Economic Representation of Agricultural Activities in
Water Resources Systems Engineering

By

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Economic Representation of Agricultural Activities in Water Resources Systems Engineering

Abstract

Water demands reflect water users' decisions in uncertain and often complex water systems, yet the driving forces behind these decisions are frequently neglected in water management engineering models. Traditional engineering modeling approaches represent economic water demands as fixed targets with pre-defined priorities and are often limited in capturing the behaviour of water users when affected by water management plans and operations. Despite the variety of solutions proposed in the fields of water resources engineering and resource economics, the understanding and simulation of economic water demands is still limited given the multiple decisions faced by water users and the uncertainty in water supplies. This dissertation presents modeling approaches for water management that borrow concepts and methods from resource economics combined with stochastic, linear, and quadratic optimization for simulating agricultural water decision and demands. The first approach is implemented with a two-stage stochastic quadratic programming model to simulate water, irrigation technology and conjunctive use decisions calibrated to real operations and marginal conditions. The model maximizes the net expected benefit of permanent and annual crop production with probabilistic water availability, and results demonstrate users' willingness to pay for increased water supply reliability and improved water management with conjunctive use operations. A second approach employs water demand functions to drive water decisions in a regional water system modeled with network flow programming and variable groundwater costs. Results demonstrate how users' decisions on supply sources and local management (conjunctive use) are influenced by water availability and price. The two-stage quadratic model is developed in the General Algebraic Modeling System (GAMS) and solved with MINOS. The network flow system model is developed in MODSIM.

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Chairperson, Dissertation Committee

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

INI_i	Total initial costs of implanting permanent crop *i*
ϕ	Fraction of irrigation applied water that deep percolates
ϕ'	Soil moisture content
$\alpha_{1,i}$	Intercept of supply functions for permanent crop *i*
$\gamma_{1,i}$	Slope of supply function for permanent crop *i*
$\alpha_{2,l}$	Intercept of supply function for annual crop *l*
$\gamma_{2,l}$	Slope of supply function for annual crop *l*
Δh	Water table change
Δh_{ij}	Difference in head between groundwater zones i and j
ξ_i	Stress irrigation threshold for permanent crop *i*
A	Area
a_j	Amount of water available to agricultural region in year type *j*
$AW_{2,j,l,k}$	Demand for applied water by annual crop *l* when irrigated with technology *k*
c_{1i}	Net average annual revenue from permanent crop *i*
c_{2l}	Net annual revenue from annual crop *l*
$CA_{1,i,j}$	Replant penalty for permanent crop *i* in year type *j*
C_{ij}^{eff}	*Effective conductance* between groundwater zones i and j
E_o	Energy required to pump a unit volume of water [kw-hr/gal]
e_o	Groundwater pump efficiency
ETa	Evapotranspiration
E_{well}	Energy consumed by a well for a given period of time tp [kw-hr]
fc	Field capacity and is
g	Number of hydrologic events
h	Number of irrigation technology types available
h_i^t, h_i^{t+1}	Head of groundwater zone i in times t and t+1
$h_{reg,j}$	Regional groundwater head
$IC_{pc,p}$, $IC_{ac,p}$	Irrigation costs to supply respectively permanent crop *i* and annual crop *l* using technology *p* (*p* is a subset of *k*)
IE_k	Efficiency of irrigation technology *k*
IP	Input power required to pump water over the total head
IR_p	Investment in irrigation technology equipment *p*
$K_{1,i,j}$	Area of permanent crop *i* lost in year type *j*
L	Total amount of land available for agricultural production
m	Number of annual crops available
n	Number of permanent crops available
PC	Groundwater pumping cost
PC	Unit groundwater pumping cost per volume of water
PCAP	Groundwater pumping capacity
PD_{fj}	Groundwater available in year *j*, given deep percolation in all other years *f* ($f \neq j$)
Peff	Effective precipitation
p_j	Probability of hydrologic event j (year type)

q_{1i}	Annual unit water use per acre of permanent crop *i*
q_{2jl}	Annual unit water use per acre of annual crop *l* in year *j*
Q_{ij}	Water flux between groundwater zones i and j
Q_{well}	Well pumping rate
RC	Annual maintenance cost of artificial recharge area
RCAP	Groundwater artificial recharge capacity
$RE_{1,pc}$, $RE_{2,ac}$	Gross revenues from permanent crop *pc* and annual crop *ac*
r_{eff}	Well effective radius
R_{fj}	Groundwater available in year *j*, given artificial recharge in all other years *f* $(f \neq j)$
R_{jf}	GW available to all other years *f*, given artificial recharge in *j*
r_{well}	Well bore radius
s	Steady-state drawdown for aquifer
Speff0	Accounting storage variable for soil moisture
Sy	Aquifer specific yield
T	Aquifer transmissivity
$TAW_{1,j,pc,k}$	Total water supplied to permanent crop *i* with technology *k* in year type *j*
tp	Period of time of well pumping
$V_{drained}$	Volume of water drained from an unconfined porous media
V_{well}	Volume of water extracted from the well after time tp
$X_{1,i,k}$,	Acreage of permanent crop *i* irrigated with technology *k*
$X_{2,j,l,k}$	Acreage of annual crop *l* irrigated with technology *k* in year type *j*
$XR_{2,j}$	Artificial groundwater recharge area in year type *j*
$Y_{1,pc,j}$	Acreage of crop *pc* irrigated with technology *k* in year type *j*

INTRODUCTION

Water users build and operate water resource systems for many purposes ranging from urban and agricultural supply to environmental protection. In times of high, increasing water demands, frequent conflicts for water and increasing environmental awareness, water users' challenges are formidable: water supplies must be enough, they must be reliable, flexible and sustainable. To cope with these challenges, water users and decision makers modify water resource systems improving their capacity, connectivity and operations, and in doing so significantly increase the complexity of such systems.

In complex systems, water users have more options and face more elaborate decisions. Water can be transferred, temporarily or permanently exchanged (in some places for compensation), using both surface and groundwater storage and conveyance systems. Agricultural and urban water users have to decide upon land use, water supply sources and application of technologies to improve efficiency in water use and conservation. These water use decisions depend on water availability, reliability, quality and cost. The latter characteristics vary by water supply source and are affected by other water users' decisions (e.g. a decision of a group of users to pump groundwater may lower the water table, increase the pumping cost and worsen its quality).

Understanding water users' decisions and their proper representation in simulation tools aimed at supporting decision and policymaking is necessary for sound water management. This ensures that the alternatives analyzed capture the water users' behavior and their reactions to structural and operational modifications on the system. In practice however, demands are often characterized as fixed in priority-based simulation approaches (Kuczera and Diment, 1988; Randall et al, 1997; Meyer et al, 1999; Dai & Labadie, 2001); users' decisions are usually either simplified, not including the full range of land use and technology options available, or do not address the stochastic nature of water supplies.

These issues become more critical in regional water systems where economic water uses, such as irrigated agriculture, are predominant. An example is the Friant region in the Central Valley of California. The Friant region includes an elaborated system of storage and conveyance infrastructure and relies strongly on groundwater supplies to buffer seasonal and multi-year water imbalances. To improve the understanding of the system's surface and groundwater operations, the United States Bureau of Reclamation (USBR) promoted the development of simulation model (FREDSIM) at the University of California, Davis, including the use of a network-flow based approach with agricultural demands driven by economics and a dynamic representation of groundwater.

The study relied on economic modeling to characterize the water demands, which was developed and applied separately (Howitt et al, 1999; Marques et al, 2003). This motivated further investigation of the water users' decision structure, and how it is affected by changes in water supply availability and uncertainty (the latter not being considered in the FREDSIM model). This culminated in the development of a new simulation model that presents an original contribution in modeling agricultural decisions on land, water use, technology application and conjunctive use operations using a multi-stage stochastic programming approach.

This dissertation investigates the water users' decision process, how this information can be used to simulate user's reactions to changes in water availability, reliability and cost; and the benefits of using a more detailed water demand representation in the simulation of regional water systems driven by economics. It includes the development and testing of the multi-stage stochastic programming in the two first chapters, and the improvement and application of the FREDSIM model of the Friant system in the third chapter. A last chapter summarizes overall conclusions. Although the models are not related, they deal with similar issues, have different capabilities and the common aim of developing methods that improve the understanding and representation of users' decisions. Agricultural water users are chosen given their large water demand and importance for many regional economies.

Specific objectives of this dissertation are:

a. To propose an engineering-economic model to simulate agricultural decisions under uncertain water supply.

b. To test the model by evaluating changes in agricultural decisions under variations in water reliability and price.

c. To use the model to evaluate improvements in water supply reliability by conjunctive use operations.

d. To improve and apply an economically-driven water system simulation model (FREDSIM) to analyze the efficacy and impacts of water management policies on a system driven by user economic decisions.

ECONOMIC MODELING OF AGRICULTURAL PRODUCTION WITH HYDROLOGIC UNCERTAINTY

Abstract

Agricultural water uses are predominant in many arid and semi-arid regions. Farmers allocate land and water for production based on water availability and reliability, which can be changed with system operation and management. To better evaluate the impact of hydrologic uncertainty in agricultural production and design of water operations, a model that simulates agricultural production decisions in two stages is proposed. The model maximizes the net expected benefit of permanent and annual crop production with probabilistic water availability. Results demonstrate effects of water availability, price and reliability on economic performance, annual and long-run cropping patterns and irrigation technology decisions. Raising water reliability increased the probability of higher economic returns, reduced the risk of failures (losing crops in extremely dry years) and promoted more efficient use of water. Such economic benefits can be compared to costs of operational changes and programs aimed at increasing water reliability to identify desirable water management solutions for agricultural areas.

Introduction

Irrigated agriculture is often the major water use in many regions. Agriculture competes for water with other sectors for water, generates environmental impacts, and is a fundamental component of the economy of many regions. When water is scarce, especially in semi-arid regions with high climatic variability and evapotranspiration, irrigation water demands are significant. Efficient water management necessary in such circumstances requires good understanding of how agricultural demands behave, how they are affected by factors such as water availability and price, and how farmers cope with uncertainty in water availability. With such understanding water policies can be designed to reduce scarcity, improve agricultural performance and reduce environmental impacts.

Agricultural water demands depend on farmers' decisions on what crops to produce when, how much water to apply, and which irrigation technology to use. Some of these decisions involve long-term investment and commitment of resources. When water availability is uncertain, farmers also make shorter term decisions to take advantage of opportunities or avoid losses from hydrologic events. Estimates of stochastic hydrology can be used to simulate and optimize farmers' short-term and long-term decisions over a wide range of situations as they seek to maximize production and net revenue.

Common methods of modeling agricultural water management decisions include behavioral models based on econometric analysis (Moore and Negri, 1992; Moore et al, 1994) and normative models that approach the problem from an agronomic/engineering perspective. Normative engineering/agronomic models usually represent production based on yield functions providing physical characterization of climate/soil/plant interaction (Dudley and Burt, 1973; Rao et al, 1990; Verdula and Kumar, 1996), and commonly use dynamic, linear or quadratic programming to optimize water allocation among crops and irrigation schedules.

The development of a model of agricultural land and water allocation decisions is presented using two-stage linear and quadratic programming to simulate permanent and annual crop production, irrigation technology decisions and economic performance considering probabilistic water availability. The model contributes to improved understanding of agricultural decisions when facing uncertainty and aggregates behavioral information and optimization. The model is developed initially with linear programming (LP) formulation and later improved with a quadratic programming (QP) formulation calibrated on the supply side. The objective function maximizes the net expected economic benefit of allocating water to crops over a range of probable water availability scenarios. The chapter begins with discussion of agricultural planning and water management issues, followed by a review of stochastic programming, presentation of model formulations with application results and discussion, and some limitations and conclusions.

Modeling Water and Agricultural Planning

Agricultural planning and water use are modeled from a normative or descriptive (policy) perspective, depending on analysis objectives. Normative models seek to represent the production technology and focus on the user objectives of production optimization guided by marginal conditions. Aggregate policy models are focused on capturing the users' behavior under different situations over a range of production levels, and are useful for evaluating impacts (especially economic) of water policies affecting prices, availability and technology (Moore and Negri, 1992).

Policy analysis often extends to situations with non-linear costs and decreasing returns, usually arising from heterogeneous land quality, management limitations, and risk aversion. These factors must be considered when using normative mathematical programming tools, such as linear programming, at the risk of producing results that are not verified in real conditions. Salman et al (2001) present a linear programming model to derive regional water demands based on optimized regional cropping pattern with variable water prices based on quality. The model is calibrated to a specific year by limiting the right-hand-side of water and land constraints to vary 20% around observed data. Results show cropping patterns exceeding the observed data, indicating possible limitations of the calibration process in capturing the factors discussed above

Water and Land Use Decisions in Agriculture

Irrigated agriculture depends on reliable water supply and proper allocation of water available in time and in space. When supplies are limited, the user will seek to optimize its allocation among competing crops within and between seasons to maximize production and farm revenue. For Dudley et al (1971b) this problem involves water allocation in time over a season (irrigation scheduling), intermediate-run decisions on what area of crops to plant at the beginning of a season, and long run decisions on what area of land to further develop for irrigation.

Crops differ significantly in growing cycle, yield, requirements for inputs and commodity prices, which affects the desirability of potential decisions. Decision timing on land allocation among different crops is affected by their growth cycle. For annual crops, decisions on how much to grow are made each year, while decisions on permanent crops are made once, with possible changes every few years, given fluctuations in exogenous factors such as crop prices.

With stochastic water supply, crop decisions also reflect farmers' flexibility in coping with uncertainty to maximize yields and profit. Permanent crop decisions are limited to more reliable water, while annual crop decisions involve intermediate-run planning with possibility of recourse every year depending on actual supply. This framework makes the problems of intermediate-run and long-run decisions suitable to be modeled with a multi-stage, probabilistic scenario-based programming approaches where decisions allocate part of the inputs in a first stage, and the remaining in the following stages (recourse decisions) based on random availability or cost of inputs.

Stochastic Programming: Methods and Application to Agricultural Decisions

Early investigations of stochastic programming include applications to agricultural economics in Tintner (1955) and to other fields of information systems and economic planning in Stancu-Minasian and Wets (1976). Stochastic programming can be applied to optimize agricultural decisions under uncertain conditions. One can optimize decisions such as land and water allocation for crop production by maximizing the expected benefit of production over a given planning horizon. Common applications include either dynamic or scenario-based approaches.

Dynamic techniques have been common for planning for the short term (scheduling), and intermediate and long terms given its ability to model sequential and recurrent decisions. Such models rely on two fundamental types of information: transition probabilities from one state to another and the returns associated with each transition. Dudley et al (1971a, 1971b) apply stochastic dynamic programming (SDP) to model short-run, intra-seasonal water allocation and the intermediate-run decisions of crop acreages at the season's beginning. The three planning time frames are integrated in a single modeling approach with SDP (Dudley, 1988). Matanga and Marino (1979) present an SDP model for interseasonal, finite and infinite irrigation planning including root zone salinity as decision variable. To keep the problem computationally tractable, few crop types are usually considered in SDP approaches. Rao et al (1990) use DP to develop water production functions based on optimal intra-seasonal scheduling in a model for optimal seasonal water allocation among multiple crops. Dimensionality is avoided by decomposing the problem into multiple single-crop model runs for multi-crop water allocation.

Other dynamic approaches apply linear programming to allocate water within a given season, coupled with a DP model to optimize crop acreages across seasons and perform inter-seasonal water allocation (Yaron and Dinar, 1982; Verdula and Kumar, 1996). Marginal values of water produced by the LP model provide a measurement of crop benefit to drive the inter-temporal water allocation. A linear programming model avoids potential computational limitations from the high number of states when optimizing for multiple decision variables such as multiple crops. Other techniques to reduce dimensionality problems, including restriction of the state-space around a given solution in discrete differential dynamic programming (DDDP), are discussed in Labadie (1997).

Problems involving decision-making under uncertainty can often be characterized by multiple scenarios resulting from a combination of random events and decisions. These problems can be modeled by structuring the process in stages with decisions occurring before the realization of an uncertain event ("here and now" or "first stage" decisions), and recourse decisions occurring after the future unfolds in different possible scenarios. The objective is to minimize the cost of the first stage decisions and the expected value of the subsequent ones.

Watkins et al (2000), point out as advantages of "scenario-based" stochastic programming the flexibility of modeling the decision process and defining different scenarios, at the cost of potential increase in the size of the models. Watkins et al (2000) apply a multi-stage scenario-based approach in a water management model to maximize expected revenue of selling surplus water while maintaining firm supply. The model includes decisions on interruptible supply contracts in the first stage, which can be re-negotiated in four following stages based on actual water available and the probability of exceedance. The model only considers decisions on the supply side and assumes deterministic, fixed demands. Huang and Loucks (2000) propose the addition of inexact optimization theory to a linear two-stage stochastic programming model to account for uncertainties in other parameters such as growing water demands.

