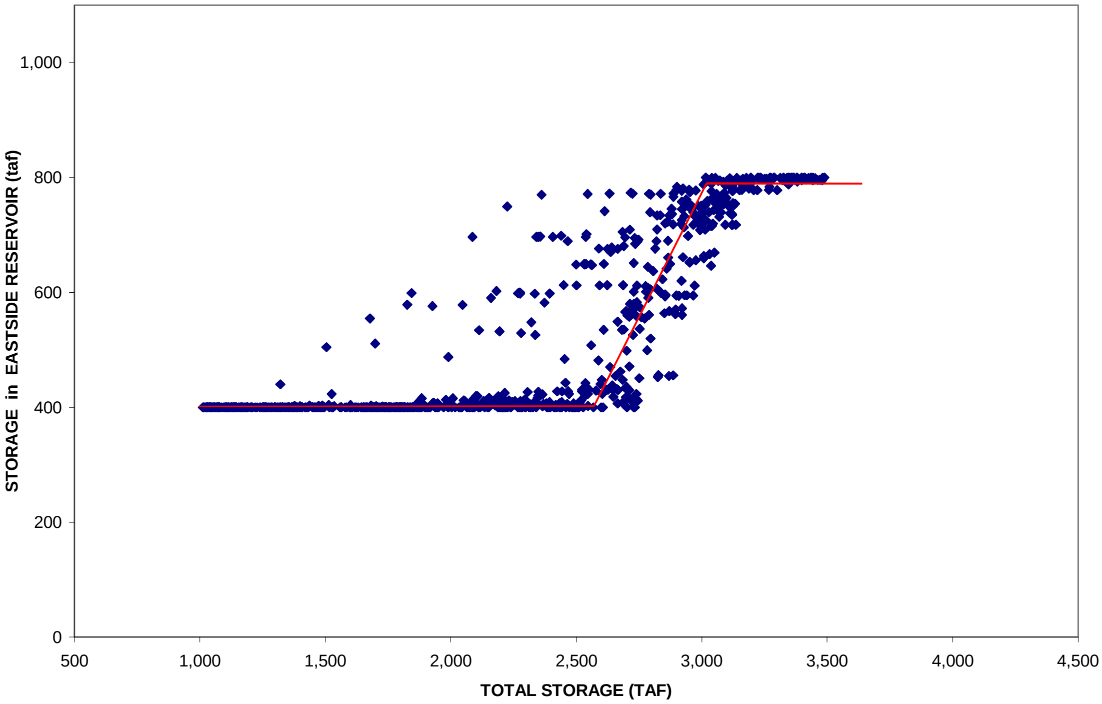


Fig. 29. Monthly Storage in Diamond Valley Reservoir vs. Total Storage (run U)

VII. INFRASTRUCTURE EXPANSION

CALVIN reports the shadow values on constraints placed on storage and conveyance capacities. These shadow values reveal the additional benefit to the region if the capacity constraint is loosed by one unit. Since there are lower and upper bound constraints, a negative shadow value is reported when the lower bound is binding, indicating that the model will benefit from a reduction in this lower bound. If the lower bound is zero in a conveyance facility, negative shadow values indicates that the optimal solution at that time step will be to inverse the flow direction. If there is a dead pool, or an emergency storage pool, negative shadow values arise when the lower bound is binding, indicating the economic desirability of using this water.

Marginal value of Storage Capacity Expansion

Table 9 displays the expected and maximum value of expanding each surface storage facility. In run U, the highest expected value corresponds to LAA storage facilities, since they can store the most valuable water (high quality, high energy production). A higher storage capacity would prevent non-power producing spill losses in the Owens Valley gorge.

Table 9. Marginal Economic Value of Reservoir Capacity Expansion

CALVIN name	*Surface Reservoir*	*Monthly Expected Value (K$/af)*		*Maximum (K$/af)*	
		U	*UNF*	*U*	*UNF*
SR-25	Silverwood Lake	4.5	3.1	323	242
SR-27	Lake Perris	4.4	2.8	322	241
SR-28	Pyramid Lake	3.9	2.6	322	241
SR-29	Castaic Lake	3.6	2.3	323	242
SR-LA	Aggregated Los Angeles Reservoir	15.4	13.1	358	356
SR-GL	Grant Lake	16.1	14.3	533	536
SR-LC	Long Valley Reservoir (Lake Crowley)	14.5	12.7	358	355
SR-LM	Lake Mathews of MWDSC	7.7	5.8	319	238
SR-LSK	Lake Skinner	10.6	8.6	317	268
SR-ER (DV)	Diamond Valley Lake	4.1	2.9	322	241

Table 9 also shows that the expected values of increasing the surface storage capacity decreases for all the reservoirs under run UNF, due mainly to the extra storage capacity the Kern groundwater basin provides.

