Marques, G.F., J.R. Lund, M.R. Leu, M.W. Jenkins, R. Howitt, T. Harter, S. Hatchett, N. Ruud, and S. Burke "Economically-Driven Simulation of Regional Water Systems: Friant-Kern, California," *Journal of Water Resources Planning and Management*, Vol. 132, No. 6, pp. 468-479, November/December 2006.

Abstract

This paper develops and applies an economically driven simulation model for California's Friant-Kern system, a region characterized by diverse water sources employed predominantly for commercial irrigated agriculture, with significant local water trading activity. The economic-engineering simulation approach highlights the importance of representing user economic decisions for water systems in a context of complex physical and infrastructure systems dominated by economic water uses. The model simulates how water users conserve, select supplies and make water exchange and market decisions in response to water costs and availability, and provides estimates of economic and operational impacts of alternative policies for the Friant –Kern system. Results show that high surface water prices cause farmers to pump more groundwater, disturbing an existing conjunctive use system and aggravating regional groundwater overdraft.

Key words**:** water management, simulation of water systems, agricultural economics, conjunctive use, MODSIM.

Introduction

Water resource systems are operated to provide water, food, power, transportation, recreation, and environmental protection (e.g., instream flows). Users who employ water to produce these outputs are organized as farms, commercial enterprises, households, and industries operating under market conditions for economic objectives.

Engineering simulation models commonly support decision-making and water management, representing storage and conveyance operations as well as physical, chemical and biological processes. Models designed to simulate economic behavior have long included price-quantity relationships (Samuelson, 1952; Takayama and Judge, 1964; Dupuit, 1844). In water management, employing price-quantity relationships to drive water use decisions can improve engineering simulation of water systems and provide better insight regarding engineering operations such as water source choice, water transfers, reservoir operation and conjunctive use of surface and groundwater, and their economic impacts. Economic demands for water express water users behavior and reactions to variations in water cost, availability, reliability and technology. Water users commonly make decisions on water use quantity and supply sources, and in some regions users interact in water markets, exchange and pricing schemes involving multiple sources for mutual profit and benefit (Vaux, 1986).

Many economic models of water management, while properly representing the economic nature of water demands, have rather limited representation of the diverse water availability and operation decisions occurring spatially and temporally in complex systems (Burt, 1964; Young and Bredehoeft, 1972; Vaux and Howitt, 1984; McCarl et al, 1999 and Gillig et al, 2001). On the other hand, traditional engineering simulation models for water management and operations typically represent water demands non-economically as requirements or strict priorities (Sigvaldason, 1976; Chung et al, 1989; Andrews et al 1992; Dai & Labadie, 2001). In some situations (e.g. systems dominated by economic water uses) it can be useful for engineering models to simulate the economic behavior of water users, including their selection of supply sources, water allocation decisions, and water conservation measures in response to complex water cost, availability, and technology conditions.

This work combines economic representation of water demands with simulation of complex physical and infrastructure water system within a contemporary, engineering water resources model MODSIM (Labadie, 1995). This approach should provide engineers and water planners with a more integrated understanding of the physical, infrastructural, and economic aspects of complex water systems and a tool to estimate the economic and operational impacts of various policy alternatives for a system driven by water users' economic decisions.

The model simulates surface and groundwater use decisions for agricultural production, surface water contract structure, surface water allocation, exchanges and surface reservoir operation, and groundwater pumping cost variations as function volumes pumped. The method is applied to investigate how changes in surface water pricing affect operational decisions of water supply mix and conjunctive use of surface and groundwater in the Friant-Kern region of California's Central Valley. Results illustrate the value of this combined economic and engineering approach for examining water scarcity and scarcity costs of specific water management policies, such as surface water and groundwater prices.

The paper begins with a review of regional water system modeling approaches, followed by theory of water system simulation driven by economic demands and application to the Friant-Kern agricultural region in California's Central Valley. Friant–Kern is predominantly occupied by commercial irrigated agriculture where water users often employ multiple water sources and engage in water exchanges and markets. The results section evaluates impacts of changes in groundwater pumping costs and surface water prices on surface and conjunctive use operations. Final sections discuss model limitations, promising extensions, and conclusions.

Regional Water System Simulation: Priority-based and Economically-driven Modeling

Simulation models have long allowed analysts to represent water system components and operations and efficiently evaluate different proposed operational strategies (Humphrey and Allan, 1959; Labadie, 1997). Real systems operate based on diverse arrangements, including water rights, environmental laws and economic relationships. For system simulation, computer models often represent such idiosyncratic rules either explicitly or implicitly by using mathematical programming to operate and allocate water according to a set of operational priorities (Labadie, 1997). Simulation models based on mathematical programming can connect many system components in a single model, and easily represent diverse goals that drive system operation through priorities or economic demands. To simulate a desired water allocation, operations and demands can be prioritized through positive/negative unit costs and upper/lower bounds on links. Simulation models based on this approach perform sequential, short-term optimizations that minimize deviations from defined goals, with results from one time step serving as initial conditions for the next time step.

Sigvaldason (1976) represented predefined reservoir operation rules with priorities to capture operator decisions to simulate a large multi-reservoir system. Penalties were assessed on deviations from predefined ideal conditions. A large California system was simulated similarly in Chung et al, (1989) to estimate water operations with priority-based water rights. To simulate more elaborate systems where users have different rights depending on the water source, Andrews et al (1992) applied a network flow optimization model that allocates water sources sequentially, in different layers according to respective users' access and rights. For such sequential priority optimization approaches, other models can be used between time-steps or interactively to represent specific components in greater detail such as groundwater (Andreu et al, 1996; Fredericks et al, 1998) and water quality (Dai & Labadie, 2001). These priority schemes must be able to represent operations under varied conditions with multiple users, a difficult task for large systems where operations involve gains and losses (i.e., canal losses, return flows). Labadie (1995) developed a generalized network flow model (MODSIM) that avoids this problem by considering gains and losses indirectly in a separate, iterative flow calculation algorithm. Israel and Lund (1999) proposed a generalized linear programming algorithm to determine priority-based unit costs for network flow models with gains to correctly reproduce the desired operating priorities. These engineering models represent the diverse, often complex topology of water systems, but are limited in capturing the real behavior behind water use decisions when the system is largely economically driven. The model presented in this paper incorporates economic water demand information to improve representation of users' behavior and simulation of operations and impacts for complex water systems driven by economic motivations.

Economic representations of water demands have been applied with stochastic dynamic programming to maximize the expected present value benefits of water allocation and conjunctive use operations (Burt, 1964), and with sequential linear programming to simulate response of irrigation water users to variations in water supply and cost coupled with a hydrologic stream-aquifer model (Young and Bredehoeft, 1972). Vaux and Howitt (1984) estimate supply and demand functions for a spatial equilibrium model to evaluate interregional water trade benefits in agricultural regions of California. McCarl et al (1999) and Gillig et al (2001) apply two-stage discrete stochastic programming to simulate choices of water use, irrigated versus dryland production and irrigation technology with economic agricultural demands developed separately by linear programming models. These models seek to internally represent economic benefits of agricultural water use and then evaluate economic outcomes of different water management strategies. However, such economic models seldom fully represent water availability in complex systems and user's access to multiple water supplies. Young and Bredehoeft (1972) allocate water to crops to maximize incremental net revenue, but water constraints remain determined by priorities, and pre-defined fixed cost penalties are used to quantify failure to meet demands. Gillig et al (2001) categorize crop water demands by sources of water supply and do not allow supply source substitution. The model presented in this paper broadens such economic analysis by simulating a diverse complex of 36 irrigation districts with explicit representation of 17 water sources, 17 reservoirs and aquifers, numerous conveyance and recharge facilities, water transfer and conjunctive use operations, and operating costs for these facilities. Along with operations and water use decision simulation, the model tracks groundwater storage, head and pumping cost sequentially based on sub-surface physical properties and hydrology, reflecting previous decisions on groundwater use.