Linear two-stage stochastic programming is also applied to model long and short-term water conservation measures to derive urban water users' willingness to pay to avoid probabilistic shortage in Lund (1995) and Garcia (2002), and to model supply and demand management to minimize supply cost for urban systems facing probabilistic shortages in Wilchfort and Lund (1997). Long-term conservation measures are modeled in the first stage, and short-term conservation measures and demand management measures in the second stage implemented as response to a water shortage event with a given probability. Cai and Rosegrant (2001) apply a two-stage stochastic programming to model decisions on adoption of irrigation technology and water allocation among crops based on probability of water availability in each scenario (second stage) and technology and crop decisions made in the first stage. McCarl and Parandvash (1988) develop a two-stage stochastic model to evaluate trade-offs of water allocation for hydroelectric generation and irrigation.

Model Formulation and Development

Model Concept

The model developed in this chapter uses two-stage mathematical programming where permanent crop decisions are made in the first stage, and annual crop decisions in the second stage, based on the probability distribution of water available in a given year. A decision tree for a similar process appears on Figure 1.1, depicting permanent and annual crop decisions as discrete while they are treated as continuous on the model formulation. Further model developments presented later on this chapter extend crop decisions to other dimensions including water application and irrigation technology decisions. It is assumed that the local surface storage operated to provide water supply is capable of offsetting eventual intra-seasonal water imbalances.

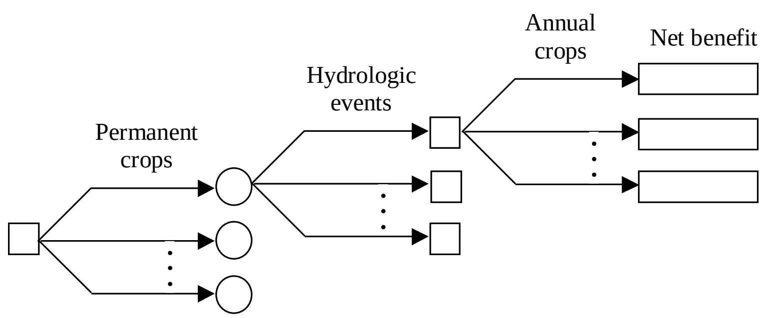

Figure 1. 1 - Problem decision tree

Naturally, no crop remains “permanent” and decisions regarding “permanent” crops may change every few years. For this initial approach, it is assumed that permanent crop decisions are made just once.

Model runs and Data

To test the model, production and hydrologic data available from irrigation districts in California’s Central Valley are used. The model is implemented in the optimization package GAMS (General Algebraic Modeling System). Data on crop prices, technical coefficients and input costs are obtained from the Statewide Agricultural Production Model (SWAP) (Howitt, 1999). The United States Bureau of Reclamation (USBR) operates surface reservoirs in the region and delivers water to irrigation districts under contract using the Friant-Kern canal. Water contracts have a price structure based on water reliability and the most reliable supply (class 1 water) is priced at $44/acre-feet. Further details about the Friant system are found in Leu (2001) and Marques et al (2003). Crop acreages in the region are found in California Department of Water Resources (DWR) 1999 land survey. Crops used in the model developed here are listed in Table 1.1.

Table 1. 1 – Annual and Permanent crops modeled

Permanent Crops	Annual Crops
Grapes	Cotton
Citrus	Field crops (one category, mostly wheat)
Nuts	Truck crops (one category, mostly melons)
	Alfalfa
	Miscellaneous Grain Crops (one category, mostly beans)

A set of hydrologic events representing amounts of water available for agricultural production are used initially with equal probabilities of occurrence for each event. This simplification makes the results and model concept easier to interpret. This initial setup is referred to as Formulation A1 in the next section. Model parameters and technical coefficients appear in the appendix A-1.

Linear Programming Formulation

For this simplest case, we define a linear profit function that maximizes the net expected economic value of crop production (formulation A1):

$$\textbf{Max Z} = \sum_{i=1}^{m} c_{1i} X_{1i} + \sum_{j=1}^{g} p_j \left[\sum_{l=1}^{n} c_{2l} X_{2jl} \right] \qquad \textbf{(1. 1)}$$

Subject to:

$$\sum_{i=1}^{m} X_{1i} q_{1i} + \sum_{l=1}^{n} X_{2jl} q_{2jl} \le a_j ....\forall j \qquad \textbf{(1. 2)}$$

$$\sum_{i=1}^{m} X_{1i} + \sum_{l=1}^{n} X_{2jl} \le L ....\forall j \qquad \textbf{(1. 3)}$$

Where

c_{1i}	Net average annual revenue from permanent crop i ($/acre*year)
X_{1i}	Permanent crop i grown in first stage (acre)
p_j	Probability of hydrologic event (year) j
c_{2l}	Net annual revenue from annual crop l ($/acre*year)
X_{2jl}	Annual crop l grown in year j (acre)
q_{1i}	Annual unit water use per acre of permanent crop i (acre-foot/acre)
q_{2jl}	Annual unit water use per acre of annual crop l in year j (acre-foot/acre)
a_j	Annual amount of water available in year j (acre-foot)
L	Total amount of land available (acre)
m	Number of annual crops available
g	Number of hydrologic events
n	Number of permanent crops available

The objective function maximizes the net expected value benefit with probabilistic water availability (1.1). Equations (1.2) and (1.3) are constraints for water and land availability respectively. Constraint (1.2) represents a series of inequalities where the water available a_j changes according to the hydrologic event.

The maximum benefit for formulation A1 is $38.9 million/year. Optimal crop acreages and input resources of land and water appear in Figures 1.2 and 1.3. Hydrologic event 1 is the driest and hydrologic event 10 is the wettest. Only one type of permanent crop (nuts) and one type of annual crop (truck crops) are produced in all events.

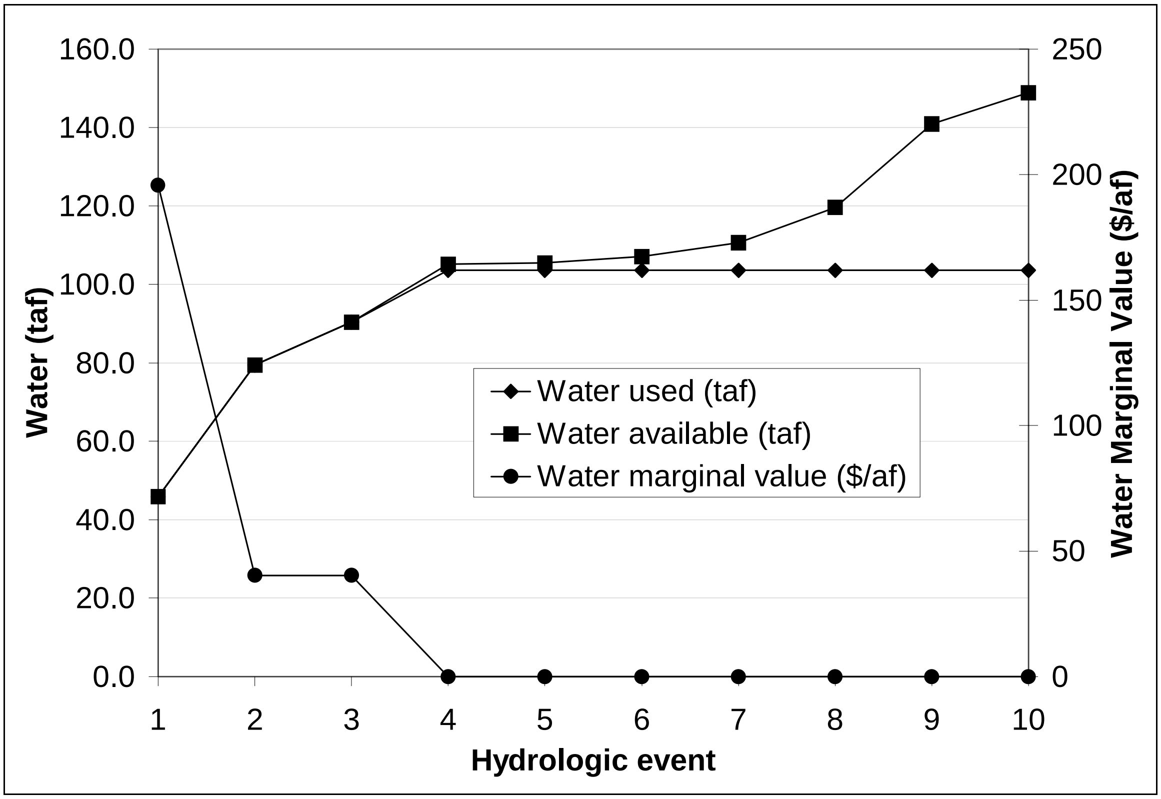

Figure 1. 2 – Water allocation for Formulation A1

Permanent crops grown in the first stage are limited by the least amount of water available in all hydrologic events, i.e., to the supplies with 100% reliability. Although in practice more reliable water is reserved to permanent crops, these results are very conservative. More flexibility is given to the model when this issue is addressed by allowing stress irrigation in the next formulation.

The marginal water values in figure 1.2 represent the increase in the expected net benefit when one more unit of water is available in a given hydrologic event with a given probability of occurrence. The water marginal value is highest for the most reliable water (driest hydrologic event), which is used to supply high value permanent crops. In Figure 3 this is reflected in the land available not being entirely used. When more water is available in wetter hydrologic events, annual crops pick up the slack land and the marginal cost of water is reduced from $196/af to $40/af reflecting expected net benefit gains with annual crops (only truck crops and nuts are produced). This result is a direct consequence of the decision structure in the model, in which permanent crops are decided upon once and kept for all events, limiting their acreage to the worst-case amount of water available. Stress irrigation or losing permanent crops is not permitted in this initial model formulation.

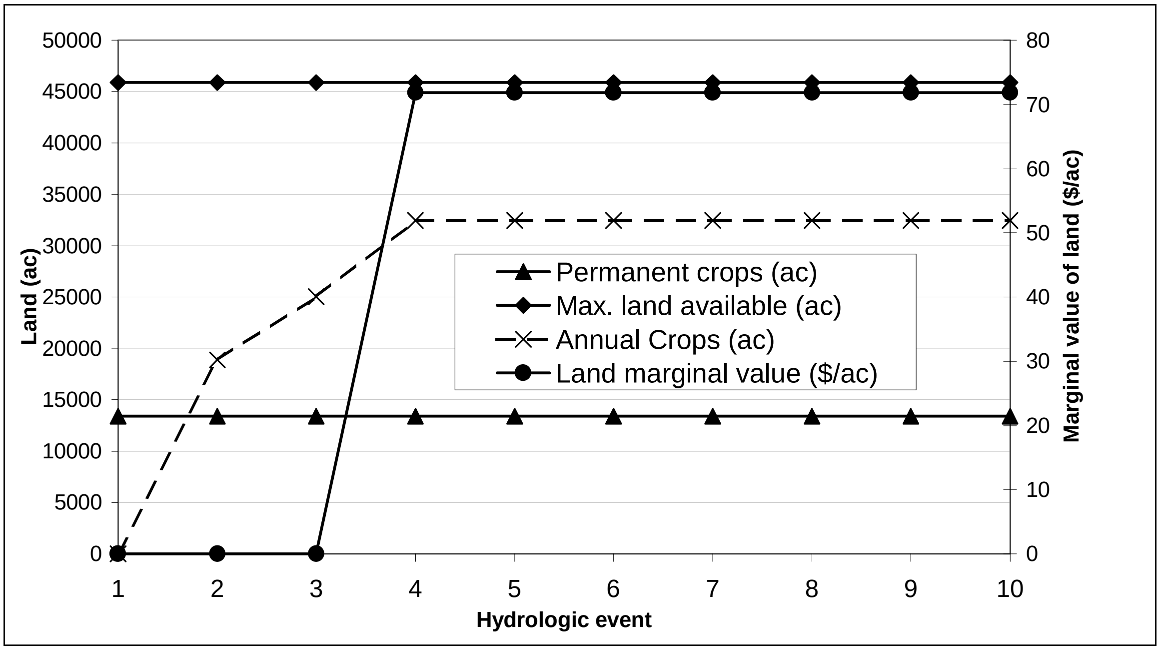

Figure 1. 3 - Land allocation for Formulation A1

With enough water available, the remaining land is brought into production with annual crops and the land marginal value rises from zero to $72/ac when annual crops enter the solution and pick up the slack land. At this point water is the slack resource once the surplus water available in very wet events cannot be used. Management of this surplus water through surface reservoir operation has been subject of investigation in many studies (Verdula and Kumar, 1996; Dudley and Burt, 1973). However farmers usually have limited access to operation of large surface reservoirs with enough carry-over storage for inter-seasonal planning. A common situation is the availability of stored water based on a forecast, which is used for crop planning through the season and is subject to later update. Groundwater resources play an important role in maintaining supply during dry years and are often used in some regions in coordination with surfaces supplies in conjunctive use operations for greater benefit. A conjunctive use version of this model simulating such operations is presented in the next chapter.

Linear Formulation with Stress Irrigation

To attenuate the permanent crop limitation to the driest water scenario, the possibility of stress irrigation is introduced in a revised (A2) formulation. The problem decision structure allows the farmer to choose a portion of the initial area grown with permanent crops to receive less than full demand, depending on the water availability in each event. With this arrangement, the initial acreage of permanent crops is no longer limited to the least amount of water available. Three issues arising with this representation are: (a) supply curtailment will reduce yields, (b) for severe supply reduction some crops may be lost, and (c) even without crop loss, several years of stress irrigation may reduce the yields in the long run. In this formulation (formulation A2), situations “a” and “b” are dealt with by including a stress irrigation threshold that if violated results in a penalty in the form of replanting costs to replace the permanent crops lost. Issue “c” is not yet addressed.

Permanent crop start up costs appear in the first stage, which includes the first year costs with land and water, plus land and water opportunity costs during the remaining years until the crops start producing. These costs are included in the INI_i variable

The revised formulation (A2) is:

$$\textbf{Max Z} = -\sum_{i=1}^{m} INI_i X_{1i} + \sum_{j=1}^{g} p_j \left[\sum_{l=1}^{n} c_{2l} X_{2jl} + \sum_{i=1}^{m} c_{1i} Y_{1ji} - \sum_{i=1}^{m} CA_{1i} K_{1ji} \right] \qquad \textbf{(1. 4)}$$

Subject to:

Land constraint (3), second stage permanent crop constraint (4), and

$$\sum_{i=1}^{m} W_{1i} + \sum_{l=1}^{n} X_{2jl} q_{2jl} \leq a_j ....\forall j \qquad \textbf{(1. 5)}$$

$$Y_{1ji} \leq X_{1ji} ....\forall i, \forall j \qquad \textbf{(1. 6)}$$

$$Y_{1ji} = \beta_{1i} W_{1ji} ....\forall i, \forall j \qquad \textbf{(1. 7)}$$

$$K_{1ji} \geq X_{1i} - \xi_i W_{1ji} ....\forall i, \forall j \qquad \textbf{(1. 8)}$$

Where,

CA_{1ji} is the replanting penalty for permanent crops. Constraint (1.2) is modified to equation (1.5) with supply of permanent crops in the second stage being represented by W_{1ji}. Two new constraints are added. Equation (1.7) now limits the acreage of permanent crop *i* irrigated in a given year *j* Y_{1ji} to a given amount of water W_{1ji}. The parameter β_{1i} (acres per acre-feet of water) indicates how many acres of Y_{1ij} can be grown for a given quantity of water W_{1ji} (inverse of the Leontieff coefficient for water input). If stress irrigation is applied (W_{1ij} less than the full demand) Y_{1ji} will be less than the area of permanent crops initially set X_{1i}. Since stress irrigation is likely to be applied over the whole area, rather than to provide full supply to Y_{1ji} and no supply at all to the remaining $X_{1i} - Y_{1ji}$, Y_{1ji} is used as an area-equivalent supply term. The whole X_{1i} will receive water and produce crops, but the water supply per acre will be reduced to W_{1ji}/X_{1i} and the crop production will be reduced by a factor of Y_{1ji}/X_{1i}. Constraint (1.6) limits the benefits from permanent crops in the second stage to the amount grown in the first stage

Equation (1.8) sets a limit for stress irrigation based on a stress threshold ξ_i, representing the acreage of a given permanent crop *i* that can be maintained alive with one unit of water. Multiplied by the water supplied to a given permanent crop W_{1ji} (af/ac) it results in the total acreage maintained. The difference from the acreage initially set in the first stage X_{1i} represents the area of permanent crops lost in the second stage K_{1ji}. This area of crops lost is multiplied by a replanting penalty in the objective function (1.4).