Fig. 30 and Fig. 31 display the storage and shadow value time series for the main surface reservoir in the system, Diamond Valley Reservoir, for runs U and UNF. Diamond Valley Reservoir is an off-stream reservoir, with a high operating cost ($21.25/af for pumping). In run U, shadow values appear in relation with the major droughts. Positive shadow values occur before droughts, when the system tries to store as much water as possible (perfect foresight), and the storage capacity binds. Negative shadow values emerge after droughts, when the lower capacity binds and the system would benefit from drawing water from the minimum pool. In run UNF, the Diamond Valley Lake remains at the minimum level most of the time, with positive and negative values substantially reduced, due to the extra storage of SWP water in Kern groundwater.

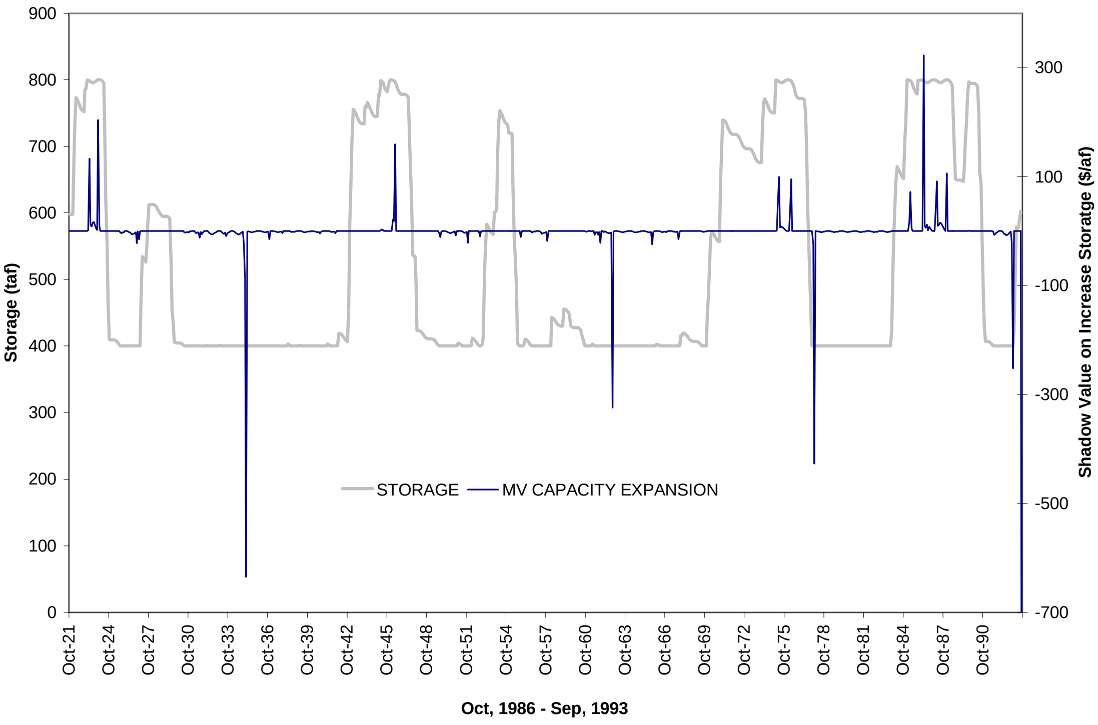


Fig. 30. Diamond Valley Reservoir Storage and Capacity Shadow Values, Run U

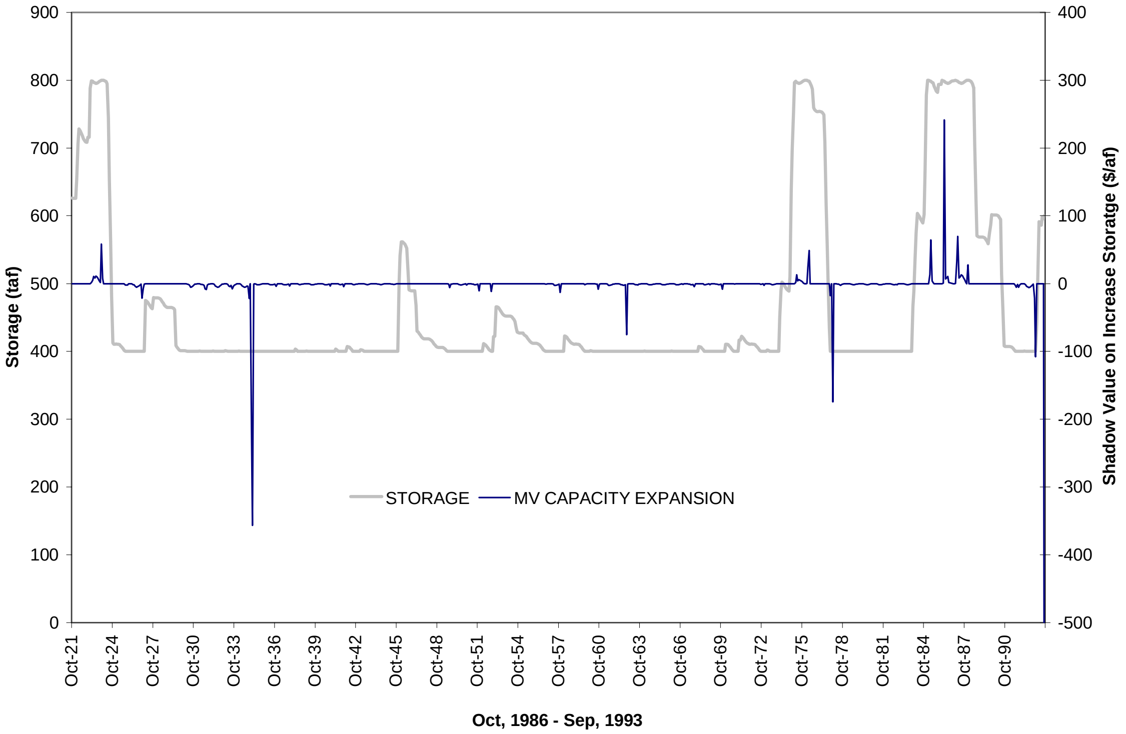


Fig. 31. Diamond Valley Reservoir Storage and Capacity Shadow Values, Run UNF

Fig. 32 shows that the capacity of the Kern groundwater basin is almost optimal, having zero shadow value most of the time. The only period when it will be worthy to expand the storage capacity will be before the most severe drought, and at end of the period of analysis.