The model's agricultural water demands are developed with an economic optimization model calibrated to observed data. The economic water demands are embedded in an engineering operations simulation model (MODSIM) to represent and drive user's economic motivation for water use, source selection and local water market activities. This economically-driven simulation extends now-common priority-based simulation to systems driven by local water user decisions, extends existing economic modeling to more diverse water supply decisions and complex infrastructure systems, and should be useful for estimating economic and operational impacts of various policy alternatives in systems where users optimize water use based on economic value. In intensely developed systems where water is scarce, such as California's Friant-Kern system, extensive conjunctive use operations, water transfers and exchanges already exist and it is important that the simulation models applied are able to represent users' economic water use decisions in a context of complex physical and infrastructure systems.

Friant-Kern System, California

The Friant-Kern Division is a United States Bureau of Reclamation (USBR) project that includes irrigation and water utility districts located in California's Tulare Basin, with over 400,000 hectares of irrigable farmland on the east side of the southern San Joaquin Valley. The districts have access to surface water through USBR's Friant project infrastructure, whose main components are Friant Dam (Millerton Lake) on the San Joaquin River, with 640 hm^3 of capacity, the Friant-Kern Canal, and the Madera canal (Figure 1). Friant Dam is operated for water supply, environmental conservation, flood control and recreation. Other supplies include groundwater and substantial local surface supplies from the Tule, Kings, Kaweah, and Kern Rivers. Groundwater is important for the region and its intensive use has led to aquifer overdraft, land subsidence, salinization, increasing groundwater pumping costs, and encroachment of poor quality groundwater into actively exploited portions of aquifers (CDWR, 2003). Historically this overdraft has provided water supply for the Central Valley's economic development and now provides dewatered storage space for water banking programs and conjunctive operations with surface water (Brown et al, 2001). However, this exploitation pattern may increase adverse impacts if groundwater use is not considered integrally in water management efforts. Conjunctive use motivated the development of a model to simulate the behavior of water users in the region, how they react to system policy and cost changes, and to evaluate overall effects on system operations and policies.

Surface Water operations

Thirty-six irrigation and water districts have water supply contracts with USBR where water deliveries are classified by reliability. The first 800,000 acre-feet (986 hm^3) are termed *class 1* water and are considered the most reliable, followed by the next 1,400,000 acre-feet (1,726 hm^3)(*class 2*). Supplies beyond class 2 (usually winter surplus or flood control releases) are delivered upon availability. Class 1 water is contracted at $44/acre-foot ($0.036/m^3) and class 2 at $34/acre-foot ($0.028/m^3) (Leu, 2001). Forecasts of annual runoff are made in March and updated throughout the irrigation season. If water is insufficient to fulfill the contracts, each contractor's allocation is reduced proportionally. At the end of the water year the delivery accounts are reset to zero (Leu, 2001).

Instream flows

The only substantial instream flow for this system is downstream of Millerton Dam. Much of the San Joaquin River has been largely dewatered by Friant-Kern project, with a small minimum flow requirement downstream of Millerton Reservoir being the only required outflow from the system. Other streams in the region terminate in the Tulare Basin floor, a closed basin except in times of extreme flooding.

Economic Demands in Simulation – Theory and Method

Water use operations and allocations often are guided by water's economic value. Water users face withdrawal decisions related to the spatial and temporal availability of water and production decisions. Under these circumstances the marginal value of water increases with scarcity and water demands reflect users' decisions. If users are not limited by water availability and price and there is no alternative use for water, water's marginal value is zero.

Based on economic values and costs, users decide on both supply source and quantity of use. Unless constrained in availability, water will be used to a point where the marginal benefit from water use equals the marginal cost of supply. An economically-driven simulation model captures this behavior using economic water demand curves to represent the marginal net benefits of water use and users' willingness-to-pay for water (Figure 2). Water scarcity quantity represents the difference between deliveries and beneficial use if supplies were unrestricted and free (Jenkins et al, 2004). Economic scarcity or scarcity cost is the economic value to users of increasing deliveries to eliminate scarcity. This *scarcity cost* is calculated as the area beneath the demand curve (Figure 2) between the points of current water supply and maximum water demand (Jenkins, et al. 2003).

The model's calibration in this work assumes that the maximum demand is the current water demand in the region, at current prices. "Scarcity" is then calculated relative to the quantity demanded at the current water price, which is assumed to be the equilibrium point.

Economic models exist for many water uses, and can be used to develop economic penalty functions. Agricultural penalty curves can be estimated with economic models that maximize agricultural profit subject to constraints on water and other inputs (USBR, 1997; Howitt, 1995; Howitt et al, 1999). Economic penalty functions also can be estimated for urban demands (Jenkins et al, 2003), flood control (Johnson et al, 1988), navigation and recreational uses (US Water Resources Council, 1983; James and Lee, 1971).

Economically-driven simulation presupposes that water users are largely profit maximizers and price takers in a system where water is scarce. Efficient water allocation in this case requires existence of well-defined property rights, information about prices and quantities, and access to water. In these circumstances users can use and exchange water according to production value and ideally reach equilibrium where the marginal value of additional water is the same for all users, except when limited by infrastructure capacities.

However, not all water management objectives can be represented economically. Operations designed for environmental and users' subsistence demands, and operations for which no economic data are available can still be represented with priorities or as constraints. By simulating these objectives as fixed priorities or constraints in an economically-driven model, it is possible to evaluate the opportunity cost of non-economic management activities in terms of the marginal and total values of water in the system.

The penalty curves used in this work were developed with the *Statewide Agricultural Production Model* (SWAP). SWAP models agricultural cropping and water, land and capital use decisions. In SWAP, demand for water for different regions in California are identified with an objective function that maximizes economic returns subject to resource, production and policy constraints, and then calculates the monthly shadow value of water for each level of water supply. The model uses quadratic production functions to allow decreasing marginal returns and substitutability of inputs, and captures farmers' adjustments in irrigated area, crop mix, and irrigation technology intensity to variations in water availability and price (Howitt and Misangi, 2002). The production function used has the following form:

$$y = [\alpha_1 \quad \alpha_2 \quad \alpha_3] . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} - [x_1 \quad x_2 \quad x_3] . \begin{bmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \end{bmatrix} . \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Where *y* is the total regional output of a given crop, *x* the quantity of inputs (land, water and capital) allocated to production, α are the Leontieff coefficients and γ is a square, positive definite matrix that captures decreasing marginal productivity of inputs and interaction effects between inputs. The formulation for "G" regions and "i" crops for a single year is given by (Howitt and Misangi, 2002).

Max $\sum_G \sum_i p_i f_{Gi}(x_1, x_2, x_3) - \omega_1 x_1 - \omega_2 x_2 - \omega_3 x_3$

Such that $\sum_G \sum_i x_{1,G,i} \le X_{1,G}$ (land constraint)

$\sum_G \sum_i x_{2,G,i} \le X_{2,G}$ (water constraint)

Where $X_{1,G}$ and $X_{2,G}$ are the amounts of land and water available to each region G respectively, ω are the marginal production costs (input prices) and p_i the price of crop "i" . The SWAP model is similar to other agricultural production models used in California water studies, but it provides monthly results with a production function calibrated against actual cropping decisions (Howitt et al, 1999; Howitt, 1995; Draper et al 2004). The penalty curves are based on piece-wise linear economic value functions developed through parametric analysis with SWAP, and are obtained by associating, for each segment of the piece-wise linear demand function, the increment on water supply to the average of the marginal values of the two extremes of the segment. Evapotranspiration data used to estimate crop water requirements in SWAP was provided by LAIUZ (Land-Atmosphere Interface and Unsaturated Zone) model (Naugle, 2001).