At W_{1ij} providing supply above the threshold, the second term of the right hand side of equation (1.8) equals the permanent crop area grown in the first stage and the right hand side cancels out, resulting in a lower bound for replanting area of zero, i.e., all area grown in the first stage can be sustained and no crops are lost. In this case W_{1ji} can still be insufficient to supply all X_{1i} and stress irrigation is applied resulting in production reduced by Y_{1ji}/X_{1i}.

The optimal net expected benefit increases slightly to $40 million for formulation A2, resulting from an additional 4,936 acres of permanent crops (nuts) grown in the first stage (a 37% increase over the 13,412 acres of nuts grown in the formulation A1). In the event of a very dry year, here represented by the driest hydrologic event, irrigation is reduced from 3.42 af/acre to the minimum 2.5 af/acre for the permanent crops. This reduction allowed a larger area to be maintained. This result also indicates potential benefits for water conservation. By reducing the applied water through increased irrigation efficiency the water saved (over the initial 13,412 acres grown) could be used to expand permanent crop acreage in the first stage without resorting to stress irrigation. Due to the high cost and time spent on replanting permanent crops, the irrigation level does not drop below the threshold and no permanent crops are lost. The crop diversification remains the same as in formulation A1's solution, only one type of permanent crop (citrus) and one type of annual crop (truck crops) are produced.

Permanent crop expansion displaces some annual crops and the marginal value for water decreases in the driest event from $196/af to $130/af. The use of stress irrigation released additional water to increase production (as if more water were available) consequently reducing its marginal value. However this effect is counter-acted by the reduction in production when stress irrigation is used, which increases the margnal willingness to pay for water. When the stress irrigation threshold is reduced from the original minimum of 2.5 af/ac to 2 af/ac allowing the crops to be further stressed (without dying) the permanent crop area is further expanded and the marginal water value in the driest event increases from $130/af to $141/af.

The permanent crops, which have increased area, have a higher water demand per acre than the annual crops they replaced. This resulted in more water being used in wetter events. Consequently water limits production in most remaining events (with a marginal value of $40/af) while land is the slack resource, as opposed to results in formulation A1

(Figures 1.2 and 1.3), where water only binds in the three driest events. However, for the three wettest events water is still the slack resource.

To further evaluate differences between formulations A1 (no stress irrigation) and A2 (with stress irrigation) the amount of water available in the driest event was varied and results appear in Figure 1.4. With stress irrigation a higher acreage of permanent crops is kept over the entire range compared to the no stress irrigation (A1), in which the only option is to reduce the acreage grown based on the water available.

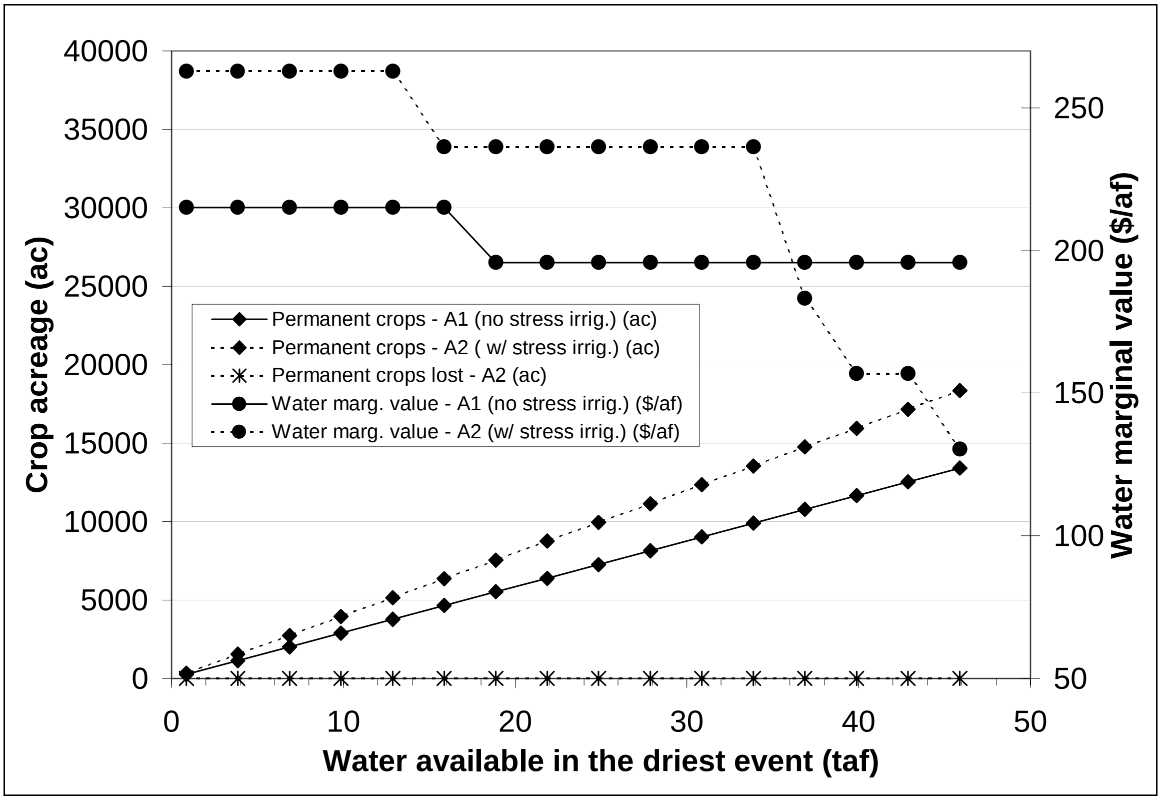

Figure 1. 4 – Sensitivity analysis on water available on driest event for formulations A1 and A2

Given the high replanting costs, no crops are lost even for a dry event with very little water available. Here the model still uses equal probabilities for all events. The lower probability of extreme drought events puts a lower weight on the replanting penalty and the acreage of lost crops under this circumstance may be higher. This result is also directly influenced by the replanting penalty used. Current replant penalty is represented by annual average replanting cost $5,043/acre for citrus, 11,457/acre for grapes, and $6,344/acre for nuts (University of California Cooperative Extension, 2001, 2002a, 2002b).

Quadratic Programming

Optimal solutions from the linear formulations developed do not represent the crop diversification commonly found in real situations. The crop production is limited only by input constraints and relies on data reflecting average, fixed coefficients such as production costs, yields and prices. This "average" scenario results in a solution where only the most profitable crops are produced. Mathematically, LP models provide solutions with the number of binding constraints being equal to the number of non-zero activities.

In practice, crop production equilibrium is determined by marginal conditions (Hatchett, 1997) and it is limited by endogenous factors such as crop rotation benefits, heterogeneous land quality, restricted management or machinery capacity (Howitt, 2002) and exogenous ones, such as risk aversion and output prices. Although those limitations can be included in the model using linear constraints, it can reduce the model's flexibility in simulating situation outside the range for which it was calibrated (Hazell & Norton, 1986, Howitt, 1985).

An alternative to a linear approach is to constrain the most profitable crops to observed acreage allocations and use their shadow value to calibrate additional cost function parameters to be included in the objective function. This approach is referred to as *Positive Mathematical Programming* (PMP) and it had been successfully applied in other studies (USBR, 1997; Bauer and Kasnakoglu, 1990; Howitt, 1985) to calibrate quadratic profit functions.

This section replaces the linear objective (profit) function with a quadratic function calibrated on the supply side with behavioral information provided by observed crop acreages. This quadratic objective function reflects marginal conditions of competitive market equilibrium and is consistent with microeconomic theory. Competitive market equilibrium conditions dictate that a price-taking producer will be willing to supply until the point where his marginal revenue (market price) is equal to his marginal cost:

$$P_i = \alpha_i + \gamma_i X_i \qquad \textbf{(1. 9)}$$

The right hand side (marginal cost) is the farmer supply function of a given product *i* in the quantity X_i with intercept α_i and slope γ_i. To arrive at these marginal conditions we can set the Lagrangean and apply the Kuhn-Tucker first order conditions ($\partial L/\partial x = 0$) to a defined objective function. Thus, the inverse path can be followed by integrating (1.9) in x to arrive at the desired objective function (Howitt, 2002). This step results in (1.10):

$$\mathbf{z} = PX - (\alpha + 0.5\gamma X)X \qquad \textbf{(1. 10)}$$

Adapting equation (1.10) to a 2-stage quadratic programming formulation (formulation A3) with the probabilities p_j on the second stage we have the non-linear problem:

$$MaxZ = -\sum_{i=1}^{m}\left(INI_i X_{1i}\right) + \sum_{j=1}^{g} p_j \left(\sum_{l=1}^{n}\left(RE_{2l} X_{2jl} - (\alpha_{2l} + 0.5\gamma_{2l} X_{2jl}) X_{2jl}\right) + \right.$$

$$\left. + \sum_{i=1}^{m}\left(RE_{1i} Y_{1ji} - (\alpha_{1i} + 0.5\gamma_{1i} Y_{1ji}) Y_{1ji}\right)\right) \qquad \textbf{(1. 11)}$$

Subject to:

$$\sum_{i=1}^{m} X_{1i} q_{1i} + \sum_{l=1}^{n} X_{2jl} q_{2jl} \le a_j \ldots\ldots\ldots\ldots\ldots \forall j$$

$$\sum_{i=1}^{m} X_{1i} + \sum_{l=1}^{n} X_{2jl} \le L \ldots\ldots\ldots\ldots\ldots \forall j$$

Where RE_{1i} and RE_{2l} are the gross revenues ($/acre) for producing permanent and annual crops respectively. Subject to the same land and water constraints as in formulation A1.

The intercept and slope of the supply functions are empirically calibrated with positive mathematical programming (PMP) based on observed acreages. PMP adds calibration constraints to the most profitable crops according to observed conditions. Given that the most profitable crops are constrained, the less profitable, unconstrained crops are where the increased resources would be applied, and they determine the opportunity cost of the resources. The dual values for the binding calibration constraints are then equal to the average net value product per acre minus the opportunity costs per acre. A rigorous demonstration is provided by Howitt (1995). The average value, from equation 1.10 is given by:

AV = $P - (\alpha + 0.5\gamma X)$

While the opportunity cost per acre, also from 1.10:

OC = $P - (\alpha + \gamma X)$

Subtracting the opportunity cost from the average value yields the calibration constraint dual λ_2:

$$\lambda_2 = 0.5\gamma X \qquad (1.\ 12)$$

We can estimate λ_2 by subtracting, for each crop, the marginal production cost per acre from the gross revenue per acre price*yield, substituting it in equation 1.12 along with the observed calibration acreage (X) and solving for γ, which is the slope of the supply function 1.9. The intercept α is calculated by substituting γ and the observed acreages X in equation 1.9, where P_i is the marginal production cost per acre.

Slope and intercept parameters, along with gross revenue (crop price times yield) calculated are presented in Table 1.2.

Table 1. 2 – Crop supply parameters – Formulation A3

Crops	Base acreage observed (ac)	Slope ($/ac*ac)	Intercept ($/ac)	Gross Revenue ($/ac)
Permanent				
CITRUS	943	5.58	1,613	7,650
Grapes	24,500	0.25	1,596	6,872
Nuts	9,963	0.59	-1,449	4,420
Annual				
COTTON	228	2.40	328	875
Fld. Crop	1,214	0.62	-50	700
Truck	319	4.51	3,360	4797
Alfalfa	2,233	0.32	17.8	737
Msc. Grain	471	0.81	9	390

Quadratic programming formulation (A3) results

Introduction of a non-linear cost function eliminates the constant returns to scale limitation of the linear formulation. Variable costs now reduce the gain in net revenue as production increases, aligned with diminishing marginal returns. The results present more crop diversification. More profitable crops enter production and stabilize with maximum revenue when more water is available. At this point remaining water is used in less profitable crops. More crop types tend to be produced. Annual crop production appears in Figure 1.5.

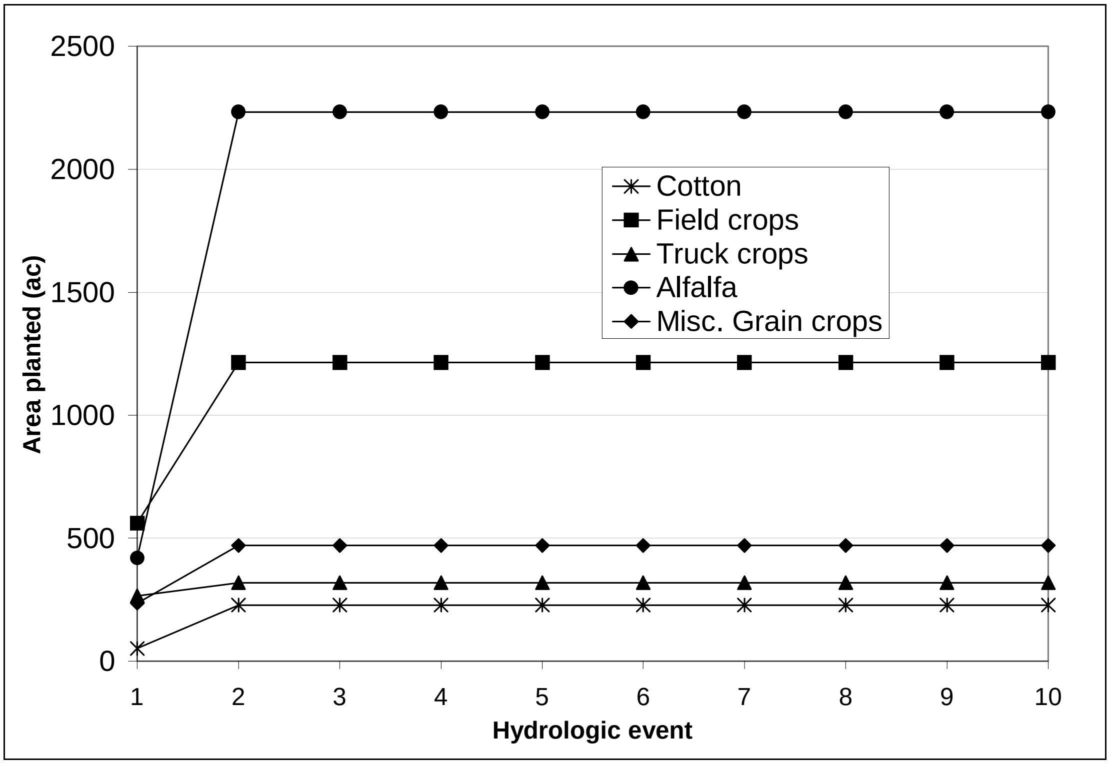

Figure 1. 5 - Annual crop production for formulation A3

However, the permanent crops may still be limited by the least amount of water in the events horizon, as in formulation A1, if it is dry enough. While this is not the case with the current water availability data (some annual crops are produced in the driest hydrologic event, as shown in figure 1.5) test runs with less water available in the driest event (30 taf instead of the original 45.9 taf) resulted in no annual crops being produced in that event and the permanent crops acreage limited by the 30 taf supply.