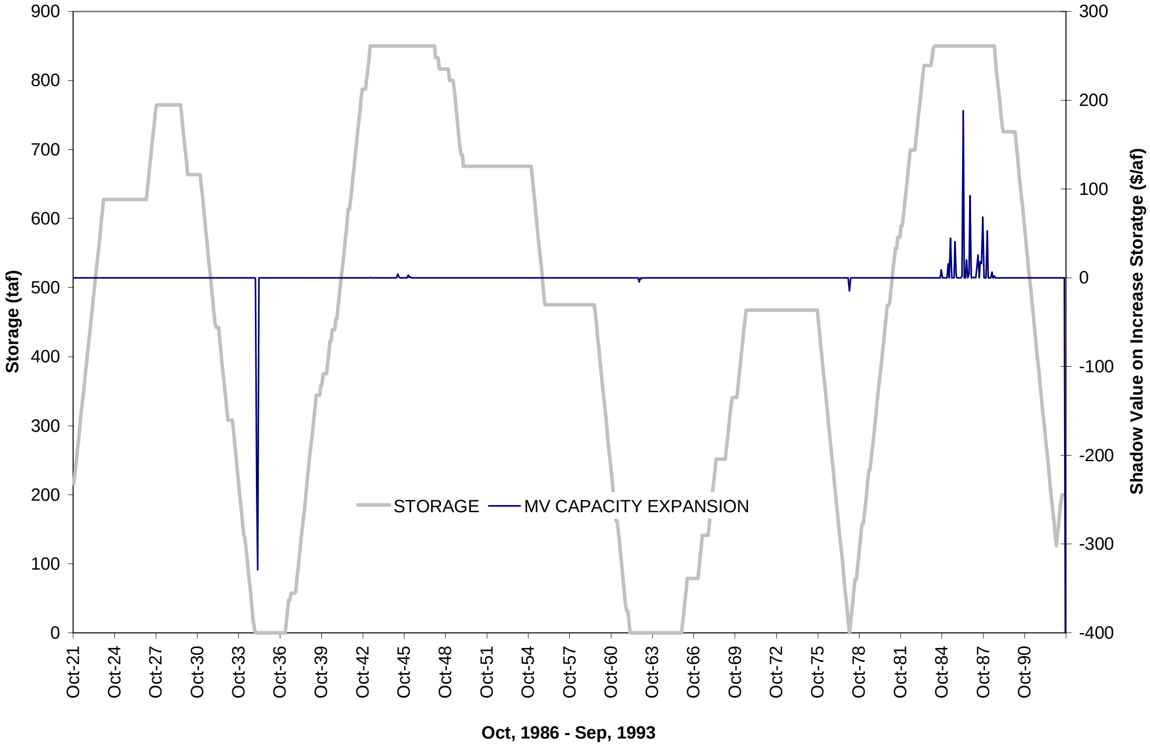


Fig. 32. Kern Groundwater Basin Storage and Capacity Shadow Values, Run UNF

Marginal Value of Conveyance Capacity Expansion

Mojave Pipeline

Fig. 33 shows the shadow value time series of increasing the capacity of the Mojave pipeline. The average positive shadow value is 450 $/af. During the three main droughts periods, since scarcities occur in all the other demands, the capacity is not binding, and the shadow values become zero during that time. For the last drought (1987-1992), negative shadow values indicates that the lower bound is binding and the system would benefit from exporting water from Mojave, because the water opportunity cost is higher than the benefit derived from recharging the Mojave groundwater basin. The reduction in shadow values for run UNF can be attributed to the additional SWP storage north of the Tehachapi Mountains (GW-Kern), allowing a more uniform distribution of the supply to the system, mitigating the effects of droughts.