Water System Simulation Method

The Friant-Kern system is modeled as a sequence of monthly network flow optimizations that simulate water operations and allocations driven by economic decisions at the irrigation district level. The model includes the physical system of canals, reservoirs, streams and demand points, the institutional framework of water contracts, and is run on a monthly time step. Groundwater is represented dynamically with variations in water table and pumping costs calculated based on storage change. The model is developed using the decision support system MODSIM (Labadie,

1995) customized with *perl script* routines. Perl script routines allow access and modifications to model variables during run time, simulating system features not available in the standard MODSIM. In MODSIM, perl script routines calculate water delivery contract accounting (Leu, 2001) and perform additional calculations for more detailed groundwater representation. MODSIM uses a capacitated network flow approach for simulation and optimization of water systems that finds penalty minimizing network flows sequentially for each time step, with results used as initial conditions for the following time step. The software has been applied to simulate diverse river basin systems (Dai and Labadie, 2001; Fredericks and Labadie, 1998).

Economics-based penalties indicate the benefits, in $\$/m^3$, of taking different supply quantities from alternative water sources. The penalty functions developed in SWAP drive the simulation of farmer's decisions on how much water to use and from which sources among various surface and groundwater sources and supply contracts available. Each piece-wise curve indicates the economic benefit of increments in water supply. These functions are represented in MODSIM as a negative cost attached to an *economic link* delivering water to a given demand. Twelve monthly economic functions are developed for each irrigation district or water district. Each piece-wise segment of the penalty function is represented by a link in the network. To minimize the objective function (total costs), water is delivered first through the highest benefit link (represented in the model as a negative cost). This is the first segment in the demand function where a higher value is placed on the first amounts of water available. As more water is available the first high value link reaches its upper bound and the next unit of water available now has a smaller marginal value (Leu, 2001; Marques et al, 2003).

Instream flow demands, downstream of Millerton Dam, are included as monthly reservoir water allocations in MODSIM, and so are abstracted before the water available for allocation within the Friant-Kern system. Instream flows are generally represented as constrained flow dedications, due to controversies in establishing demand curves for environmental flows.

Groundwater representation

The groundwater representation updates water table elevations each time step based on changes in storage due to pumping, artificial recharge, deep percolation and subsurface flows. The water table at the end of a time step is used to calculate groundwater pumping costs for the next time step. A 3D groundwater flow simulation model developed separately (Ruud et al 2002) estimated hydraulic conductance used as response parameter. The aquifer overlaid by the groundwater model was divided into separate "groundwater zones" based on specific yield information, and each GW zone is represented in MODSIM as a storage node.

The 11 irrigation districts covered by the groundwater model are simulated with variable pumping costs in some water systems simulation model runs, while the remaining 25 irrigation districts (representing 73 % of total water use) are always simulated with fixed unit pumping cost.

Model Results and Discussion

Model results explore the effects of surface water prices on conjunctive use and groundwater sustainability, and the effects and implications of variable head representation of groundwater pumping cost. Model runs are made with a variable groundwater pumping (VP) model version, and fixed head pumping cost (FPhigh and FPlow) model versions for comparison purposes. In VP, 11 irrigation districts are simulated with variable groundwater pumping costs, and 25 irrigation districts are simulated with fixed updated groundwater pumping costs. In FPlow, all 36 irrigation districts are simulated with fixed original groundwater pumping costs. In FPhigh, all 36 irrigation districts are simulated with fixed updated groundwater pumping costs. The groundwater pumping costs and model versions are summarized in Table 1. Fixed original groundwater pumping costs are based on Leu (2001), and fixed updated groundwater pumping costs are calculated from Ruud et al (2002).

Surface Water Prices – Policy changes and management implications

Friant users employ conjunctive use operations extensively to increase water availability and flexibility. These operations include artificial recharge through infiltration ponds and natural streams and groundwater pumping (Naugle, 2001; Arvin Edison, 2000a, 2000b). Policies such as surface water price changes can affect conjunctive use operations of irrigation districts by altering the relative costs of surface water and groundwater use, which can be represented by a simulation model driven by economics. This section analyses effects of surface water price changes on the system, subject to variable groundwater pumping costs.

Given the large size of the groundwater reservoirs, the cumulative effects of different groundwater/surface water operations may take a long time to develop. Thus, a 73 year run period was used, based on historical hydrology. The forecast for class 1 and class 2 deliveries to Friant was correlated with annual inflows at Millerton (Friant Dam) and the correlation function was used to extend class 1 and class 2 forecasts for the entire historical inflow record. Although the correlation coefficient was acceptable (0.95), the ten years of class 1 and class 2 deliveries used in the correlation are a small sample for statistical analysis.

Class 1 and class 2 water are the most important components of surface water supply to contractors and changes in their price are expected to affect the relative value of groundwater, pumping patterns, operating costs and end-of-period groundwater storage. Friant contract water prices increased in 1992 due to increasing operation and maintenance costs and environmental regulation (Leu, 2001). To simulate the effects of surface water price changes in the Friant system, ten runs using the VP (variable groundwater pumping cost) model version were made with the Friant surface water price contract varying from \$0.019/m^3 and \$0.011/m^3 to \$0.165/m^3 and \$0.157/m^3 (class 1 and class 2 respectively) across the runs. For each run the surface water price is held constant for the entire period.

With lower groundwater pumping costs, and long-term externalities not internalized in the pumping cost, higher surface water prices cause users to switch to groundwater supplies and intensify aquifer overdraft. Drawdown can accumulate over the years causing a decline in groundwater use once pumping costs become too high. At the highest surface water prices, the aquifer is so intensely exploited in the first years that groundwater pumping declines after 40 years and is pumped in much less quantity during drought years compared to scenarios with lower surface water prices (Figure 3). At this high surface water price there is a large economic impact and drought conjunctive use operations are compromised. Figure 3 depicts the time series of combined groundwater pumping of the 11 irrigation districts modeled with variable groundwater pumping cost for three different scenarios of Friant surface water price contract: 0.036/0.029, 0.084/0.076 and 0.165/0.157 ($\$/m^3$ of class1/class2).

Figure 4 illustrates the effects of class 1 water price on average region-wide scarcity costs and end-of-period overdraft, based on 73 year runs with a given Friant surface water price contract. End-of-period overdraft is the cumulative overdraft at the end of the 73 year run period in the groundwater basins modeled with variable pumping cost. Significant increase in surface water prices leads to severe overdraft in parts of the system and scarcity costs over $35 million/year.

Figure 5 presents end-of-period (EOP) groundwater storage of several sections (groundwater zones) of the aquifer for different Friant surface water prices. EOP storage is decreases greatly when surface water costs surpass the groundwater pumping cost and groundwater pumping replaces surface water. Groundwater basins exploited by irrigation districts with higher value crops and high demands are more susceptible to higher overdraft. Groundwater zone GW06 is shared by most districts and suffers a high overdraft as surface water price increases (Figure 5). Groundwater zone GW04 also is affected, but not until the surface water price exceeds $\$0.101/m^3$. Most water in GW04 is used for high value crops.