When more water is available annual crops enter production in the mix presented in Figure 1.5. The marginal value for water is greater than zero in the driest hydrologic event, reflecting the willingness to expand or change crop acreage, while the marginal value for land is zero. When more water is available in the remaining events, the marginal value of additional water is zero, along with the marginal value for land. This result reflects the non-linearity in the cost function. As seen in Figure 1.6, as production reaches the maximum net revenue point, increase in acreage reduces the net benefit causing the crop production to stabilize (Figure 1.5). Beyond this point land and water have no value to production. As expected, applying the Kuhn-Tucker first order condition to equation 9 and solving for x one can obtain the maximum acreage shown in Figure 1.7 for annual crops:

$$\frac{\partial Z}{\partial x} = 0 \therefore P - \alpha - \gamma X = 0 \therefore X = \frac{P - \alpha}{\gamma} \qquad \textbf{(1. 13)}$$

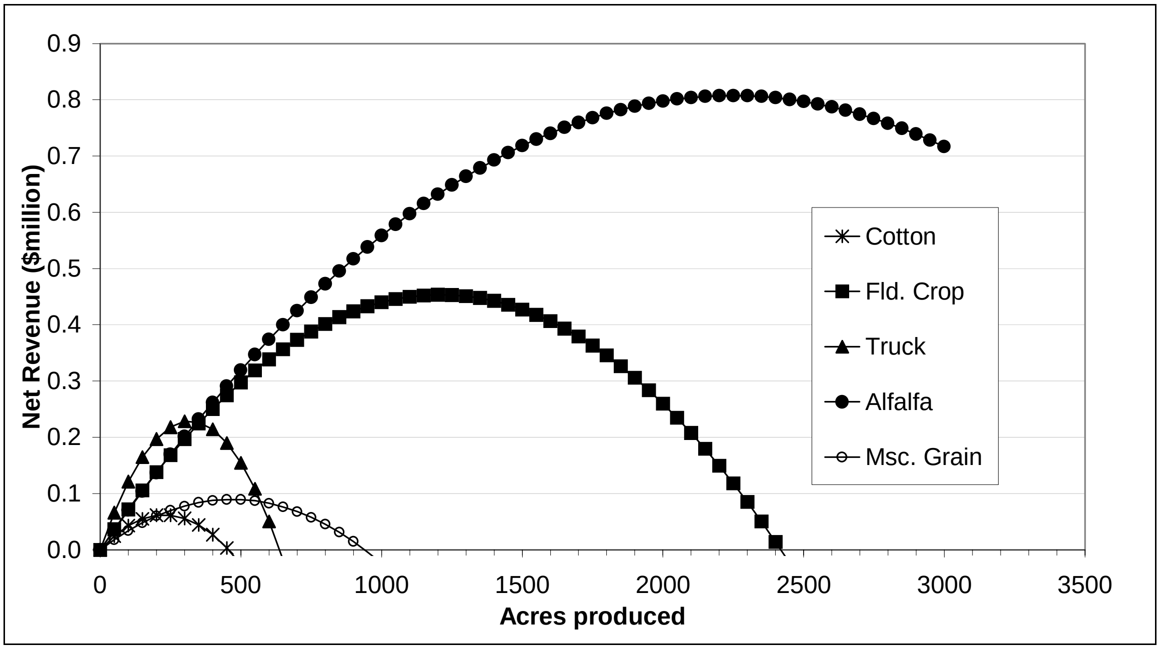

Figure 1. 6 - Net Revenues for formulation A3, based on equation 9

The maximum production of annual crops being reached in the second hydrologic state suggests that the discretization of water availability is too coarse to capture the production behavior in more detail. From hydrologic event 1 to hydrologic event 2, the production costs rise and limit production before water does. To analyze the production function behavior in more detail, we should look at what happens between hydrologic events 1 and 2. Water availability is increased in smaller increments from hydrologic state 1 to 8, while hydrologic states 9 and 10 preserve the same value as the previous formulations (A1 to A3). The water availability in event 1 (driest) is reduced from the original 45.9 taf to 30 taf. The water availability data used appear on Table 1.3. This new modified water data will also be used in subsequent formulations.

Table 1. 3 - Water availability data: Original and modified

Hydrologic event	Original water availability	Modified water availability
	taf/year	taf/year
HYD1	45.9	30.0
HYD2	46.8	32.9
HYD3	47.7	35.7
HYD4	48.6	38.6
HYD5	49.5	41.4
HYD6	50.4	44.3
HYD7	51.3	47.1
HYD8	52.2	50.0
HYD9	140.9	140.9
HYD10	148.9	148.9

With this modification production of annual crops changes according to the changes in water availability (Figure 1.7)

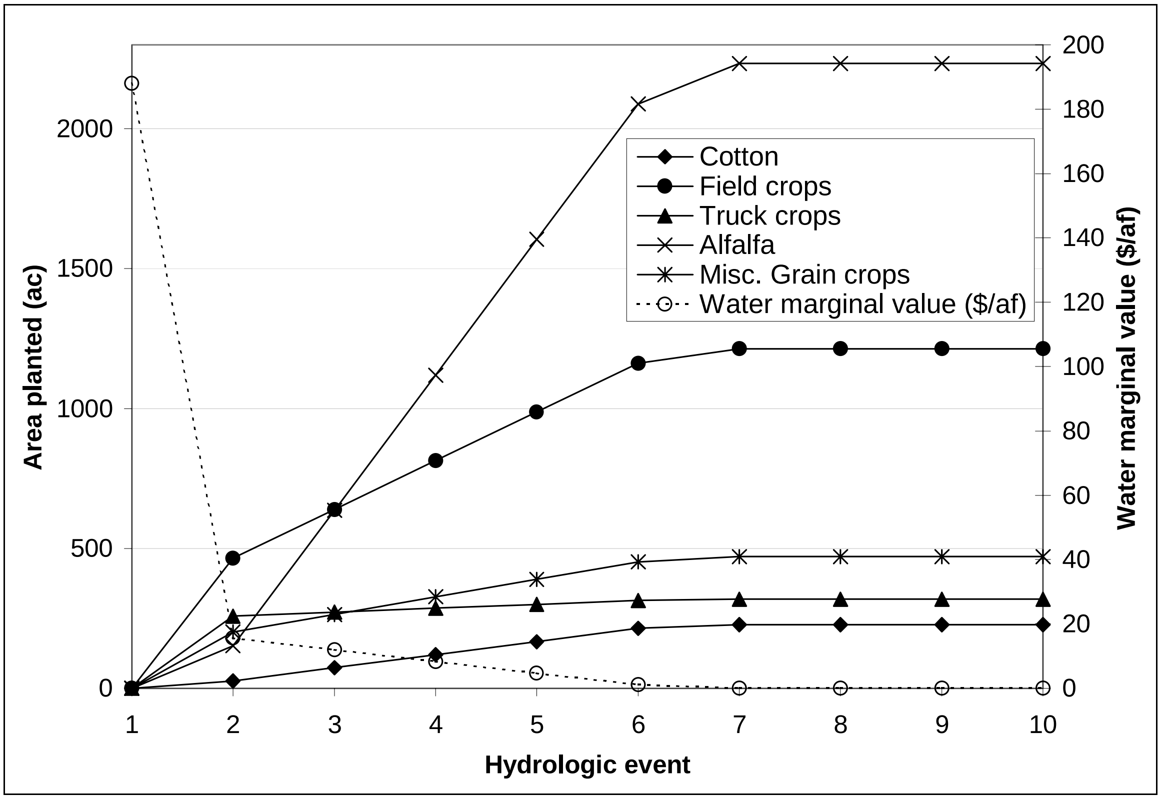

Figure 1. 7 - Annual crops production for formulation A3 modified

The behavior of the annual crops production is consistent with the net revenue curves in figure 1.6. When more water is available, more land is brought into production, occupied by crops depending on their value and marginal coast and benefits. Truck crops have the highest value and a steeper revenue function (Figure 6) among the annual crops and approach peak production quickly. After the first 250 acres enter production, the gain in net revenue is considerably smaller (close to the peak the net revenue curves are flatter) while the cost increases in the same rate. This makes Truck crops less attractive than the other annual crops resulting in very small acreage increments until it reaches peak production in hydrologic events with water availability equal or greater than event 7. The reduction in revenue gains for Truck crops cause additional water to be allocated to other crops with higher marginal gains. Field crops follow with the largest increment in production land from hydrologic events 1 to 6. As expected, this change in water allocation is followed by a reduction in the marginal value of water (Figure 1.7), which reflects the value of the next higher valued crop.

Marginal values for water are very high in hydrologic event 1 reflecting water limitation for permanent crops in the first stage (Figure 1.8). In hydrologic events with more water available lower value annual crops are predominant and the marginal value for water drops considerably, reaching zero along with marginal value for land for events 8, 9 and

10, when production is limited by production costs reflected in the non-linearity of the objective function.

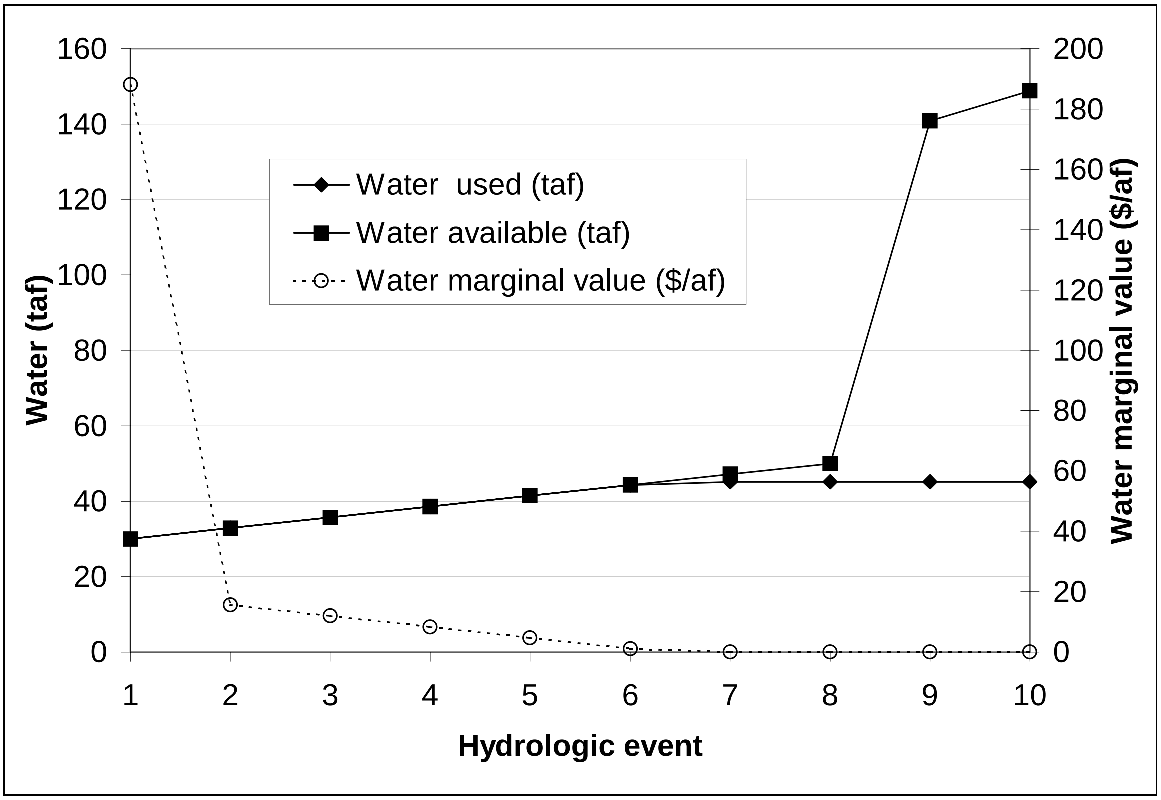

Figure 1. 8 – Water allocation for formulation A3 modified

Under hydrologic events 1 to 10, about 70% of the land available is not used due mostly to permanent crops establishment costs and the severe water limitation imposed by most hydrologic events (Figures 1.8 and 1.9). Additional model test runs indicate that if more water is available permanent crop acreage will expand from the current 9,360 acres to 13,412 acres along with annual crops expanding to the calibration acreages in all hydrologic events. However, all this expansion brings only 40% of the land into production, the remaining land is fallowed due to permanent crop establishment costs, to which the model is fairly sensitive. At full water supply in all hydrologic events, a 10% reduction in the permanent crop establishment cost increases the permanent crop acreage by 16.4%, and the optimal net expected benefit in 19.5%.

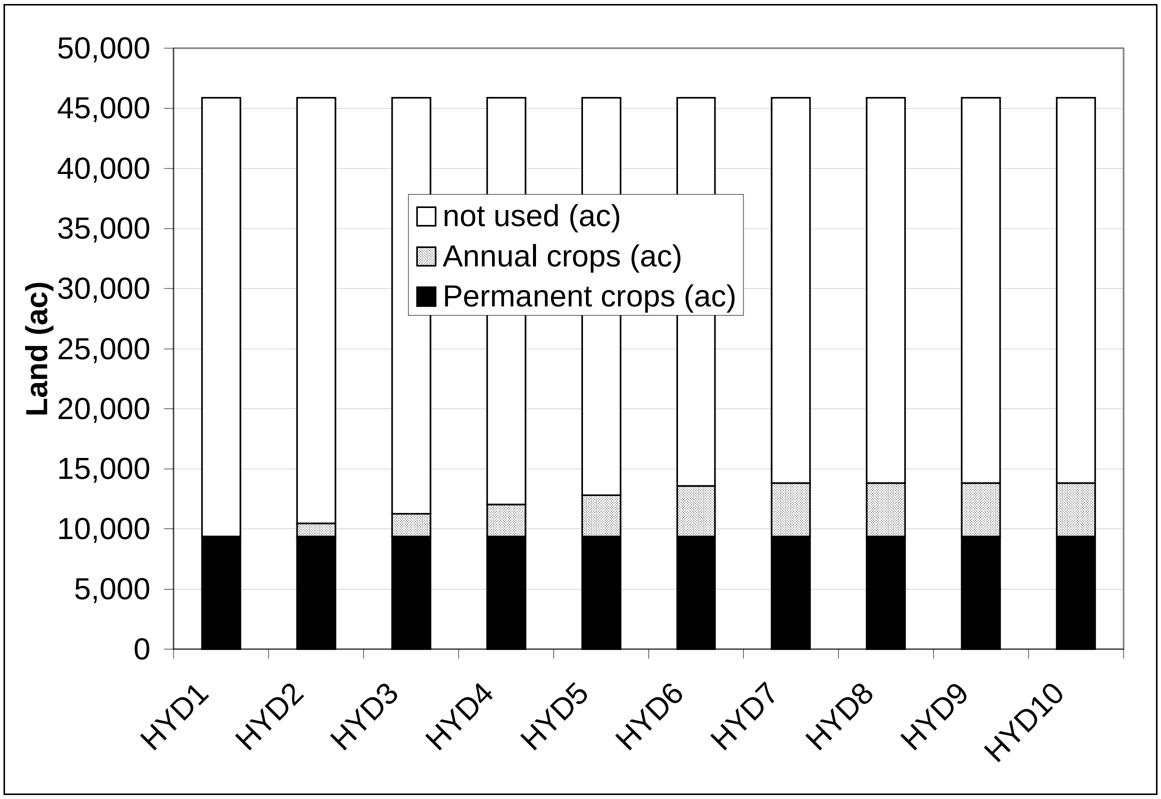

Figure 1. 9 – Land allocation for formulation A3 modified

The next section updates the quadratic formulation with stress irrigation and stress irrigation threshold (formulation A4), allowing production of permanent crops to expand beyond the driest event in the hydrologic events horizon.

The updated formulation A4 is given by:

$$MaxZ = -\sum_{i=1}^{m}\left(INI_i X_{1i}\right) + \sum_{j=1}^{g} p_j \left(\sum_{l=1}^{n}\left(RE_{2l}X_{2jl} - (\alpha_{2l} + 0.5\gamma_{2l}X_{2jl})X_{2jl}\right) + \right.$$

$$\left. + \sum_{i=1}^{m}\left(RE_{1i}Y_{1ji} - (\alpha_{1i} + 0.5\gamma_{1i}Y_{1ji})Y_{1ji}\right) - \sum_{i=1}^{m} CA_{1i}K_{1ji} \right) \qquad \textbf{(1. 14)}$$

Subject to the same previous land , water, second stage permanent crops, stress irrigatio, and stress irrigation threshold .

$$\sum_{i=1}^{m} X_{1i} + \sum_{l=1}^{n} X_{2jl} \leq L ....\forall j \qquad \text{(land)}$$

$$\sum_{i=1}^{m} W_{1ji} + \sum_{l=1}^{n} X_{2jl} q_{2jl} \leq a_j ....\forall j \quad \text{(water constraint)}$$

$$Y_{1ji} \leq X_{1ji} ....\forall i, \forall j \qquad \text{(second stage permanent crops}$$

$$Y_{1ji} = \beta_{1i} W_{1ji} \text{..........} \forall i, \forall j \qquad \text{(stress irrigation)}$$

$$K_{1ji} \geq X_{1i} - \xi_i W_{1ji} \text{..........} \forall i, \forall j \qquad \text{(stress irrigation threshold)}$$

Formulation A4 results and discussion

Formulation A4 was run with the modified water availability data (Table 1.3). As expected, the acreage of permanent crops can be extended at the cost of curtailing supply per acre (Table 1.4). Stress irrigation is applied in the driest event only, and only for the crop with the highest consumptive demand (nuts). Given the high replanting costs, no crops are lost.

Table 1. 4 - Expansion in permanent crops area with stress irrigation

Permanent crop	Area grown in the driest event (ac)	
	without stress irrigation (A3)	with stress irrigation (A4)
Citrus	71	96
Grapes	3,186	3,761
Nuts	6,108	6,501
Total	**9,364**	**10,358**

Marginal water value is highest in the two driest events, when stress irrigation takes place, and it drops significantly as stress irrigation is reduced from events 1 to 3 (Figure 1.10). From events 3 to 8 more water is available and the marginal water value decreases at a slower rate, as there is no stress irrigation. Finally, in events 9 and 10 water is abundant, permanent crops receive full supply, and the water marginal value is zero.