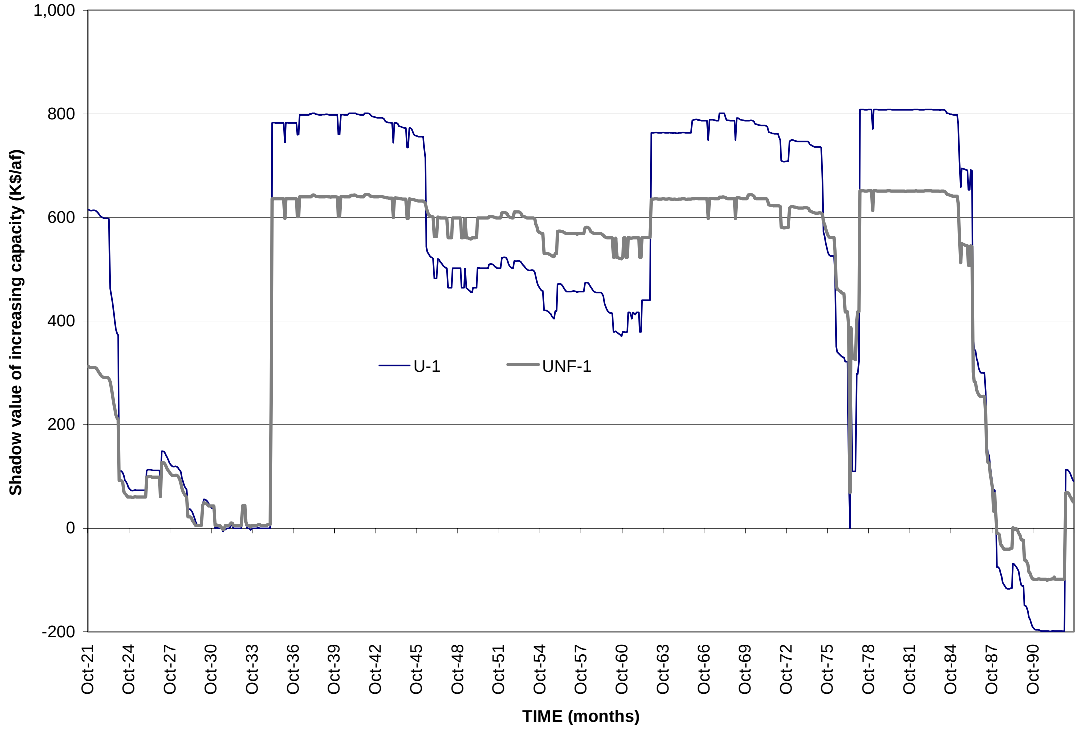


Fig. 33. Shadow Values of Mojave Pipeline Capacity

Conjunctive Use in Coachella – Artificial Recharge

Fig. 34 shows that artificial recharge capacity in the Upper Coachella Valley has a significant reduction in its shadow values in run UNF. Increased conjunctive use operation in the Coachella system (including recharge in the Lower Valley) in run UNF allows significant scarcity reduction in Coachella. Although the capacity is still binding most of the time, the marginal economic benefit of its expansion is not as high as in run U.

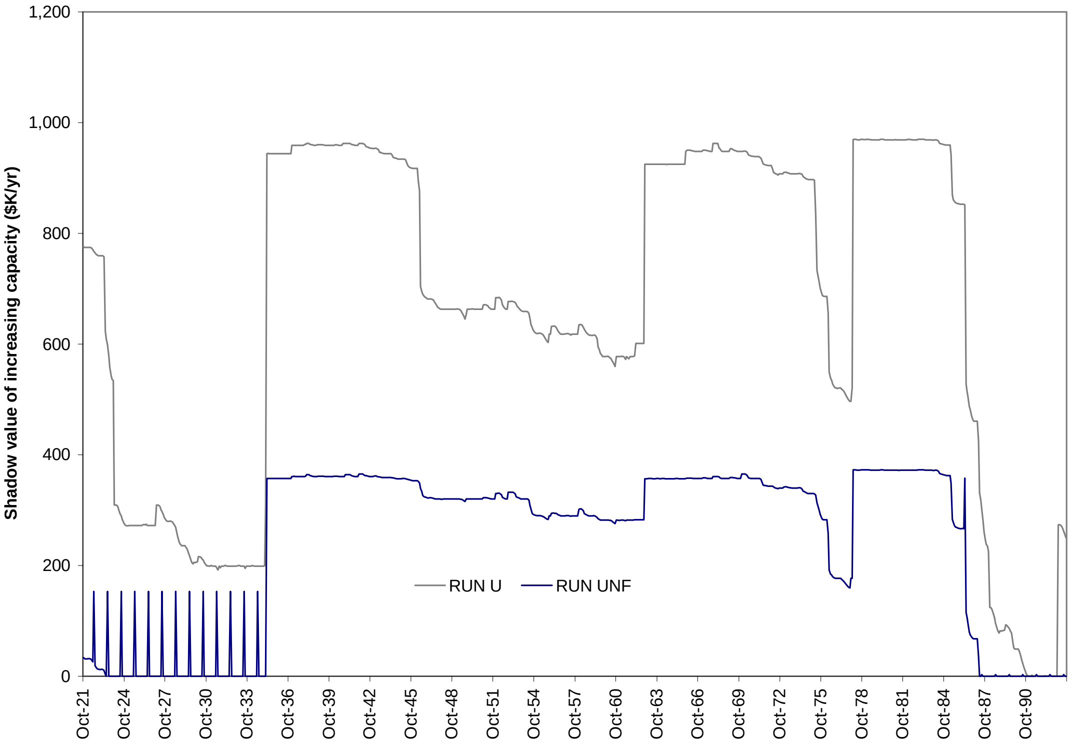


Fig. 34. Shadow Values of Artificial Recharge in Coachella Upper Valley

Colorado River Aqueduct

The Colorado River Aqueduct capacity is also binding during most of the months in the period of analysis. Although the shadow values' temporal pattern is similar in both runs, the values are significantly lower in run UNF, due to the reduction in scarcities and scarcity cost in run UNF (Fig. 35).