Tables 2 and 3 depict average scarcity and scarcity costs. The scarcity quantity represents the difference between deliveries and beneficial use if supplies were unrestricted and free (Jenkins et al, 2004). Increases in surface water costs raise scarcity and scarcity costs, although some distortions in model behavior are found. Increases in contract price up to $\$0.088/m^3$ class 1 and $\$0.076/m^3$ class 2, reduce scarcities for some districts. For lower contract water prices, surface water is used whenever demand exists. During the drier, high demand months, a district will not have enough contract water available and resorts to groundwater, sometimes reaching the pumping capacity and facing scarcity. This mis-represents farmer behavior for very low surface water prices. In practice, farmers have enough foresight to better allocate surface and groundwater use over a growing season. Even for low surface water prices, groundwater will supplement surface water in early months (March-April). The surface water “saved” will be available during later dry months, when pumping capacity is reached, avoiding scarcity. This problem may be addressed either by multi-period optimization or by allowing farmers to store their shares of surface water driven by carry-over storage value functions able to represent such operations properly. For higher surface water prices, the model’s behavior is consistent and scarcity and scarcity costs increase for most districts.

Groundwater Pumping Costs – management implications
To evaluate the effect of groundwater pumping cost representations, a variable pumping cost (VP) model version run is compared to fixed groundwater pumping cost model results (FPhigh and FPlow). Variations in groundwater pumping costs affect the mix of surface water and groundwater use, and so affect conjunctive use and other operations. Effects on water supply and allocation are evaluated through changes in surface and groundwater operations and use, and system states, characterized by groundwater storages and heads. Groundwater pumping costs for different model versions and irrigation districts appear in Table 1.

The higher groundwater pumping cost used in FPhigh reduce average groundwater pumpage by over 50% (except for LTID, 32%) compared to the FPlow run for the 11 districts with greater groundwater detail. Terra Bella irrigation district (TBID) reduces groundwater pumping by 97% as the cost increases from \$0.036/m^3 in FPlow to \$0.095/m^3 in FPhigh. This operation is followed by an increase in class 1 TBID water use from 10.4 hm^3/year to 30 hm^3/year, on average.

With higher groundwater pumping costs, irrigation districts switch to cheaper sources to maximize net revenue and avoid scarcity, affecting surface water operations. Following contract water, the next least expensive supply source is other local, non-contract surface water supply. Irrigation districts with higher crop values will switch to other local surface supplies reducing their availability to other districts. Porterville Irrigation District (POID) and Lower Tule River Irrigation District (LTID) reduce groundwater pumping by 56% and 32% respectively and increase class 1 and other surface supplies (in this case, from Tule River). This increase in withdrawals from Tule River affects Pixley Irrigation District (PXID), whose average Tule River supply is reduced from 21.3 hm^3/year to 15.8 hm^3/year. These results demonstrate the effect of each district's operations on water allocation in the system when users make economics-based decisions on water sources.

When groundwater pumping costs exceed costs for surface supply sources, further increase in groundwater costs has little effect on pumping until pumping costs exceed the district's marginal willingness to pay for irrigation water. This is because class 1 and class 2 water are constrained by contractual amounts (districts cannot trade USBR contract water among themselves in the model) limiting the system's flexibility to cope with increases in groundwater costs by switching to surface water supplies.

Groundwater pumping costs calculated in run VP are higher than the other runs and increase in time with overdraft, resulting in less groundwater use and higher scarcity. Of the 202 hm^3/year average reduction in groundwater use, 170 hm^3/year are replaced by contract water (Table 4), and the remaining 32 hm^3/year are scarcity increases. This difference between modeling scenarios indicates the region can operationally accommodate most variations in groundwater pumping costs modeled/represented.

Minor differences from FPhigh to run VP are limited to irrigation districts highly dependent on groundwater supply, like Pixley. Groundwater pumping in Pixley is reduced in March and April and replaced by class 1 water. In drier months class 1 water availability is reduced and Pixley resorts to groundwater pumping. With fixed pumping cost, variations in groundwater pumping are driven by surface water availability. With variable pumping cost, some change is seen in the pumping pattern (Figure 6). Faster increases in cost during dry years reduces pumping in VP, as opposed to a more variable pumping pattern in the fixed pumping cost run FPhigh. Pixley is willing to pay \$0.101/m^3 for the last portion of supply and since pumping costs increase up to \$0.088/m^3, there is no reduction in pumping in run VP, because groundwater remains economically attractive at the margin.

Conjunctive use operations in the region are presented in Figure 7, which depicts time series of pumping heads and respective pumping costs for groundwater zone GW12. To aid visualization of seasonal variations in groundwater pumping and head, a shorter time window (1970-1992) is

displayed instead of the whole time series. This period includes both a very dry period (1976-1977) and a wet period (1987-1992). Conjunctive use operations include:
A) *Seasonal operations*. Use of groundwater and surface water alternates within the year, typically with groundwater pumping concentrated in dry months and artificial recharge undertaken in wet months with surplus floodwater. Results in Figure 7 show the effects of seasonal and multi-year operation on groundwater pumping cost and heads, with groundwater pumping concentrated in the steep sections of the chart, and surface water and artificial recharge in the flat sections. (October marks the end of the dry season and beginning of the wet season.)

B) *Drought management*. The distinct groundwater head and pumping cost patterns in Figure 7 presents groundwater pumping concentrated in dry years (steeper head and cost increases during the dry years of 1976-1977) and reduced groundwater use in wet years (minimal head and cost increase during the wet years of 1978-1984).

C) *Continuous overexploitation*. The overall trend of increasing pumping costs and heads indicates that historical overdraft continues. According to the model's economic framework, it may still be economically worthwhile to maintain current groundwater pumping volumes for most irrigation districts, despite increases in the pumping cost. Further conclusions depend on more detailed knowledge of other impacts, such as land subsidence, and externalities such as groundwater pumping cost increases from neighboring groundwater use. These negative externalities highlight the problem of exploiting groundwater as a common pool resource. Optimal pumping for each individual user is to withdraw groundwater up to the point where pumping cost equals his marginal benefit (willingness-to-pay). Thus users with high crop production values may increase the groundwater costs for neighbors with lower crop production value. As long as some users see economic gain, the model allocates water in this fashion and neglects subsequent negative impacts, which groundwater users have little individual incentive to consider. An example of impact from neighboring groundwater operations is found for POID district, which despite pumping considerably less groundwater than other districts sharing the same aquifer faces steep increases in groundwater pumping costs. Coordination efforts among districts may be needed for successful conjunctive use programs that avoid this type of externality.

Effects of reduced groundwater pumping are overdraft reduction from 26 km^3 to 11.3 km^3 from FPlow to the variable pumping VP run, over the 73-year period. However, reduction in aquifer overdraft raises average annual water scarcity from 10 hm^3 to 42 hm^3, comparing FPlow to FPhigh runs. This increase in scarcity is attenuated by reduced pumping expenses.

The 26 km^3 overdraft under the lower groundwater cost scenario (FPlow) translates to $19 million/yr average scarcity costs. Avoiding this overdraft would require reducing groundwater pumping by either reducing production or acquiring supplemental non-local surface supplies averaging 355 hm^3/year. The groundwater pumping curtailment seen in the VP run could reduce the overdraft to 11.3 km^3 with a cost of $24 million/year in scarcity costs, without supplemental surface supplies. To eliminate the 11.3 km^3 overdraft, 155 hm^3/year average of supplemental surface supplies would be needed, or a high tax on groundwater pumping.

Model Limitations, Promising Extensions and Future Developments

The first integrated system model developed for the Friant-Kern system has several significant model limitations. Response factors for calculating inter-district subsurface flows require a detailed groundwater model. So far only a small portion of the project area has such a groundwater model (11 of 32 irrigation districts). The method used to estimate total pumping lift does not account for overlapping cones of depression, which could further increase pumping heads.