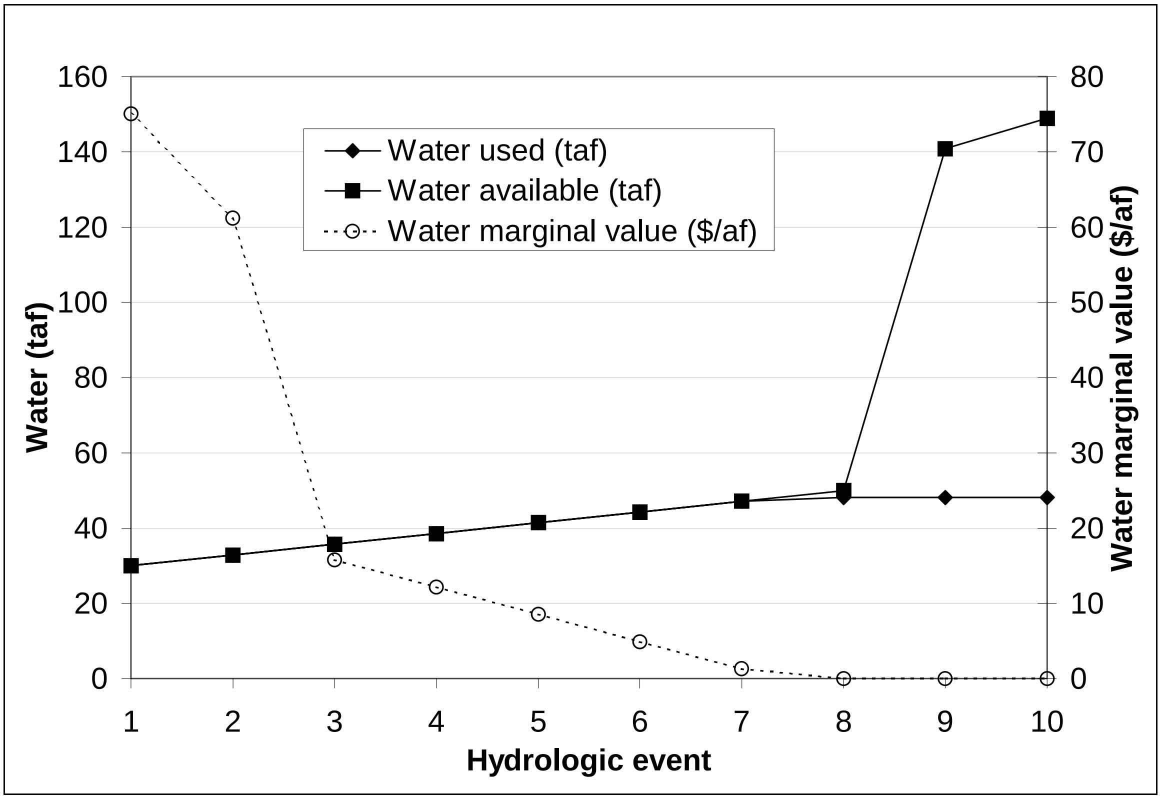

Figure 1. 10 – Water allocation for formulation A4

Irrigation Technology

Irrigation technology plays an important role in agricultural water management. So far the model development assumes uniform irrigation with fixed technology. Adoption of more advanced irrigation technology results in a higher percentage of the water applied being used to meet the agronomic objectives, a desirable characteristic when water is scarce, but also implies higher costs from capital investment, energy and labor. Crops differ in irrigation requirements and the adoption of a given irrigation technology may be desirable or not depending on water demand, water supply, crop value, climate and soil conditions. Variations in water availability and reliability affect farmer's decisions on water use and consequently on the technology adopted. This section introduces the possibility of changing the irrigation technology used for a given crop to maintain the yield while reducing the water application per area. The water saved will be available to irrigate other crops. The optimal decision is a balance between irrigation costs and benefits from additional crops being grown with the water saved. Cai and Rosegrant (1999) present a stochastic model to optimize irrigation technology under hydrologic uncertainty, however only irrigation technology and crop water allocation decisions are considered, and technology decisions are all made in the first stage. The model presented here includes decisions on crop acreages, crops types, water allocation and irrigation technologies.

Irrigation technology is incorporated into the model by representing decisions on permanent crops and investment in irrigation equipment in the first stage and annual crops in the second stage. The irrigation equipment available will be used on the permanent crops and annual crops in the second stage, and includes drip irrigation, sprinkler and Low Energy Precise Application (LEPA). In addition to these three technologies, furrow irrigation is available in any given year without prior investment in the first stage decision. The decision variables are combinations of crops and irrigation technologies.

Many definitions are used to indicate the performance an irrigation system. Irrigation performance relates to how effectively the water applied contributes to the agronomic objectives, or *beneficial uses*. Some beneficial uses include crop evapotranspiration, salt leaching and climate control. To meet these objectives, efficient and uniform application of water is necessary. Burt et al (1997) define multiple performance indicators commonly used and describe *irrigation efficiency* as the ratio between the volume beneficially used and the applied water.

In this work, the term irrigation efficiency (IE) will be used to indicate performance in meeting the beneficial use of evapotranspiration only. The water requirements are defined through the *evapotranspiration of applied water* (ETAW), which is the portion of irrigation water consumptively used by the plants. This discards consumptive demands met by other water supplies such as rainfall or water previously stored in the soil. Thus defining the irrigation supply as AW we have:

$$IE_{ETAW} = \frac{ETAW}{AW} \qquad \textbf{(1. 15)}$$

A more realistic efficiency depends on climate, soil and plant characteristics, however a single IE value is adopted here for each irrigation technique for simplicity. The model can be improved in the future by including different values of IE for multiple combinations of crop type, soil, and climate conditions.

Irrigation costs are estimated based on irrigation technology functions developed in USBR (1997), which used irrigation performance and cost characteristics of 8 crop types and 15 irrigation systems developed by CH2MHILL (1994). In USBR (1997), feasible technology-management combinations for each crop and region were plotted and fitted with a constant elasticity of substitution isoquant, with the form:

$$a\left(b\left(\frac{AW}{ETAW}\right)^{\rho} + (1-b)IC^{\rho}\right)^{\frac{1}{\rho}} = 1 \qquad \textbf{(1. 16)}$$

Where a,b and ρ are fitting parameters and IC is the annualized irrigation cost in $/acre*year. This curve allows trade-offs between irrigation technologies and cost, while maintaining the same yield. Irrigation technology is represented by the ratio AW/ETAW.

The two-stage model uses this equation to estimate the irrigation cost ($/acre*year) for a decision on a given irrigation technology for a given crop, reflected in the AW/ETAW ratio. A more efficient technology applies less water AW to meet ETAW, which reduces the AW/ETAW ratio on 1.16 and consequently increases the IC.

A final model version (formulation A5) including irrigation technology decisions is:

$$MaxZ = -\sum_{i=1}^{m}\sum_{k=1}^{h}\left(INI_i X_{1ik}\right) - \sum_{p=1}^{u} IR_p + \sum_{j=1}^{g} p_j \left(\sum_{l=1}^{n}\sum_{k=1}^{h}\left(RE_{2l} X_{2jlk} - (\alpha_{2lk} + 0.5\gamma_{2lk} X_{2jlk}) X_{2jlk}\right) + \right.$$
$$\left. + \sum_{i=1}^{m}\sum_{k=1}^{h}\left(RE_{1i} Y_{1jik} - (\alpha_{1ik} + 0.5\gamma_{1ik} Y_{1jik}) Y_{1jik}\right) - \sum_{i=1}^{m}\sum_{k=1}^{h} CA_{1i} K_{1jik} \right) \quad \textbf{(1. 17)}$$

Subject to:

$$\sum_{i=1}^{m}\sum_{k=1}^{h} X_{1ik} + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2ljk} \leq L ....\forall j$$ Land constraint **(1. 18)**

$$Y_{1jik} \leq X_{1jik} ....\forall j, \forall i, \forall k$$ Second stage permanent crops **(1. 19)**

$$\sum_{i=1}^{m}\sum_{k=1}^{h} TAW_{1jik} + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2jlk} AW_{2jlk} \leq a_j ...\forall j$$ Water constraint **(1. 20)**

$$Y_{1jik} = \frac{1}{AW_{1jik}} TAW_{1jik} ....\forall j, \forall i, \forall k$$ Stress irrigation **(1. 21)**

$$K_{1jik} \geq X_{1ik} - \xi_i TAW_{1jik} ....\forall j, \forall i, \forall k$$ Stress irrigation threshold **(1. 22)**

$$\sum_{i=1}^{m} X_{1ip} IC_{ip} + \sum_{l=1}^{n} X_{2jlp} IC_{lp} \leq IR_p ...\forall j, \forall p$$ Irrigation technology constraint **(1. 23)**

Where IR_p ($) is the first stage investment decision in irrigation equipment for technology *p* and IC_{ip} and IC_{lp} ($/acre*year) are the irrigation costs to supply respectively permanent crop *i* and annual crop *l* using technology p. The group k includes all technologies that depend on equipment investment in the first stage (group *p*) plus other technologies that are available in any given year (*p* is a subset of *k*). The group k includes sprinkler, drip, LEPA and furrow irrigation, while the group p includes the same technologies as in k except for furrow irrigation. Irrigation costs are calculated using equation 1.16.

The decision variables of acreages of annual and permanent crops are split in combinations of crop type and irrigation technology. The irrigation technology choice will affect the applied water AW (af/acre) based on equation (1.15). More technology (higher IE) results in a lower AW. AW values are calculated previously and the decision upon a given crop and irrigation technology uses the corresponding AW.

The irrigation costs IC for a given combination crop-irrigation technology are added to the left-hand side of equation 1.23. The calculation of the production costs on equation 1.17 is also changed to use the AW value times the water price. This setup has the irrigation costs balancing the water costs in the total production cost for a given combination of crop-irrigation technology. Each combination has its own supply function intercept and slope.

Once the problem is formulated with a quadratic function calibrated to an observed base acreage, the profit functions of individual combinations of crop-irrigation technology must be calibrated to fractions of this observed acreage. This approach will generate a diversity of technology use based on the calibration values, and may offset the desirability of a given technology based on price only. For example, if water is abundant and available at a very low price one would expect to see most of crops irrigated with furrow given its low irrigation cost. However the quadratic revenue functions present diminishing returns, and as the furrow irrigated acreage gets close to the peak the other technologies' gains per acre may offset the furrow advantage and other technologies will start being used. The advantage of this approach is that it allows the model to implicitly represent other reasons for technology diversification, just like for crop diversification, without the use of artificial constraints. The disadvantage is that it may limit the model's response to variations in water price for extreme situations (i.e., water price very low). As an initial simplified approach aimed at evaluating the model's behavior, the observed acreages are split in equal amounts among the available irrigation technologies to calibrate supply functions. Current values of technology diversification can be used in future model developments.

The stress irrigation feature is maintained by modifying (1.7) into (1.21) and including the variable TAW_{1jik} (af) as total water applied to the area of permanent crops *i* in a given hydrologic event *j* using a given irrigation technology *k*.

A last constraint includes limits on the use of irrigation technology in the second stage to the initial investment made in the first stage IP_p (1.23).

<u>Some considerations</u>

An alternative way to solve the irrigation technology problem would be to define the ratios ETAW/AW as decision variables along with the crops acreages. This would enable the model to search continuously over ETAW/AW variables across the constant elasticity of substitution isoquant (equation 1.16). Every ratio would be used to calculate the respective AW, irrigation costs, total production costs, slopes and intercepts of the revenue functions used to evaluate the benefits and costs of the crop acreage decision variables. This approach would reduce the limitation and uncertainties in defining specific efficiency values for the irrigation technologies considered. It would present an optimal ETAW/AW reflecting the level of technology applied. The drawback of this approach is that the calculation of the irrigation cost and the profit function parameters now depend on a decision variable (ETAW/AW ratio) and must be made inside the problem either as constraints or within the objective function. This increases the complexity of the formulation and may lead to discontinuities in the objective function and solution difficulties, including the presence of multiple local optima if constraints are non-convex and/or the objective function is non-concave.

Formulation A5 results and discussion

Results present crop production and diversification for permanent crops similar to the previous formulation A4. Total acreage of annual crops is smaller since more water is required to grow crops (technology is not perfectly efficient as in formulation A4) and production costs are more realistically represented with irrigation technology costs. Permanent crop acreage remains the same.

Technology use presents the expected diversification based on calibration acreages. Factors affecting irrigation technology choices include water availability, water price and crop consumptive demand (other factors such as soil type and climate are not considered). Results from initial runs with water at $44/af appear in Tables 1.5, 1.6 and 1.7. Nut crops have the highest consumptive demand (3.42 af/acre, compared to 2.8 af/ac for grapes and 2.7 af/ac for citrus) and uses higher efficiency irrigation technologies in about 75% of its acreage (Table 1.5). Given the low water availability in most hydrologic events, water use is concentrated in the most profitable permanent crops (grapes and nuts) and the limited amount of water allocated to citrus crops being mostly applied through high efficiency drip irrigation (62% in Table 1.5).

Table 1. 5 – Technology decisions for permanent crops

	Furrow irrigation		Sprinkler irrigation		LEPA irrigation		Drip irrigation	
	(ac)	% from total of crop	(ac)	% from total of crop	(ac)	% from total of crop	(ac)	% from total of crop
Citrus	0	0.0%	0	0.0%	7	37.6%	12	62.4%
Grapes	515	8.2%	1,781	28.5%	1,928	30.8%	2,028	32.4%
Nuts	729	16.5%	1,188	26.9%	1,243	28.1%	1,258	28.5%

The water constraint binds for hydrologic events 1 through 8 which motivates more investment in technologies that conserve more water (Table 1.6). Both permanent and annual crops share the initial capital investment in technology. Initial investment is based on expectation of future water availability, and not all equipment acquired is used in all hydrologic events.

Drip irrigation accounts for almost half of the total investment and twice the amount invested in sprinkler irrigation. In the first stage, drip irrigation uses 43% of the total investment in high value permanent crops (Table 1.6). The remaining equipment purchased is either used to irrigate annual crops when there is enough water available, or remains idle if water is scarce. In hydrologic events 1 through 6 about 97% of the initial irrigation investment is used, entirely in permanent crops. When more water is available in events 7 to 10 the annual crop acreage is expanded using the remaining 3% of total investment in equipment (Table 1.7).

Table 1. 6 – Irrigation technology investment and permanent crop decisions in the first stage

	Initial Investment		Permanent Crops	
	(k$)	% from total invested	(ac)	% use from total invested
Furrow	-	-	1,245	-
Sprinkler	302	23.86%	2,969	22.69%
LEPA	412	32.54%	3,178	31.54%
Drip	552	43.60%	3,298	42.84%
Total	**1,267**	**100%**	**10,690**	**97.06%**

Technologies applied to annual crops also follow the water availability pattern. As hydrologic events get wetter (i.e. from HYD 7 to HYD 10) furrow irrigation takes over most the area plated. It shares about the same percentage of the annual crops acreage as drip irrigation in hydrologic event HYD 7 (47 taf of water available) but when water is abundant (149 taf in HYD 10) it is applied in over 75% of the total annual crops acreage, while drip irrigation is used in only 3.6%. In drier events (e.g. HYD 7) sprinkler irrigation predominates over furrow occupying 41% of the annual crops area given its higher efficiency in using scarce water. However even under very abundant water supply about 14% of the area planed is irrigated with higher efficiency technologies (LEPA, drip and sprinkler), indicating that use of water efficient technology is desirable even when water is not scarce. This fact is strongly influenced by the water price ($44/af). More expensive water will reinforce preference for efficient irrigation.

Table 1. 7 – Annual crop and irrigation technology decision in the second stage

	Furrow		Sprinkler		LEPA		Drip	
Hydrologic event	(ac)	% from total annual crops	(ac)	% from total annual crops	(ac)	% from total annual crops	(ac)	% from total annual crops
HYD6	0	0.0%	0	0.0%	0	0.0%	1	100.00%
HYD7	54	14.8%	151	40.9%	111	30.1%	52	14.2%
HYD8	373	45.2%	189	22.8%	110	13.3%	52	6.3%
HYD9	1,117	76.1%	188	12.8%	110	7.5%	52	3.6%
HYD10	1,117	76.1%	188	12.8%	110	7.5%	52	3.6%

To further investigate the effect of water price in technology choice, multiple runs were made with water price varying from $10/af to $250/af. Results appear in Figures 1.11 and 1.12, comparing the percent acreage of annual crops irrigated with furrow (least efficient) and drip (most efficient) irrigation technologies for different water availability and price.

Percent acreages are relative to the total acreage of annual crops. As expected, when water is cheap and abundant furrow irrigation predominates and drip irrigation is little used (about 2 to 3% of the total). This result is slightly affected by the technology diversification in the calibration process which causes some crops be irrigated with furrow and a decline in the percentage irrigated with drip as the acreage of annual crops drops significantly consequence of water prices increase (Figure 1.11). However the overall results present a consistent behavior, with furrow irrigation being replaced by drip when water gets very expensive and the opposite occurring when water is cheaper. Increasing the water price from $10/af to $250/af results in an annual crops acreage reduction of 92% (for the wettest hydrologic event) leaving only higher value truck crops in production.