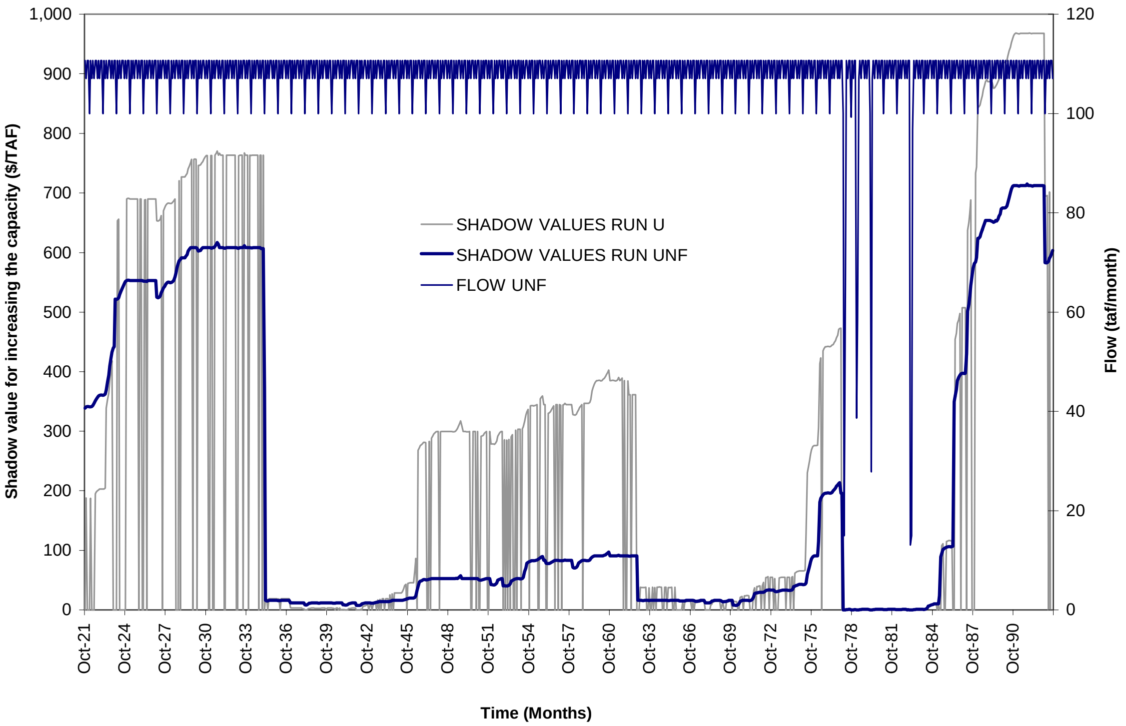


Fig. 35. Shadow Values of the Capacity Constraint in the Colorado River Aqueduct

Kern Groundwater Basin Pumping and Recharge Links

The operation of Kern groundwater basin differs from the operation of most aquifers in the system, since Kern is used for long-term storage, and not for short-term supply of the demands. There is a time-lag between the recharge and the pumping and this is reflected in the shadow values time series (Fig. 36). Expanding the recharge capacity is only worthwhile at the beginning of the period of analysis, when the system is trying to recharge as much as possible. Expanding the pumping capacity will be especially worthwhile during the 1976-77 drought, but also in the last severe drought, at the end of the period (1987-1992). The average positive shadow values are very low ($8/TAF for pumping, and $6/TAF for recharge). Therefore, we can conclude that there is not much economic incentive to expand recharge, pumping capacity or storage capacity for the Kern groundwater basin.