The monthly demands are not interrelated. The economic demand functions used in the model vary by month to motivate higher deliveries in critical months, and thus better represent water operations required for engineering purposes. Farmers plan the cropping season based on a forecast of surface water availability at the beginning of the year. Thus the forecast of a dry year results in some readjustment in demands (e.g. reduced area of annual crops). Depending on how the loss functions are calibrated, crop losses could either be under or over estimated. However, evidence of this potential problem has not been verified in the results. This condition is explained by the typical ability of the farmers to move water between time periods within a season, either contractually or via groundwater storage. There also are problems if the groundwater pumping capacity is reached in a given month, since the model does not anticipate this.

In practice, the trade-off between immediate use of water versus surface or groundwater storage is based on future benefits. To estimate economically worthwhile levels of storage or groundwater recharge, future benefits must be identified. Economic value functions for water storage would also remove the limitation of “zero-foresight” and the distortions seen in the results. This approach would improve inter-temporal water allocation. Carry-over storage value functions, like those developed by Draper (2001) could be used in this extension. Another alternative is to extend the optimization period over multiple time steps, perhaps spanning an irrigation season, giving the model some foresight over future hydrology and operations.

Friant users operate a highly dynamic and closely coordinated system to cope with limited water supply. Coordination includes multiple and complex operations of water conveyance and water exchanges and trades. Model results indicate potential for water transfers but the current simulation is still inflexible regarding USBR contract water. Further model improvements should look at possibilities of contract water exchanges and its consequences for the system’s water management.

This improvement could be attained at the expense of added complexity in the form of operational policies, such as water transfers, water quality management and conjunctive use, posing limitations for simulation with network flow programming. Although iterative approaches may reduce such limitations, LP solvers take advantage of dedicated constraints to allow more explicit representation of complex operations that often depend on flows in other parts of the system, like water exports, exchanges and conjunctive use operations, while the model structure allows more straightforward problem formulation by the user.

Linear Programming approaches have been applied with priority-based objective function to simulate detailed diversion and water blending operations for water quality (Randall et al, 1997), in representation of reservoir target curves with a multiple constraints generalized model

(WASP) (Kuczera and Diment, 1988), and other frameworks using generalized LP and mixed integer (MILP) solvers to model large systems including OASIS (Meyer et al, 1999) and CALSIM (Draper, et al. 2003). The combination of such methods with the economically-driven approach presented in this paper will allow the simulation of increasingly complex problems with effective representation of different goals driven by institutional frameworks, economic relationships, agreements and environmental regulations.

Conclusions

An economically-driven engineering simulation model was applied to California's Friant-Kern water system. The approach extends conventional use of priority-based penalty functions in engineering system simulation models by representing demands based on users' willingness to pay for water, and improves economic approaches to water management with a detailed engineering representation of water availability, infrastructure, water transfers, groundwater and conjunctive use operations. Results show that users change supply sources and quantities and transfer water reacting to variations in water price, economic value and water availability. By capturing this behavior, the model highlights the importance of representing user economic decisions in a context of complex physical and water infrastructure, and provides insights on how management and policy alternatives affect regional economy and water operations in the Friant-Kern system, including water transfers, levels of surface and groundwater exploitation, water scarcity and scarcity costs. Further conclusions are:

1) Use of economic functions in the model's objective function allows evaluation of economic losses when demands are not met. This enables the model to evaluate economic feasibility of supply expansion projects and water importation programs.

2) Where economic effects determine users' reactions to changes in the system, a water system populated by users with high production values for water will take more time to react to groundwater overdraft and increased pumping cost (all other factors being equal).

3) Simulation performance is affected by future operations and events. Actual water users have some foresight in making decisions that may not be captured in a simulation model unless: a) The simulation time step is large enough to cover users' foresight, b) Optimization spans several time steps, or c) Present operations account for "value" of resource being allocated in the future through carryover storage value functions.

Variations in surface and groundwater prices, and water use have implications for local policy and water operations. Reduction of historical overdraft requires reduction of groundwater pumping and the transfer of additional water supplies to avoid increase in scarcity. A 57% reduction in overdraft requires additional supply equivalent to 44% of total current surface supplies in the lower groundwater cost model version (FPlow). Without additional surface supplies, this reduction in overdraft would cost an additional $5 million/year average in scarcity costs, a 26% increase. Transfers to higher value production should consider compensation mechanisms to improve equity and mitigate third party impacts.

The direct implication of surface water availability and prices on surface and groundwater use has consequences for management programs including conjunctive use operations. Intensive groundwater pumping under high surface water prices aggravated overdraft conditions, further limiting groundwater supply in dry seasons and dry years. High surface water prices reduce the efficacy of conjunctive use programs relying on alternation between recharge in wet periods and pumping in dry periods. This requires improved coordination among users through water transfers, exchanges and artificial recharge operations that increase flexibility in local water operations and support conjunctive use operations.

Economically-driven simulation can be applied to other regions where water is scarce, economic water uses are predominant, and data is available to calibrate supporting economic models. Other productive sectors, such as hydropower, navigation and urban uses can be modeled with this approach, while non-economic demands (e.g., environmental) and operations can still be included with priority-based penalties. The approach is recommended for supporting decision making on regional water resources systems where competition for water is intense, water users operate the system based on economic decisions, and the economic and operational impacts of proposed management alternatives are of interest.

Acknowledgements

The authors thank Randi Field (USBR), Mike Tansey (USBR), Marc Baldo, Mark Jensen (HEC) and Lenore Thomas for valuable contributions during development of this work, and several anonymous reviewers for their suggestions.

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Table 1 – Groundwater Pumping Costs used in the 11 irrigation districts modeled with greater groundwater detail for different model versions.

Higher groundwater detail	Irrigation District	Irrigation District name	FPlow ($\$/m^3$)	FPhigh ($\$/m^3$)	VP average[1] ($\$/m^3$)	VP minimum[1] ($\$/m^3$)	VP maximum[1] ($\$/m^3$)
Yes	DEID	Delano-Earlimart	0.036	0.048	0.061	0.047	0.079
Yes	KTWD	Kern-Tulare	0.036	0.078	0.078	0.049	0.097
Yes	LIID	Lindmore	0.036	0.099	0.104	0.092	0.115
Yes	LSID	Lindsay-Strathmore	0.036	0.107	0.108	0.101	0.119
Yes	LTID	Lower Tule River	0.036	0.059	0.071	0.042	0.097
Yes	PXID	Pixley	0.036	0.036	0.066	0.036	0.091
Yes	POID	Porterville	0.036	0.092	0.103	0.092	0.113
Yes	RGWD	Rag Gulch	0.036	0.049	0.074	0.049	0.110
Yes	SAID	Saucelito	0.036	0.063	0.089	0.063	0.105
Yes	TPWD	Tea Pot Dome	0.036	0.095	0.105	0.095	0.116
Yes	TBID	Terra Bella	0.036	0.095	0.105	0.095	0.115
No	All remaining 25 districts		0.036	0.036	0.036	0.036	0.036

[1] average, max and min values for 73 years run period

Table 2 – Average water scarcity for the 11 irrigation districts with greater groundwater detail in VP model version for varying surface water prices.