No annual crops are produced in the two driest years, regardless of the technology used for irrigation or the water price. Drip irrigation is mostly used when annual crops enter production at 44 taf/year (Figure 1.12), and below $40/af water price it does not become less attractive. However when water gets more expensive the water conservation heavily affects production costs and drip irrigation remains in 28% of the area, while furrow technology is completely abandoned (Figure 1.11).

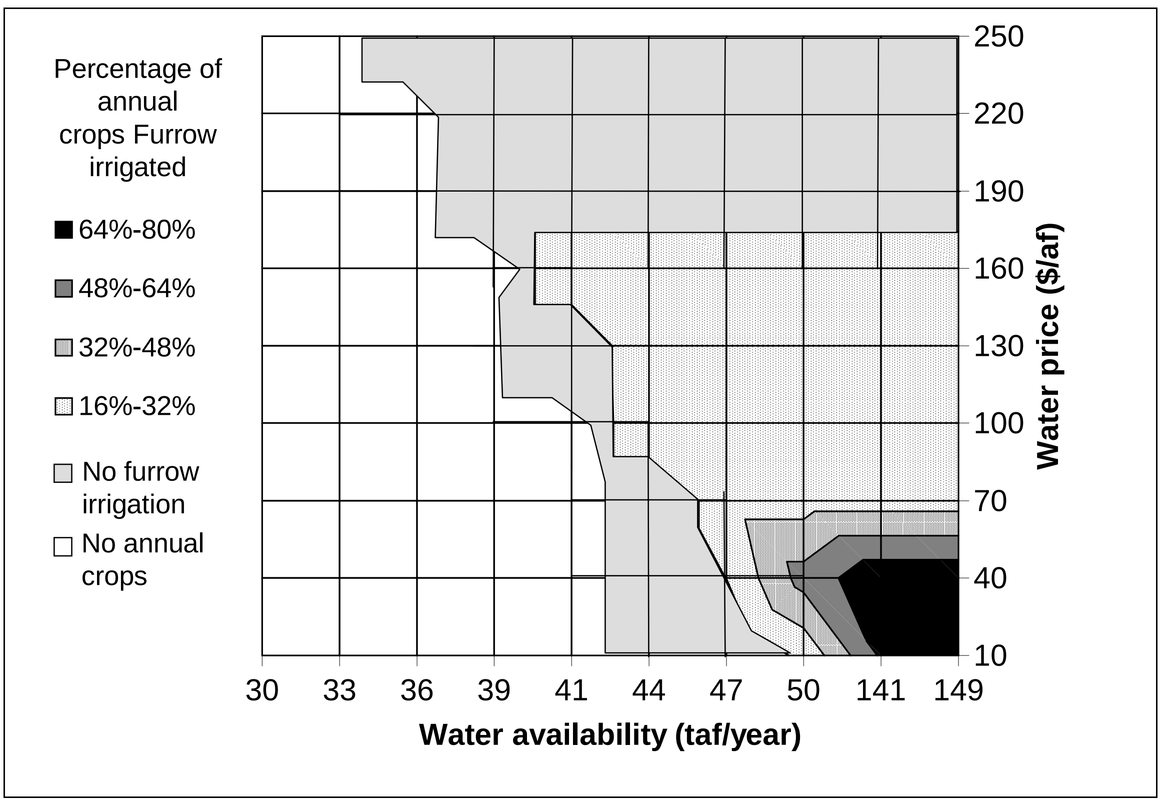

Figure 1. 11 – Surface chart of annual crops irrigated with Furrow for different water prices and water availability

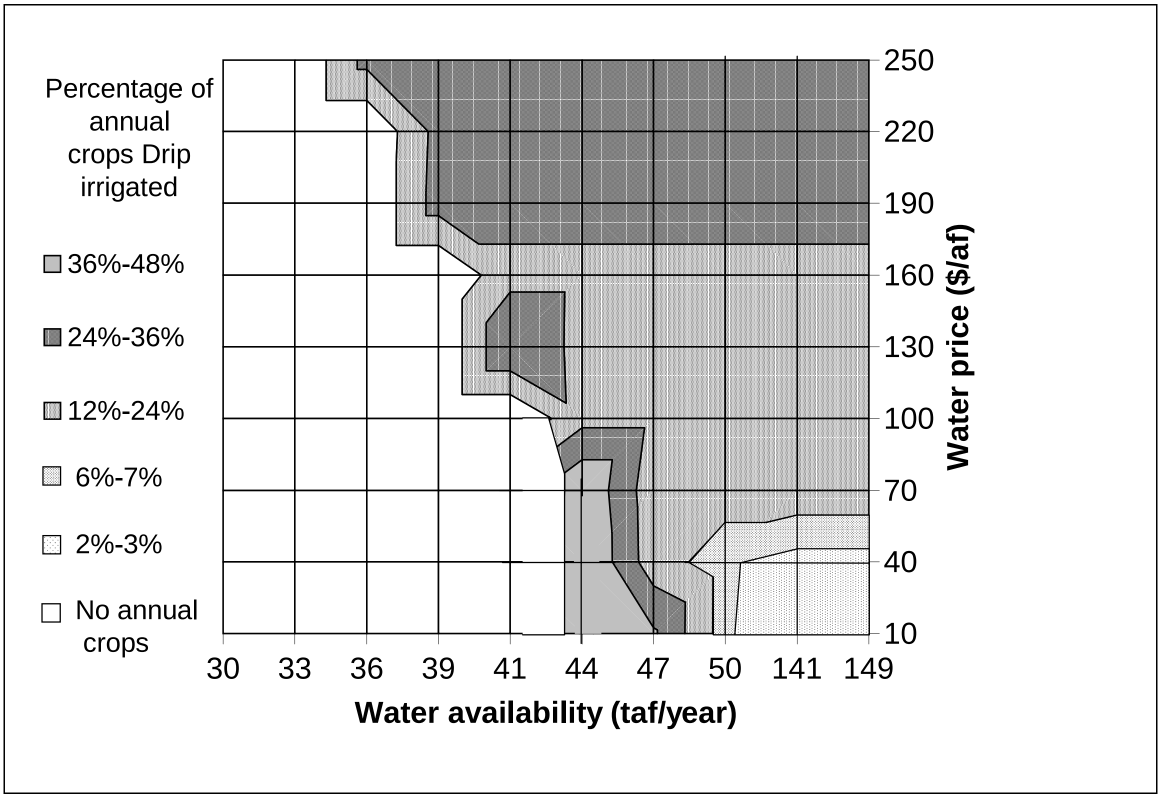

Figure 1. 12 - Surface chart of annual crops irrigated with Drip for different water prices and water availability

When more than 44 taf/year water is available drip irrigation use is reduced if water is cheaper (below $100/af in Figure 1.12) and is replaced by furrow irrigation. However if water is more costly (above $100/af in Figure 1.12) drip irrigation will remain in use for about 20% of the total annual crops area even if water is abundant (above 44 taf/year, Figure 1.12).

Permanent crop decisions are also subject to changes in water price to a lesser extent. The total acreage of 10,796 acres (at $10/af) is reduced by 17% (down to 8,930 acres at $250/af) mostly due to the elimination of the 1,390 acres irrigated with furrow, which is not economically worthwhile when water has a high price.

Total investment in irrigation equipment in the first stage (mostly for permanent crops) is slightly reduced as water becomes more expensive (due mostly to acreage reductions), but it is concentrated in more efficient technologies (Table 1.8) and the technology investment per acre also increases. The pattern is similar to the earlier analysis of technology use with water availability, where higher efficiency technology were still used in 14% of the area even when water was abundant. Here high efficiency technology remains widely applied even when water is very cheap. Compared to water availability variation, water price causes less impact in technology decisions for this case.

Table 1. 8 – Variation in irrigation technology investment for different water prices

Water price ($/af)	Total investment (k$)	Total irrigated acreage	% of investment applied to irrigation technology			Irrigation technology investment per acre ($/acre)
			Sprinkler	LEPA	Drip	
10	1,286	10,796	25.1%	32.3%	42.6%	119
40	1,267	10,722	23.9%	32.5%	43.6%	118
100	1,255	10,351	23.2%	32.5%	44.4%	121
160	1,254	9,764	22.8%	32.5%	44.7%	128
250	1,189	8,930	21.9%	32.6%	45.5%	133

Although the model could be helpful identifying desirable water pricing policies, other agronomic variables are also important in production and may either enhance or diminish the effectiveness of water pricing policies. Green and Sunding (1997) modeled adoption of low-pressure (higher efficiency) irrigation as a function of water price and field characteristics; and found that agronomic factors such as soil permeability and field gradient trigger different technology decisions leading to some crops being less sensitive to changes in irrigation technology with water price change than others. This issue highlights the importance of considering current land allocation when analyzing the effects of different water pricing policies.

Water Availability Probabilities

To finalize the development of this part of the model, more hydrologic events are simulated based on annual water deliveries and probabilities. A time series of 73 years of water deliveries obtained as result from a simulation model (Marques et al, 2003) are used. The moments of this series are used to widen the range of hydrologic events by generating lognormal random variables.

Given a normal distribution defined as $Y \sim N(\mu,\sigma^2)$, a lognormal distribution have the property that $e^Y \sim LN((\mu,\sigma^2)$. This property can be used to generate lognormal variables X (Law and Kelton, 1991) by calculating the first two moments of a normal distribution (μ,σ^2) as function of the moments of the initial series (μ_l,σ^2_l):

$$\mu = \ln\left(\frac{\mu_l^{\,2}}{\sqrt{\sigma_l^{\,2} + \mu_l^{\,2}}}\right)$$

$$\sigma^2 = \ln\left(\frac{\sigma_l^{\,2} + \mu_l^{\,2}}{\mu_l^{\,2}}\right)$$

Given then a generating function $Y \sim N(\mu,\sigma^2)$ and the returning function $X = e^Y$, a long series was generated and divided into 25 intervals. The frequency of each interval was calculated and paired with the lower bound of the interval. A histogram of this water distribution appears on Figure 1.13.

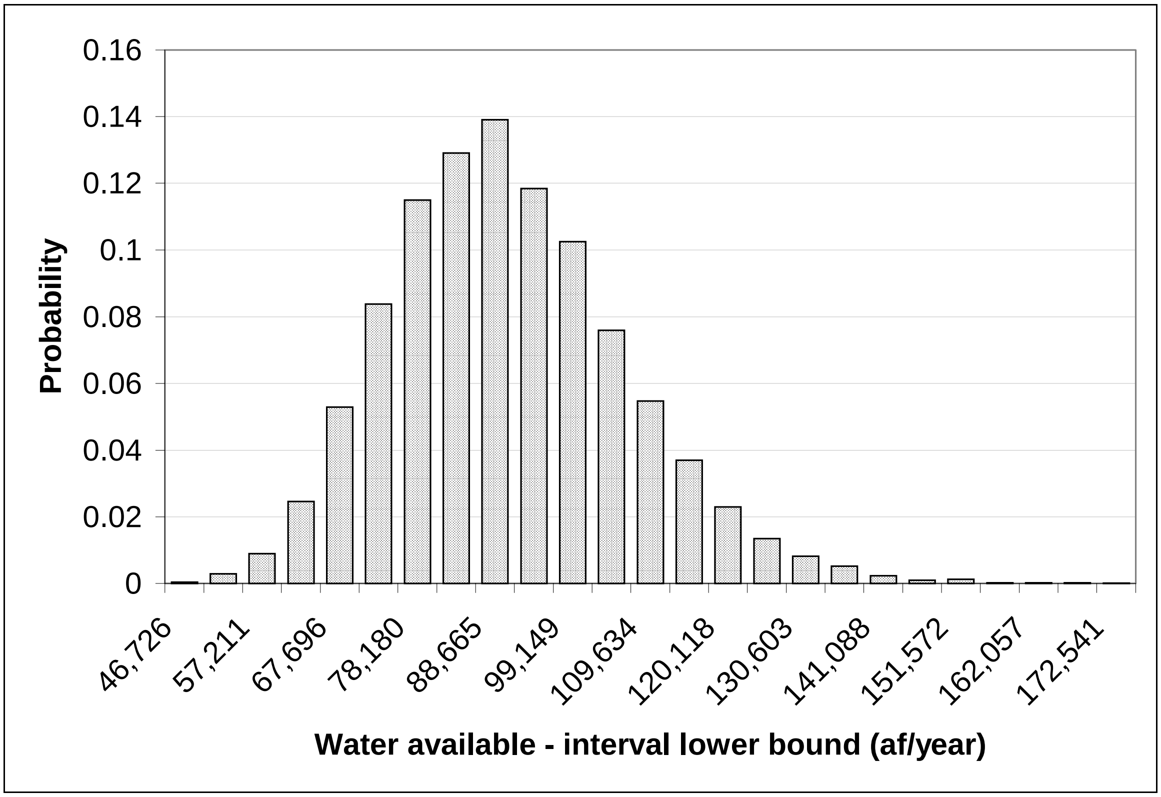

Figure 1. 13 – Water availability distribution used as original input data

This information reflects the variability and reliability of the water available, and it may be affected by decisions on reservoir operation or factors that modify the natural runoff and inflows, such as climate change. The two-stage model can be used to investigate the effects in agricultural production and behavior when the temporal distribution of the water supply is modified by such factors.

The presence of high water marginal values in dry hydrologic events and zero marginal values in very wet events indicates that there are potential benefits in reducing the supply variability. In the case of crop production, less variation in water supply translates to fewer chances to make “wrong” long-term decisions in permanent crops and irrigation technology investment that will result in loss due to water scarcity in the future.

To evaluate supply reliability benefits and the effects on crop production and irrigation technology use, two model runs are executed with different variances in the distribution of water availability, for a same average. The original data run has a 93,000 af/year average and 15,800 af/year standard deviation. The second (less variance) run has the same average and about 8,000 af/year standard deviation. As shown in Figure 1.14, with less variance a given water availability level will have a higher probability of being exceeded in the dry years, resulting in less chances of the supply not being enough to meet demands of permanent crops or to expand production of annual crops.

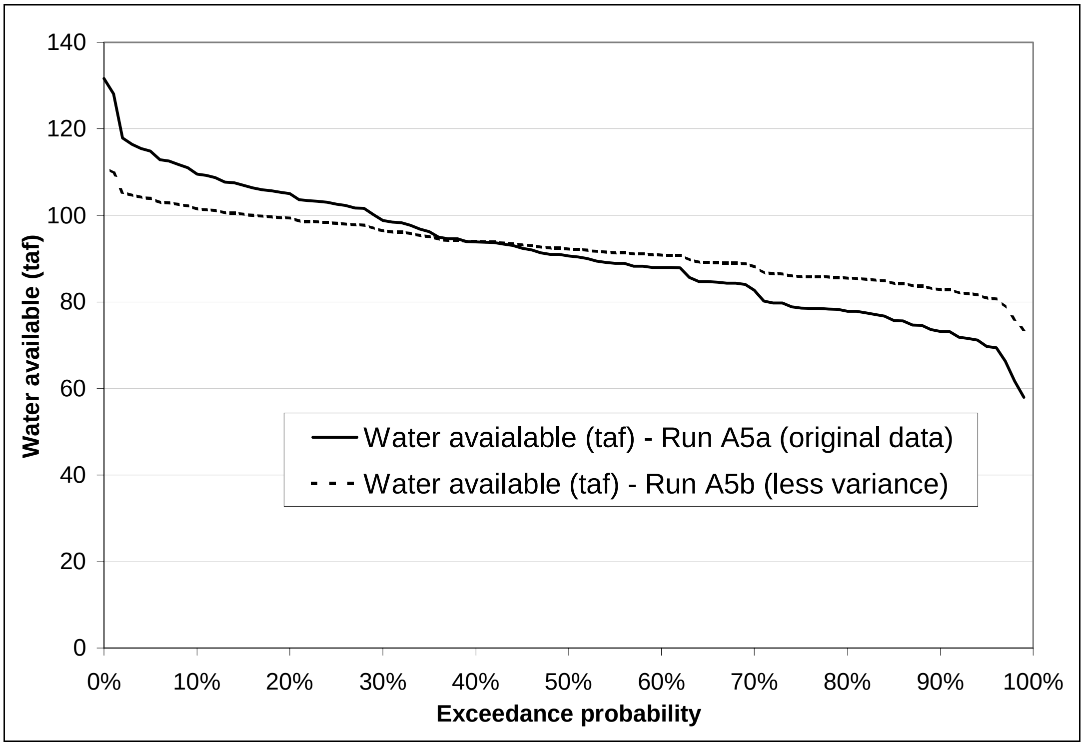

Figure 1. 14 – Water availability for different variances

Marginal water values and probabilities for both runs appear in Figure 1.15 for different water availability (different hydrologic events). *Marginal expected water values* in Figure 1.15 represent the gain in expectednet revenue in the specific year corresponding to the water availability in the x axis (i.e, it is the water marginal value of a given year divided by the probability of water availability in that year). With less variance, the chances of having a year with less water available than 62 taf are virtually zero (and so are the chances of having a year with more than 125 taf). This reduces the chances of severe droughts. In the drier years, for the less variance run (from 63 to 87 taf/year) the marginal water values are slightly higher than the original data run indicating that users are willing to pay more for higher reliability in water supply. The total net expected value benefit increased from $47.8 million to $49.2 million (3% increase) per year.