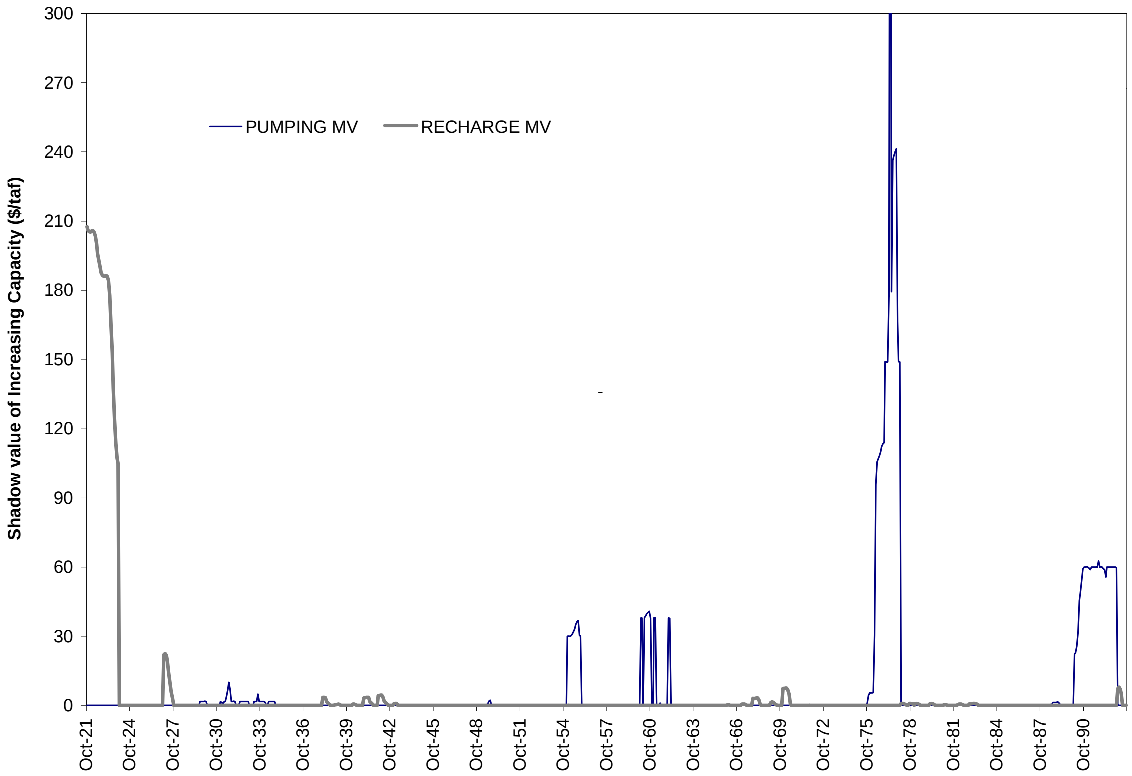


Fig. 36. Shadow Values of Pumping and Artificial Recharge in Kern Groundwater Basin

VIII. CONCLUSIONS, LIMITATIONS AND IMPROVEMENTS

Conclusions

Considering the limitations of this modeling approach (discussed in the next section), several conclusions are presented below.

Flexible water allocation (such as water markets), together with improved conjunctive use operation of surface and groundwater, can reduce drastically scarcity and scarcity costs in Southern California. Small reallocations of water to the demands with higher economic values can substantially decrease regional scarcity cost. The most promising transfers come from the agricultural regions on the Colorado River to the urban demands, limited by the capacity of the Colorado River Aqueduct.

Operation of additional conjunctive use facilities and storage capacity under flexible water allocation (water transfers) can generate substantial economic benefits to the region. Conjunctive use adds operational flexibility needed to take full advantage of water transfers, and transfers provide the allocation flexibility needed to take economical advantage of conjunctive use. The value of projected conjunctive use facilities under the optimal operation of the system (in the sense of maximizing net benefits for the region over the period of analysis) has been examined. Increased conjunctive use operation improves the yield and yield-reliability of the system, and reduces evaporation and spill losses. Additional storage capacity north of the Tehachapi Mountains allows better regulation of SWP flows, and increases long-term storage for droughts. Improving the hedging of stored water in the system can diminish scarcity costs. By adding artificial recharge in the Lower Valley in Coachella, conjunctively managed with direct reuse for golf irrigation, and the current recharge in the Upper Valley, scarcity and scarcity cost in the Coachella subsystem can be substantially reduced, allowing increased CRA deliveries to Central MWD. Central MWD can decrease its scarcity, and SWP water can be transferred to other urban users. The implementation of these conjunctive use projects could produce a net average benefit for the region as high as $98 million/year.

Additional groundwater storage along the CRA (Cadiz, Hayfiled, Upper Chuckwalla) does not show any benefit to the region under the situation of foresight and flexible water allocation, especially given Coachella conjunctive use facilities and additional groundwater storage in Kern-Semitropic-Arvin Edison.