	Scarcity (hm^3/year)					
class1 and class2 prices ($\$/m^3$) →	**0.011 and 0.019**	**0.028 and 0.036**	**0.060 and 0.068**	**0.092 and 0.101**	**0.109 and 0.117**	**0.157 and 0.165**
Friant contractor						
↓						
Delano-Earlimart	7.0	7.8	4.7	17.1	43.9	58.8
Kern-Tulare WD	1.6	1.6	1.6	1.6	1.6	1.6
Lindmore	1.5	1.6	1.6	1.1	1.8	17.6
Lindsay-Strathmore	9.0	9.0	9.0	8.9	8.1	12.3
Lower Tule River	18.2	18.4	12.2	17.5	57.2	138.7
Pixley	0.0	0.0	0.0	8.0	14.5	19.6
Porterville	0.2	0.4	0.2	0.1	0.9	8.6

Rag Gulch	1.2	1.2	1.1	0.6	0.2	0.1
Saucelito	1.1	1.2	1.1	3.3	6.5	25.4
Tea Pot Dome	0.2	0.2	0.2	0.1	0.0	0.0
Terra Bella	0.1	0.1	0.1	0.1	3.2	8.1
Total (hm^3/yr)	**40**	**42**	**32**	**59**	**138**	**291**
All contractors (hm^3/yr)	**175**	**147**	**187**	**313**	**419**	**587**

Table 3 - Average scarcity costs for the 11 irrigation districts with greater groundwater detail in VP model version for varying surface water prices.

	Scarcity cost ($1,000/year)					
class1 and class2 prices ($/m^3) →	**0.011 and 0.019**	**0.028 and 0.036**	**0.060 and 0.068**	**0.92 and 0.101**	**0.109 and 0.117**	**0.157 and 0.165**
Friant contractor						
↓						
Delano-Earlimart	928	1062	626	1782	4826	7010
Kern-Tulare WD	669	669	669	669	669	669
Lindmore	204	215	215	152	255	2469
Lindsay-Strathmore	3747	3750	3750	3696	3411	2372
Lower Tule River	2044	2060	1369	1958	6429	17368
Pixley	0	0	0	877	1606	2197
Porterville	37	44	31	21	111	1153
Rag Gulch	557	569	523	304	97	41

Saucelito	136	144	134	406	820	3819
Tea Pot Dome	70	71	71	46	15	2
Terra Bella	17	18	18	18	401	1134
Total ($million/yr)	**8.4**	**8.6**	**7.4**	**9.9**	**18.6**	**38.2**
Total all contractors ($million/yr)	**26.2**	**24**	**25.6**	**36.7**	**48.2**	**69.6**

Table 4 - Overall results, 73 year average – 11 districts with greater groundwater detail

	Fixed groundwater pumping cost **FPlow run**		Variable groundwater pumping cost **VP run**	
Totals (taf/yr avg)		% Total demand		% Total demand
Demand	979	100.0%	979	100.0%
Total Supply	969	99.0%	937	95.7%
Scarcity	10	1.1%	42	4.3%
		% Total supply		% Total supply
Surface contract supply	335	34.6%	506	53.9%
Surface other supply[2]	115	11.8%	115	12.2%
GW supply	519	53.6%	317	33.8%

[2] Excluding artificial recharge

CAPTIONS OF FIGURES

Figure 1 – Friant-Kern System, California
Figure 2 – Marginal net benefit and water scarcity
Figure 3 – Time series of combined groundwater pumping under different scenarios of Friant surface water price contract

Figure 4 – End-of-Period overdraft and average scarcity costs
Figure 5 – End-of-Period groundwater storage for different surface water prices
Figure 6 – Time series of groundwater pumping in Pixley (PXID) irrigation district
Figure 7 - Time series of heads and pumping costs for Groundwater zone GW12 for the period 1970-1991