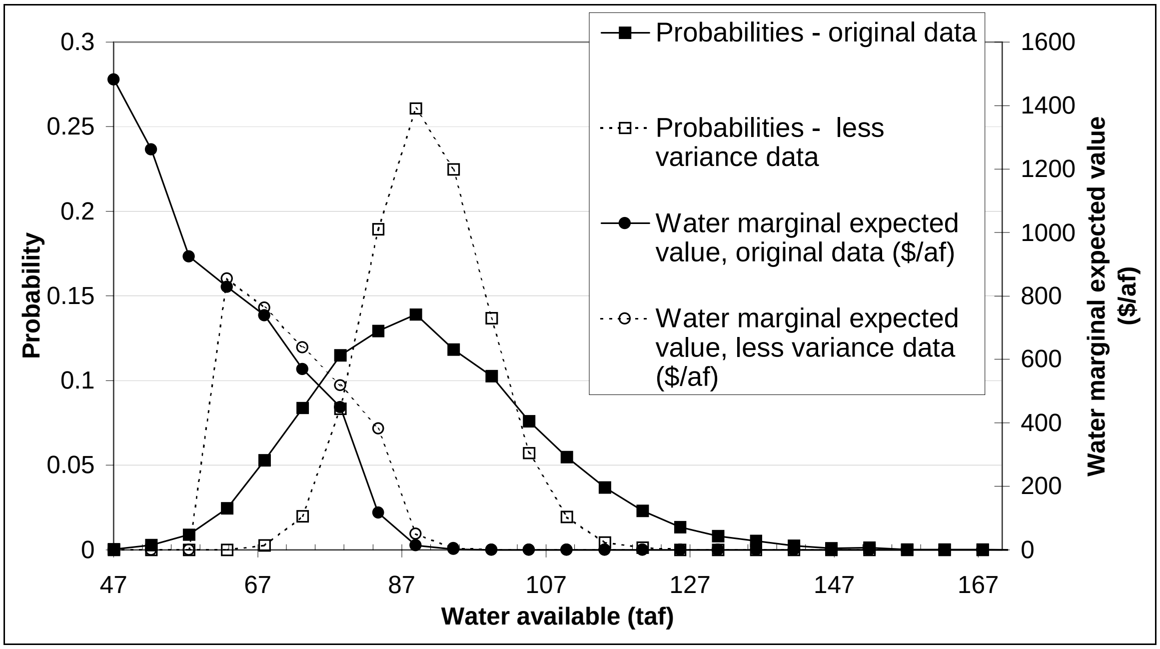

Figure 1. 15 – Water availability and marginal values for runs A5a and A5b

The increase in supply reliability allowed a 3.8% expansion in the area of permanent crops (at the expense of a small reduction in annual crops acreage). The larger permanent crops area takes more advantage of the higher probability of average supply conditions, (around 90 taf/year) increasing the expected benefit. The trade-off is some increase in stress irrigation in drier years, (between 63 and 78 taf/year water supply) but since the probability of these years occurring is smaller (Figure 1.15) they cause little effect on the total expected benefit. This increase in stress irrigation is noted in Figure 1.15 through the slightly higher water marginal expected value for the run with less variance in water availability.

To accommodate the expansion in permanent crops, investment in irrigation technology in the first stage is increased by 1.8%. The increase in investment in the highest efficiency technology (drip) is slightly greater than the other technologies (3% increase against 1.6% in LEPA). This translates into an increase in the acreage irrigated with drip from 4,670 acres to 4,812 acres (3% increase), while the acreage of furrow irrigated crops increases from 3,860 to 4,100 (6% increase), given the lower cost of furrow irrigation. However for years of average supply conditions (which have their probability increased when water is more reliable) annual crop acreages are reduced to increase water supply to permanent crops and most of the reduction is made in the crops irrigated with low efficiency technologies (89 and 94 taf/year in Table 1.9) and crops with highest consumptive water demand. This indicates that under more reliable water supply the water reallocation among permanent and annual crops relies on higher efficiency technologies to maximize beneficial use of water.

Table 1. 9 – Reduction in annual crops acreage from run with original water availability data to run with less variance water availability.

	Annual crops			
Water available	Furrow	Sprinkler	LEPA	Drip
(taf/year)	(ac)	(ac)	(ac)	(ac)
78	0	9	10	9
83	46	42	58	42
89	313	182	60	0
94	227	139	61	1
99	0	139	61	1
104	0	139	61	1
110	0	139	61	1
115	0	139	61	1
120	0	139	61	1
125	0	139	61	1

Annual crop decisions are more flexible and present higher variation between runs with original and less variance water availability. Annual crop acreages decrease by up to 72% in some drier years (water marginal value greater than zero) depending on water availability and probability, and by 9.8% in some wetter years with water supply slightly above average (99 to 125 taf/year) (Figure 1.16). One would expect annual crop acreage to be maintained for the wet years where the water marginal value is zero (99 taf/year and above), however some water application is influenced by irrigation technology investments made in the first stage which are concentrated towards expansion of permanent crops in the less variance water availability run.

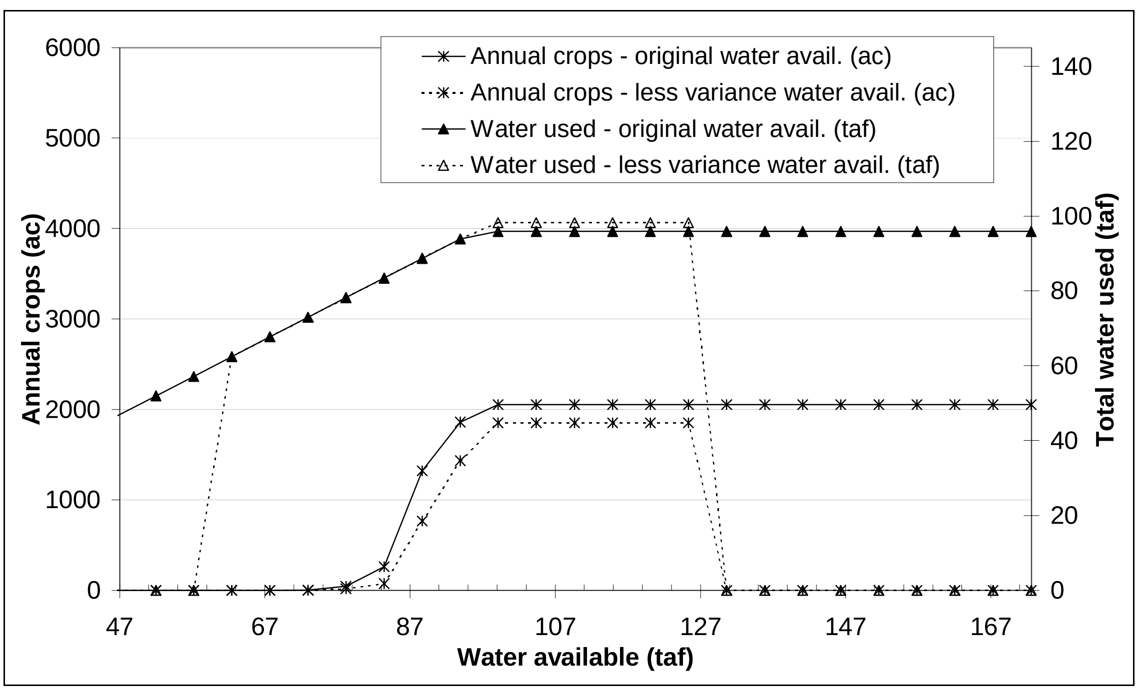

Figure 1. 16 – Water consumption and annual crops production for runs with original and less variance water availability.

Acreages of crops grown with technologies that do not depend on initial investment (furrow irrigation) do not decrease in wetter years. If the desirability for furrow irrigation was based on costs only, it could expand in the wetter years and use up the available water. However the profit function presents diminishing returns and the current acreage of crops furrow irrigated in the original water availability run is already close to the maximum return point, which discourages further expansion in the run with less variance in water availability. This behavior can be adjusted to real situations by calibrating the model to current technology diversification (acreages of crops using different irrigation systems) and water availability conditions.

Further benefits of more reliable water supply are less variability in farmer’s income. The range of possible returns in a given year (difference between the highest and the smallest probable returns) is reduced from $29.6 to $14.7 million. Also, the probability of having a return that exceeds $44.6 million in any given year increases from 82% to 95%, and the return with 100% chance of being exceeded increases from $19.8 to $35.8 million in the less variance run (Figure 1.17). How much exactly is this worth depends on user’s risk aversion. More risk averse users may be willing to receive less water (smaller average) and having a smaller, albeit more predictable return. The model could be used to evaluate this trade-off between expected returns and return reliability by performing different runs with less water available (smaller average supply) but higher reliability (smaller deviation). Depending on user’s risk aversion, conditions can be improved with the use of less water, but with more demand for operational changes (i.e. more reservoir carry-over storage use to reduce supply variability).

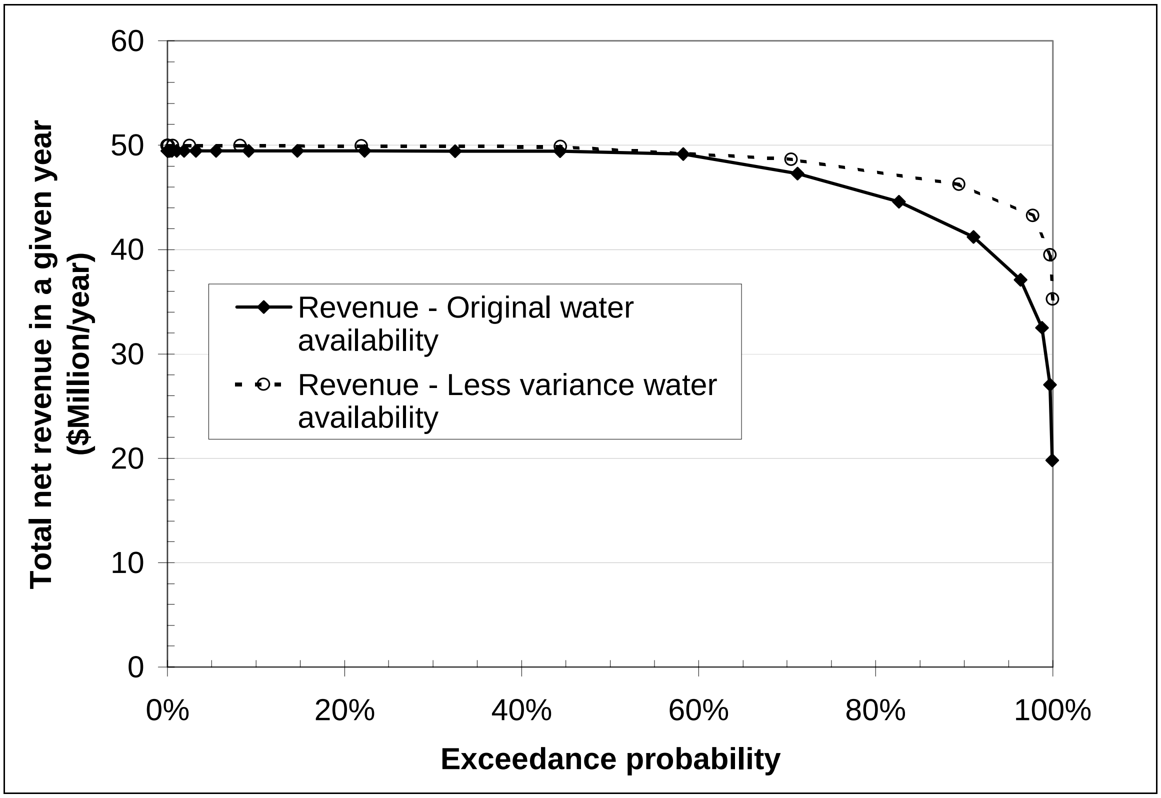

Figure 1. 17 – Probabilities of return for runs with original and less variance water availability

Limitations

Given the primary purpose of presenting and developing the concept of applying a two-stage stochastic programming approach to simulate agricultural decisions several limitations are present in the model. These limitations identify areas for future model improvement.

Permanent crop decisions are not subject to recourse in the model and crop prices are fixed. A major factor affecting cropping decisions is crop prices. Fluctuations in crop prices can result permanent crop acreage changes in the long run. This issue could be addressed in the model by representing crop prices as a second random variable if probabilistic estimates on crop prices are available.

Yields are primarily fixed and do not vary directly with water application. In stress irrigation conditions yields are reduced by the factor Y_{1ji}/X_{1ji} to represent the penalty of reducing supply. This factor could be adjusted based on production functions developed with detailed agronomic relationships of plant/soil/water/climate. Farmers also use crop rotation to increase productivity. The model currently simulates decisions in random, independent hydrologic events and does not consider benefits from alternating crops from one year to the other. This issue also limits representation of stress irrigation long-term negative effects. If stress irrigation is applied in multiple, consecutive dry years, yields of permanent crops may be adversely affected.

No reuse and no water quality. Agricultural water use often includes more complex operations with use of return flows, which vary in quality from initial supply. Use of return flows reduces the overall demand for applied water but may also reduce yields if salinity problems are present. Thus a given total amount of water delivered to an irrigation district may supply different acreages of crops depending on return flows use, water salinity and crop tolerance to salts. The model could be improved to represent water with varying quality and crops with varying tolerance to salts. This improvement would enable it to model decisions on water reuse and crop acreages. Reuse can be increased in very dry periods to grow more salt tolerant annual crops instead of fallowing land..

Other factors affecting irrigation technology decisions. Soil and climate conditions also affect decision on irrigation technology use and are not considered. Irrigation efficiency is also considered for meeting ETAW only. Other beneficial uses may also be relevant depending on the region, including salt leaching and climate control. The combination of these objectives with specific soil or climate conditions can increase or decrease the desirability for a given irrigation technology regardless of its efficiency or cost.

Groundwater is not available. Groundwater is a common supply source for agricultural use given its vast, often easily available storage. However, groundwater use should be properly managed to avoid overdraft negative impacts. Conjunctive use operations of groundwater and surface water can improve supply reliability and flexibility without compromising groundwater resources in the long-run. Groundwater and conjunctive use operations are incorporated in the next chapter.

Conclusions

The two-stage stochastic programming model developed is capable of simulating agricultural intermediate and long-term decisions for different conditions. Decisions on permanent crops and irrigation technology investment (long-term) are modeled in the first stage, and decisions on annual crops, crop water applications and irrigation technology use are modeled in a second stage. A linear profit function provided a straightforward approach to represent annual and permanent crops, but showed limitations in representing crop diversification observed in practice due to constant returns. To overcome this limitation without using artificial constraints at the risk of reducing model flexibility, a quadratic profit function reflecting competitive market marginal conditions calibrated with observed acreage data through positive mathematical programming (PMP) was developed. The quadratic objective function allows a mix of different crops to be produced as the returns vary for each crop.

Water price and availability affect crops and irrigation technology decisions, with more efficient technologies predominating in dry years. Wet years still present some preference for efficient technologies to simulate other reasons influencing decisions, such as application uniformity. Water prices also affect technology decisions, and for prices above $160/af low efficiency technologies (furrow irrigation) are not used regardless of water availability. However in wetter years other intermediate efficiency technologies are slightly more attractive once they provide a better balance of water savings and irrigation cost.

There are clear benefits in improving the water reliability in the system for a given average supply, and the model presented can be used to evaluate these benefits and potential changes in water demands due to variations on crop and technology choices. Water delivery reliability can be changed by reservoir operation, conjunctive use, or water transfer programs. The cost of these operations can be compared to the reliability gains (in this case an increase in the net expected revenue with 100% exceedance probability from $19.8 to $35.8 million) to help identify desirable solutions for water management in the region.

Some immediate conclusions drawn from running the model with higher water reliability are:

1. Marginal value for water is reduced in very dry events, consequently reducing competition for water in critical dry years.
2. Higher reliability shifts production to average conditions. Permanent crop acreages are slightly increased to take advantage of more reliable water under average conditions at the expense of some stress irrigation in drier (and less probable) years.

3. Capital investment in irrigation technology in the first stage is increased to support additional permanent crops. Concentration of irrigation equipment available to permanent crops results in annual crops area being reduced.