The flexible operation of the system with conjunctive use reduces reliance on imported sources. Increased conjunctive use and more flexible allocations reduce significantly the marginal willingness to pay for both SWP and Colorado River waters. Once the CRA is operated at full capacity, little economic incentive exits to increase California’s supply from the Colorado River, given the low marginal willingness-to-pay for additional water in the agricultural demands that depends on the Colorado River deliveries (Imperial and Palo Verde).

The results derived for optimal flexible conjunctive use suggest substantial changes in the operation of the system. Some operating rules can be inferred from the optimal results.

The results appear to present a pattern in balancing total storage between the two main storages in the system, Kern groundwater basin and Diamond Valley reservoir.

The highest marginal economic value of storage capacity expansion is for LAA storage facilities, due to the high quality of the water and their high energy production. Substantial benefits would be gained from expanding capacity to deliver Colorado River to the Metropolitan service area. Important benefits can be also derived from expanding other facilities (for example, the Mojave pipeline). With flexible allocation and increased conjunctive use operations, the marginal values of facility expansions decrease considerably.

Limitations and Possible Improvements

Several limitations of the CALVIN approach are discussed elsewhere (Howitt et al. 1999, Jenkins et al. 2001). Although the model presented can be useful for general investigations of conjunctive use potential in Southern California, the representation of the system would provide more accurate outputs with some refinements. Some limitations of the modeling approach and some possible improvements are discussed in this section.

Perfect Foresight

The model uses a deterministic optimization technique, and optimizes the operation over the entire 72-year period simultaneously. Therefore, the model is optimizing with perfect knowledge of future inflows to the system, not necessary a realistic situation. Reservoir and aquifer conjunctive operations are adjusted in anticipation of floods and droughts, causing large carryover storage prior to droughts (aggressive hedging) and little carryover storage previous to wet years (lack of hedging). Perfect foresight can lead to overvaluation of existing facilities, and underestimation of the value of new storage. The model also should underestimate scarcity and scarcity cost. In perfect foresight there is no risk adverse management, since there is no risk (the future is taken in account in the optimal decision).

Draper (2001) proposed an implicit stochastic model with limit foresight and a carryover storage function optimized by a nonlinear search algorithm, and compares the solution for several cases with CALVIN´s perfect foresight. He found that in general the importance of perfect foresight decreases significantly in the presence of greater amounts of groundwater storage available (representing carryover storage), and also that integrated conjunctive use reduces greatly the effects of perfect foresight.

Ideal Flexible Conjunctive Use and Water Allocation

The assumptions of flexible conjunctive use operations and water allocation diverge somewhat from managerial and institutional reality. However, they allow the investigation of promising alternatives of operation of the system, and identify the regional and local benefits associated with these alternatives.

Groundwater Representation

Some limitations of CALVIN's groundwater representation were outlined in Chapter 4. Deep percolation from conveyance losses and rainfall, and stream-aquifer and inter-basin interactions are preprocessed as a fixed time series of groundwater inflows, and thus, not dynamically represented in CALVIN.

The use of fixed groundwater pumping costs hides the effect that variable pumping cost can have on the benefits and the operation of the system. Since groundwater is more aggressively operated in the alternatives studied, changes in pumping cost can be significant through the period of analysis. Besides the substantial additional computation time that modeling variable pumping cost would require with the current solver, lack of reliable and consistent data hinder its implementation (Jenkins et al., 2001).

Simplified Representation of Water Demands and Deliveries

Modeling of demands and water deliveries requires many assumptions, discussed in detail elsewhere (Howitt et al. 1999, Jenkins et al. 2001). The usual lack of available empirical economic data is an important obstacle for a more accurate economic representation of demands.

Other simplifications and possible improvements

Hydropower is represented as fixed-head hydropower, but the HEC-PRM solver allows the inclusion of variable-head hydropower using an iterative solution algorithm.

Due to the limitations of network flow formulation, CALVIN has little ability to explicitly represent water quality (Jenkins et al. 2001). For urban demands, water quality costs are added to the different sources.

Recreation, flood control, navigation, and other operating purposes are not included in the model. They can be included in the future with the addition of appropriate economic functions.

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