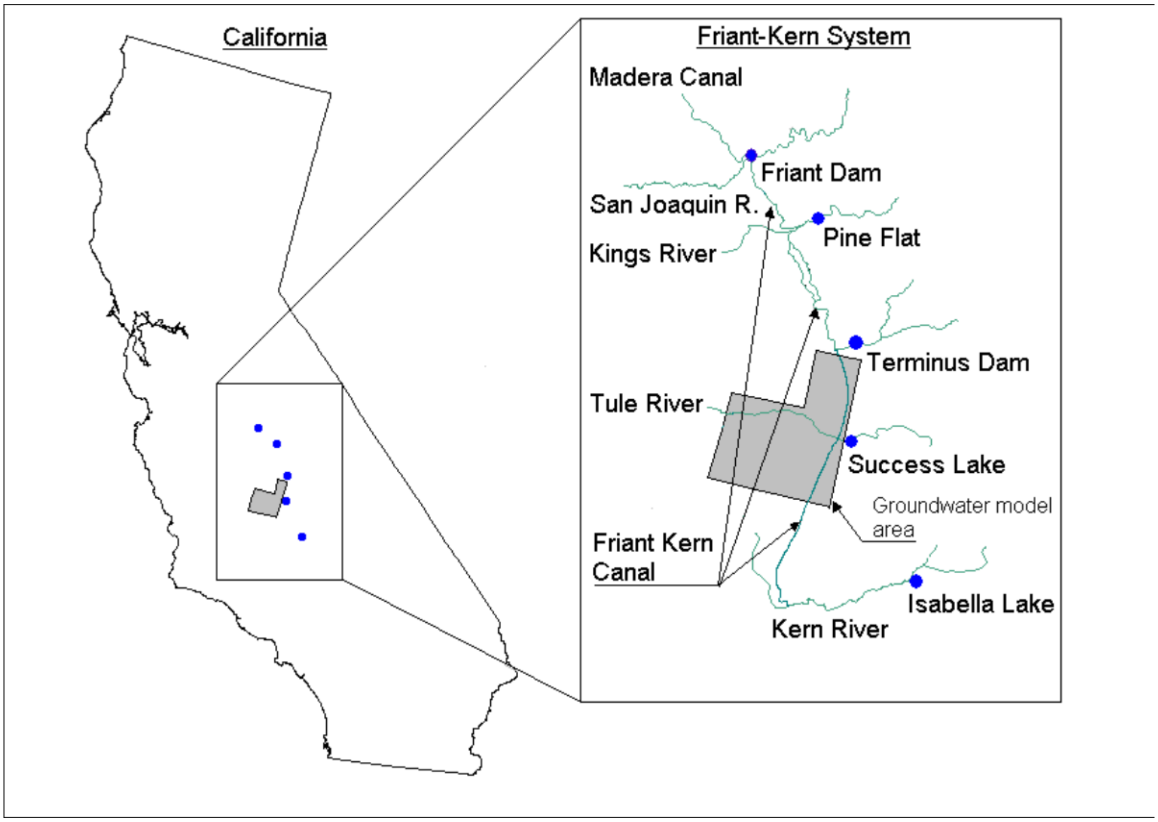

Figure 1 – Friant-Kern System, California

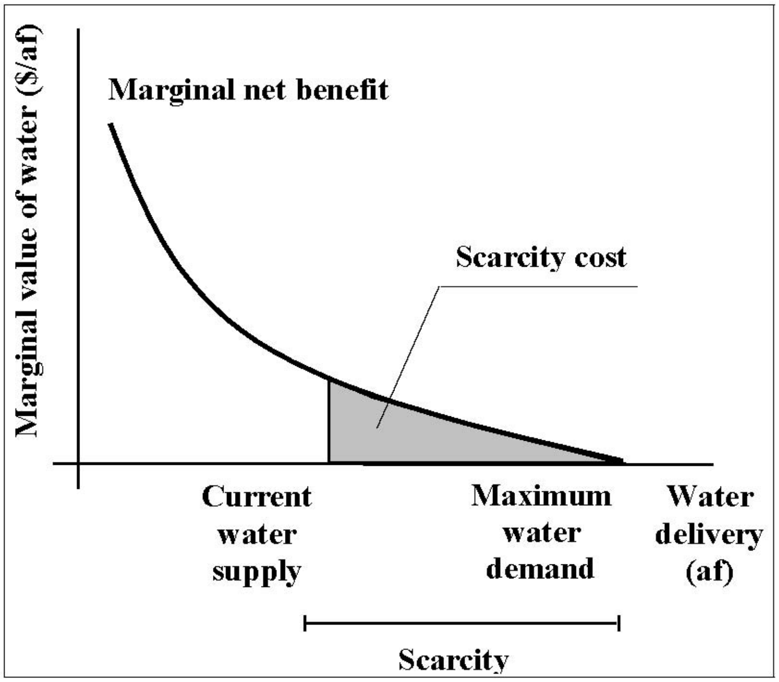

Figure 2 – Marginal net benefit and water scarcity

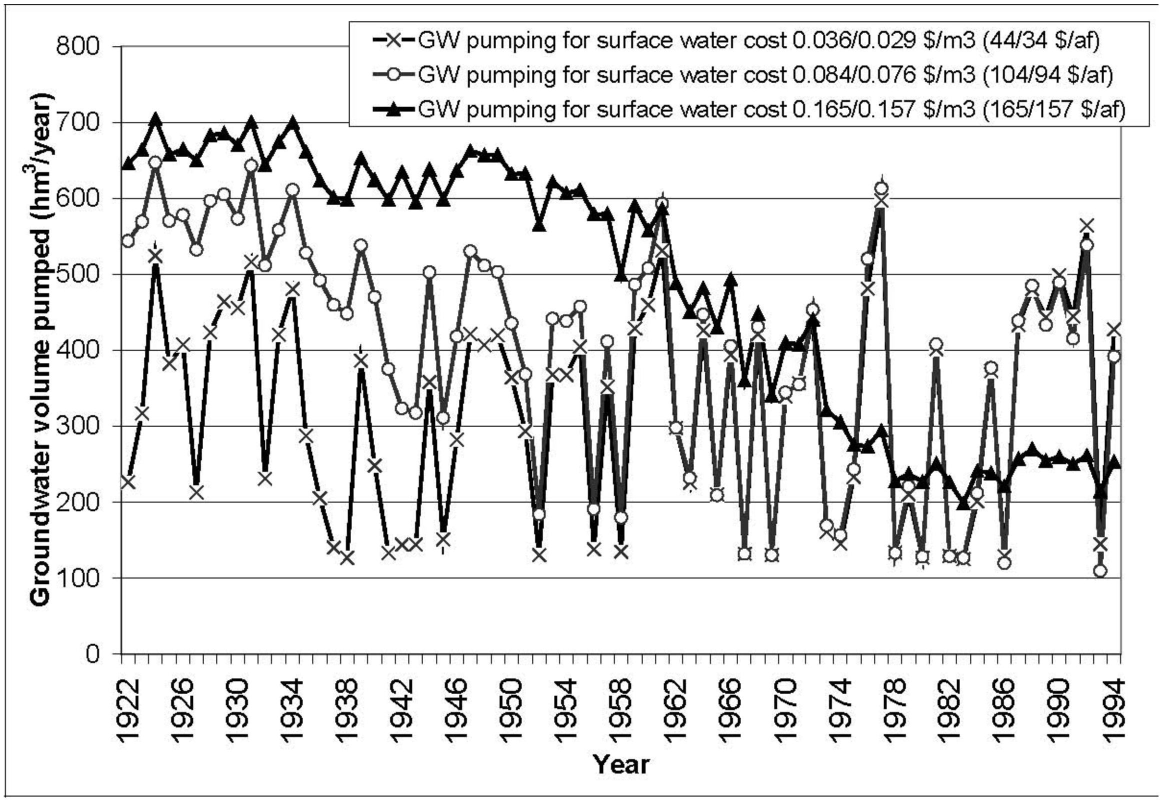

Figure 3 – Time series of combined groundwater pumping under different scenarios of Friant surface water price contract

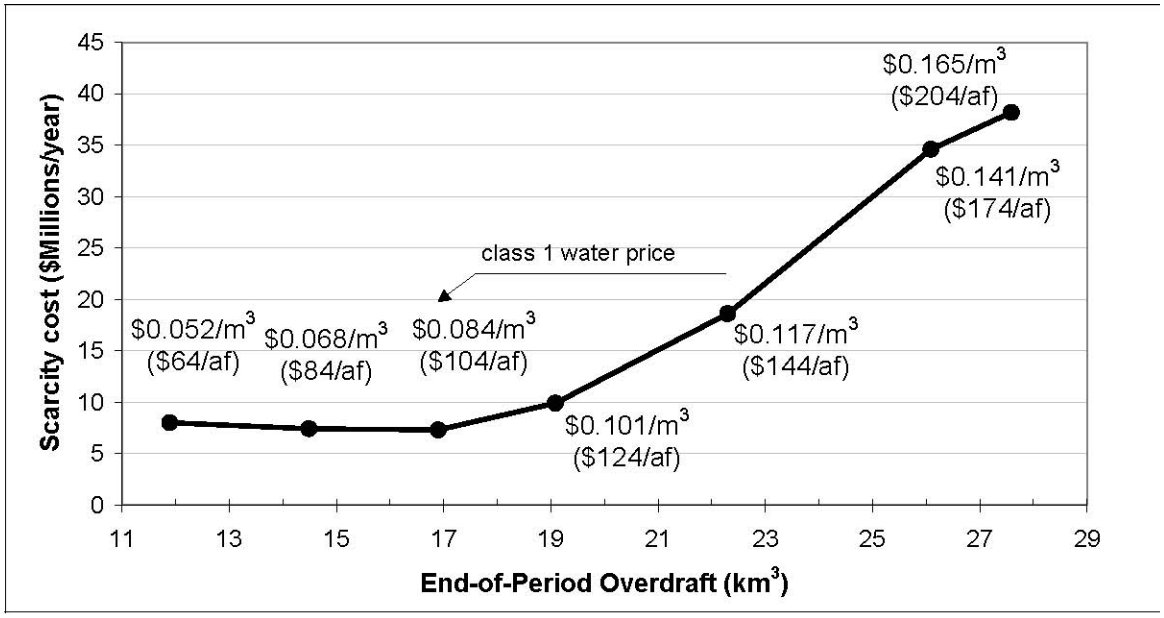

Figure 4 – End-of-Period overdraft and average scarcity costs

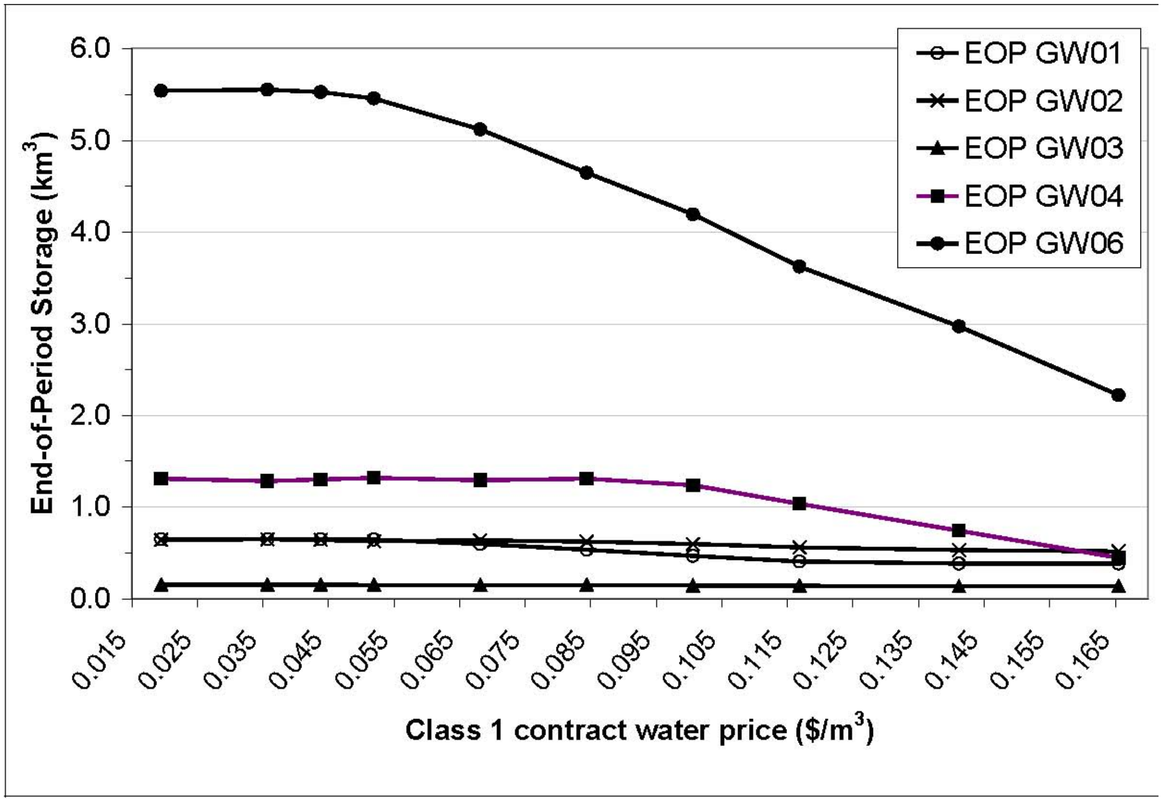

Figure 5 – End-of-Period groundwater storage for different surface water prices

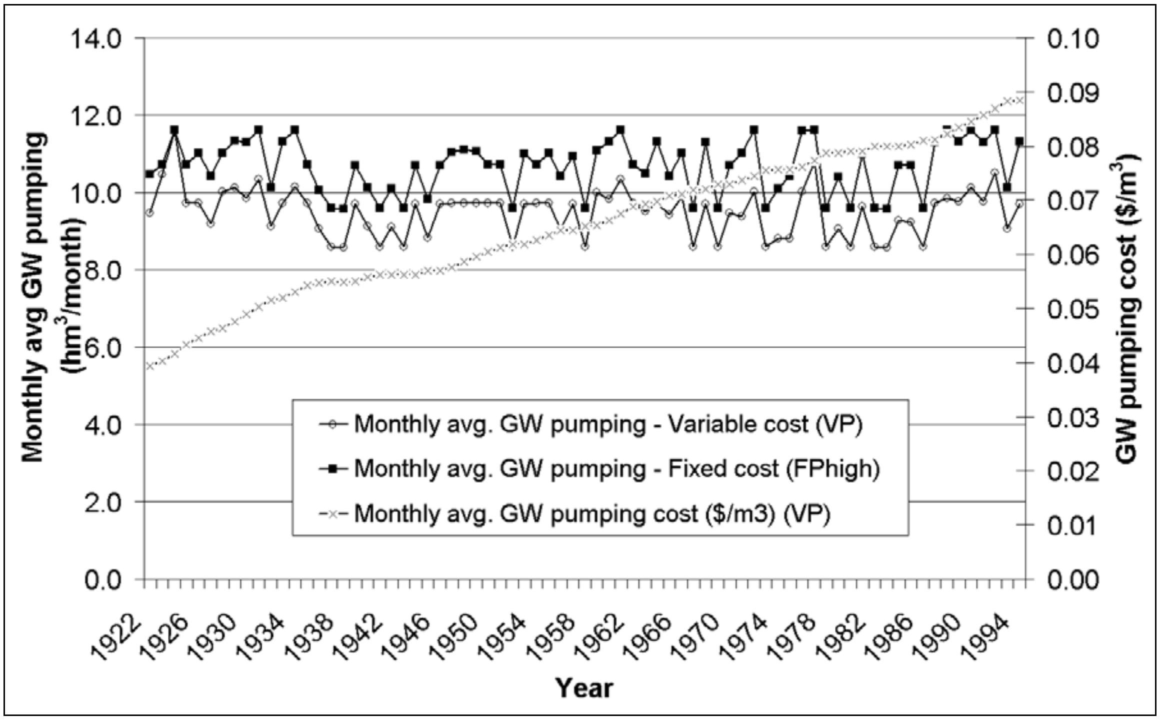

Figure 6 – Time series of groundwater pumping in Pixley (PXID) irrigation district

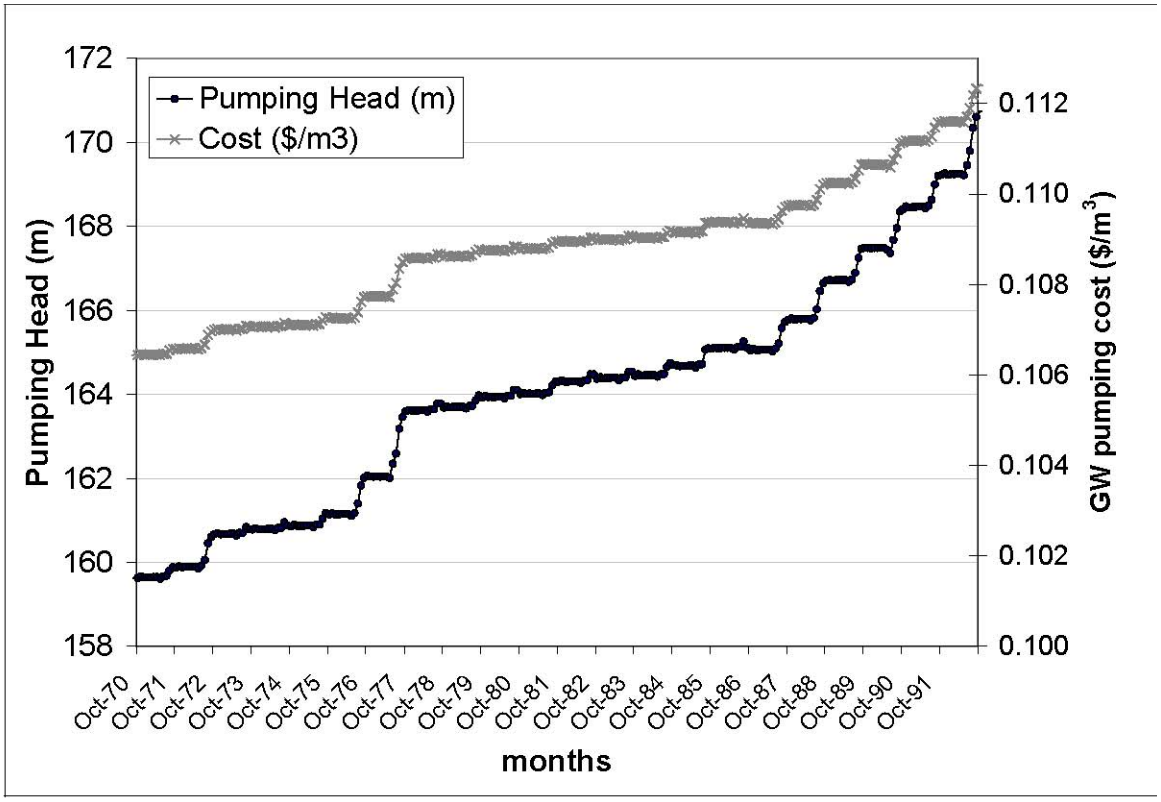

Figure 7 - Time series of heads and pumping costs for Groundwater zone GW12 for the period 1970-1991