4. To maximize production with limited investment in irrigation technology and limited water available under average conditions, more efficient technologies are prioritized, especially for annual crops.

This modeling approach helps improve our understanding and quantification of agricultural decisions under uncertain water supply, water price and other variables. These decisions significantly affect economic production and water use in regions with intense agricultural development, and their understanding provides basis for the development of water management solutions able to address conflicting demands with more favorable economic performance.

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MODELING CONJUNCTIVE USE OPERATIONS AND FARM DECISIONS WITH MULTI-STAGE STOCHASTIC QUADRATIC PROGRAMMING

Introduction

The two-stage stochastic programming method developed in the previous chapter is updated to model conjunctive use operations of groundwater pumping and artificial recharge. The multi-stage programming approach allows for modeling of decisions with recourse, which is suitable for uncertain conditions such as stochastic hydrology, and it allows the inclusion of multiple decision variables to represent more detailed decisions such as permanent, annual crops and irrigation technology. Results from last chapter indicated potential benefits from increasing supply reliability in uncertain conditions. This chapter takes another step and evaluates how conjunctive use operations of groundwater pumping and artificial recharge can improve supply reliability and how that affects decisions on permanent, annual crops and irrigation technology.

Agricultural water demands often depend on uncertain water supplies. High water supply variability and uncertainty increases economic returns variability, can lower average economic returns and farmer welfare, and may ultimately limit agricultural development. Surface water reservoirs provide carry-over storage to reduce variability, but their operation is also required to meet other competing demands (e.g. environmental, flood control), which often limit operation of carry-over storage by agricultural water users.

Agricultural water users have long resorted to groundwater resources as a supplement to surface supplies, or even as major supply source. In California, direct groundwater exploitation with pumping was already intense in the Santa Clara Valley in the late 1800’s (Walker and Williams, 1982), becoming more heavily exploited in other regions with pumping and well drilling technology improvements in the last hundred years (Coe, 1988). The existence of vast, relatively available groundwater supplies, and the common lack of groundwater regulation contributed to this development. The water supply stabilization benefits of groundwater as a supplemental supply when paired with stochastic surface water are discussed in Tsur (1990) and Tsur and Graham-Tomasi (1991).

Groundwater development has resulted in undesired impacts in many regions where it started early and proceeded intensively, including land subsidence, saline intrusion in coastal regions, increase in groundwater pumping costs, reduction in stream flows and soil salinization. Lee and Lacewell (1990) evaluate effects of intensive agricultural development based on groundwater in the Texas High Plains and point out that continuing aquifer exploitation above recharge rates will result in reversion to dryland agriculture given the reduction of profitability as costs increase and yields declined. To keep groundwater exploitation sustainable in many regions it must be managed in coordination with surface supplies, taking advantage of each supply source’s storage capacity, development cost, seasonal availability and recharge times.

This coordinated, conjunctive use, may include a broad range of temporal patterns, management and operational decisions (Pulido et al, 2003), and target different infrastructure depending on specific objectives. Although agricultural users in many regions depend largely on groundwater and can benefit greatly from this management, few studies model agricultural decisions explicitly at the light of conjunctive use operations. Examples including identification of optimal groundwater operations with stochastic surface water are found in Burt (1964), Young and Bredehoeft (1972), Provencher and Burt (1994), Azaiez and Hariga (2001) and Gillig et al (2001).

The approach presented in this chapter simulates and optimizes coordinated farmer decisions on permanent and annual crops, water application, irrigation technology, artificial recharge and groundwater pumping using a two-stage stochastic programming model. The model maximizes the net expected benefit of allocating land and water to permanent and annual crops, and represents conjunctive use with artificial recharge and groundwater pumping decisions. Instead of driving artificial recharge by valuing groundwater storage explicitly with an artificial weight (Azaiez, 2002), or as a constraint based on the difference between water imported and water used (Schuck and Green, 2002), the proposed model is based on a long term equilibrium between pumping and recharge such that water can only be extracted in a given year if it is being recharged in other years. This motivates artificial recharge in wet years, and groundwater pumping in dry years.

This chapter begins with a review of conjunctive use operations for agricultural water use, followed by model approach formulation, application and results discussion, limitations, and conclusions.

Groundwater and surface water operations for conjunctive use

Conjunctive use operations are broad and may serve many different objectives, including managing impact of pumping in surface streams and regional operations aimed at improving water supply reliability involving policy objectives. The operations discussed in this section address the latter.

Infrastructure involved in such conjunctive use operations may include dedicated artificial recharge facilities, pumping sites and operation of existing canals and reservoirs to produce aquifer recharge through deep percolation. Operation of groundwater pumping and recharge are planned with different temporal patterns. This may include a more exclusive focus on groundwater use during an early period of regional economic development (Shwartz, 1980) when surface infrastructure is not yet fully developed, or more balanced operations alternating use of surface and groundwater supplies (Sahuquillo and Lluria, 2003). Operations alternating the use of surface and groundwater seasonally and yearly are common given their long term performance and usefulness to overcome seasonal water imbalances and droughts, while maintaining groundwater sustainability.

This alternating pattern of conjunctive use increases groundwater storage during wet periods and uses it in dry periods. Groundwater storage can be increased in wet periods by direct artificial recharge, by substituting groundwater use with surplus surface water and letting infiltration/deep percolation from water used and from natural runoff replenish groundwater storage, or both. This pattern can produce greater benefits when paired with the operation of surface reservoirs to "cycle" the storage (Lettenmaier and Burges, 1982) from surface to groundwater according to the hydrologic period. The result is more flexibility in the operation of surface reservoirs, fewer undesired spills and availability of more space for other competing uses such as flood control.

These operations may be applied at scales ranging from local storage, conveyance and pumping facilities to complex regional water transfers and exchanges involving multiple facilities and requiring a high level of cooperation and coordination among water users and government agencies. Regional operations are designed to cope with temporal and spatial differences in water availability, water demands, infrastructure, recharge and pumping conditions to maintain supply in dry periods and replenish the aquifer in wet periods. Although high transaction costs can be a challenge (Sahuquillo and Lluria, 2003; Marino, 2001), conjunctive use operations often depend on elaborate water transfers, exchange programs and infrastructure operation (Brown et al 2001, Jones, 2003).

Identification of desirable operations and policies

Many simulation and optimization models have been proposed for designining effective conjunctive programs and operations, including approaches with detailed representation of physical stream/aquifer interaction (Gorelick, 1983; Peralta et al, 1995; Fredericks et al, 1998; Belanieh et al, 1999). Although these methods fill an important gap helping to understand how surface and groundwater interact, application to support regional management is limited by the simplified representation of users' decisions behind water demands. Peralta et al (1995) point out that water demands could not be satisfied in any of the tested scenarios, and that an appropriate future scenario could involve full satisfaction of urban demands at the cost of some water conservation on the agricultural side. Analysis of alternatives requires more detailed modeling of water demand decisions and economics.

Bredenhoeft and Young (1983) assess optimal groundwater capacity to reduce income variability by simulating conjunctive use of surface/groundwater and crop planting decisions through sequences of linear programs based on estimates of water available, groundwater response and irrigation operations. Although it is found that maximum groundwater exploitation capacity maximizes the expected benefits and practically eliminates income variance, the authors assume the necessity of augmenting the stream flow in low flow periods. High pumping costs from this operation can be avoided with artificial recharge to prevent excessive aquifer overdraft, which is not considered in the model. Burt (1964) and Philbrick and Kitanidis (1998) include recharge operations in stochastic dynamic programming (SDP) approaches to identify optimal extraction and recharge rates in wet and dry periods. Philbrick and Kitanidis (1998) model is driven by the cost of control decisions where demands are represented by a single shortage cost function estimated with elasticity of demand for water, and does not consider impacts of pumping and recharging decisions on future pumping lifts. In Marques et al (2003) representation of decisions is improved with individual, monthly variable, penalty functions reflecting each user's (irrigation district) willingness-to-pay for water in a simulation model driven by economics with variable pumping cost.

Model Formulation

Formulation B1 expands the previous formulation A5 to investigate benefits of conjunctive use operations by including decision variables and constraints representing artificial recharge and pumping. Artificial recharge requires allocating land to this purpose in event j represented in second-stage decision variable XR_{2j}, subject to operational costs RC. Water recharged in a given hydrologic event f will be available for pumping in event j through decision variable UR_{fj}, subject to pumping costs PC. The term $\sum_{f=1}^{g} UR_{fj}$ then gives the total water available to a given event j, given the artificial recharge made in all other events f $(f \neq j)$. The same reasoning is used for artificial recharge, represented by R_{jf} which accounts for the water recharged in hydrologic event j that will be available for pumping in event f, so the term $\sum_{f=1}^{g} R_{jf}$ represents the summation of water available to all other events f, through artificial recharge in event j $(j \neq f)$.

A fraction of the applied water in excess of consumptive demand is expected to deep percolate and recharge the aquifer. This water is handled by the decision variable UPD_{jf} which measures water available in a given hydrologic event j, due to deep percolation in other hydrologic events f (f≠j). More realistic deep percolation calculations require tracking water content in the soil. This depends on a series of factors such as the vadose zone hydraulic conductivity, effective porosity and soil moisture content, which depends on vadose zone thickness and soil's field capacity. For simplicity and due to the model approach used here, a single factor is used to estimate the percentage of water applied that deep percolates.

For this formulation water from deep percolation and artificial recharge will be considered "available" even when recharge and deep percolation take place after groundwater pumping. This is based on the assumptions that (a) groundwater storage is large enough to not constrain the transfer of water from one hydrologic event to the other, (b) the hydrologic events time scale of one year is long enough to ensure that water recharged in one event will have time to reach any other event, and (c) that the variation in the water table does not affect pumping costs significantly. Groundwater withdrawals and recharge are be balanced in the long run by a mass balance constraint to prevent overdraft.

To ensure mass conservation when water is transferred between hydrologic events with different probabilities, the terms representing groundwater pumping are adjusted by the ratio of the probabilities of the hydrologic events (year types). For a given amount of water recharged in hydrologic event *f*, with a probability p_f, the amount actually available in another event *j* ($j \neq f$) is multiplied by $\frac{p_j}{p_f}$, effectively reducing (or increasing) the water available for pumping depending if it is recharged in an hydrologic event with lower or higher probability than the even where it is pumped.

Objective function (2.1) maximizes net expected economic benefit from crop, technology use, water application and conjunctive use decisions.

$$MaxZ = -\sum_{i=1}^{m}\sum_{k=1}^{h}\left(INI_i X_{1ik}\right) - \sum_{p=1}^{u} IR_p + \sum_{j=1}^{g} p_j\left(\sum_{l=1}^{n}\sum_{k=1}^{h}\left(RE_{2l}X_{2jlk} - (\alpha_{2lk} + 0.5\gamma_{2lk}X_{2jlk})X_{2jlk}\right) + \sum_{i=1}^{m}\sum_{k=1}^{h}\left(RE_{1i}Y_{1jik} - (\alpha_{1ik} + 0.5\gamma_{1ik}Y_{1jik})Y_{1jik}\right) - \sum_{i=1}^{m}\sum_{k=1}^{h} CA_{1i}K_{1jik} - XR_{2j}RC - \left(\sum_{f=1}^{g} UR_{fj} + \sum_{f=1}^{g} UPD_{fj}\right)PC\right) \ldots \forall f \neq j \quad \textbf{(2. 1)}$$

Subject to:

$$\sum_{i=1}^{m}\sum_{k=1}^{h} TAW_{1jik} + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2jlk}AW_{2jlk} + \sum_{f=1}^{g} R_{jf} - \sum_{f=1}^{g} UR_{fj} - \sum_{f=1}^{g} UPD_{fj} \leq a_j \ldots\ldots. \forall k, \forall j, f \neq j$$

(2. 2)

$$\sum_{i=1}^{m}\sum_{k=1}^{h} X_{1ik} + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2jlk} + XR_{2j} \leq L \ldots\ldots\ldots\ldots. \forall j \quad \textbf{(2. 3)}$$

$$Y_{1jik} \leq X_{1jik} \ldots\ldots\ldots\ldots. \forall j, \forall i, \forall k \quad \textbf{(2. 4)}$$

$$Y_{1jik} = \frac{1}{AW_{1jik}} TAW_{1jik} \ldots\ldots\ldots.. \forall j, \forall i, \forall k \quad \textbf{(2. 5)}$$

$$K_{1jik} \geq X_{1ik} - \xi_i TAW_{1jik} \ldots\ldots\ldots. \forall j, \forall i, \forall k \quad \textbf{(2. 6)}$$

$$\sum_{i=1}^{m} X_{1ip}IC_{ip} + \sum_{l=1}^{n} X_{2jlp}IC_{lp} \leq IR_p \ldots \forall j, \forall p \quad \textbf{(2. 7)}$$

$$\sum_{f=1}^{g} R_{jf} \leq XR_{2j}RCAP \ldots\ldots.. \forall j, f \neq j \quad \textbf{(2. 8)}$$

$$\sum_{f=1}^{g} UR_{fj} + \sum_{f=1}^{g} UPD_{fj} \leq PCAP \ldots. \forall j, f \neq j \quad \textbf{(2. 9)}$$

$$\sum_{f=1}^{g} PD_{jf} \leq \left(\sum_{i=1}^{m}\sum_{k=1}^{h} TAW_{1jik}(1 - IE_k) + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2jlk}AW_{2jlk}(1 - IE_k)\right)\phi \ldots. \forall j, f \neq j \quad \textbf{(2. 10)}$$

$$UR_{fj} \le \frac{p_f}{p_j} R_{fj} \ldots \forall j, \forall f, f \ne j \qquad \textbf{(2. 11)}$$

$$UPD_{fj} \le \frac{p_f}{p_j} PD_{fj} \ldots \forall j, \forall f, f \ne j \qquad \textbf{(2. 12)}$$

Constraint set includes water balance (2.2), land (2.3), second stage permanent crops (2.4), stress irrigation (2.5), stress irrigation threshold (2.6), irrigation technology (2.7), and the newly added artificial recharge (2.8), groundwater pumping capacity (2.9), and deep percolation (2.10).

Water balance (2.2) is updated with the recharge (R_{jf}) and pumping (UR_{fj} and UPD_{fj}) terms for water balance. Artificial recharge constraint (2.8) limits the amount recharged in event j to the recharge area allocated in j XR_{2j} times a recharge capacity $RCAP$ in af/ac*year. Groundwater pumping capacity (2.9) limits pumping from deep percolation and artificial recharge to installed capacity. Although there is no separation between pumped water by source (deep percolated or artificially recharged), separate variables for those sources are used in equation 2.9 since they are limited by different decisions. UR_{fj} reflects artificial recharge, while deep percolation UPD_{fj} depends on both water and irrigation technology decisions used in other hydrologic events, according to equation 2.10. The fraction of applied water that deep percolates and contributes to aquifer recharge is represented by the parameter ϕ.
The pumping variables (UR_{fj} and UPD_{fj}) are limited by two probabilistic mass balance equations (2.11 and 2.12) to take into account the effect of different hydrologic event probabilities in the water quantities. Equations 2.11 and 2.12 reduce (or extend) the upper bound on how much water is available for pumping by multiplying the intermediate pumping variables (R_{fj} *and* PD_{fj}) by the hydrologic events probability ratio $\frac{p_j}{p_f}$.

<u>Formulation B1 results discussion</u>

Two initial runs were executed for this analysis. One with groundwater pumping and artificial recharge (CU) and a base run without groundwater pumping (no CU). CU run allows groundwater pumping from deep percolation and artificially recharged water. Conjunctive use operational data appears on Table 2.1.

Table 2. 1 – Conjunctive use operational data

Element	unit	
Capacities		
Artificial recharge	af/acre*year[1]	36.06
Groundwater pumping	af/year	43,000
Costs		
Artificial recharge	$/acre	1,000
Groundwater pumping	$/af	45

[1] volume of water per unit area of recharge pond.

Even though deep percolation alone provides a significant portion of water available for groundwater pumping in dry years, in two very wet years land is allocated to artificial recharge to further improve groundwater supply (Figure 2.1). This results in a 4.8% gain in the total net expected benefit (from $47.8 to $50.1 million/year), slightly higher than the 3% gain obtained by only reducing surface supply variability in the previous chapter. The separation between deep percolation and artificial recharge in Figure 2.1 is made only to illustrate the relative importance of each; in practice there is no distinction in the groundwater pumped. Deep percolation occurs in all events with some minor fluctuations from changes in acreages of annual crops and irrigation technologies across the year types. Very dry and very wet years have deep percolation from applied water (irrigation) slightly reduced since water has a higher value either for crop production or for artificial recharge. This leads to higher acreages of crops irrigated with more efficient technologies (such as drip irrigation) relative to crops irrigated with low efficiency technologies (such as furrow) and consequent reduction in total applied water and deep percolation.

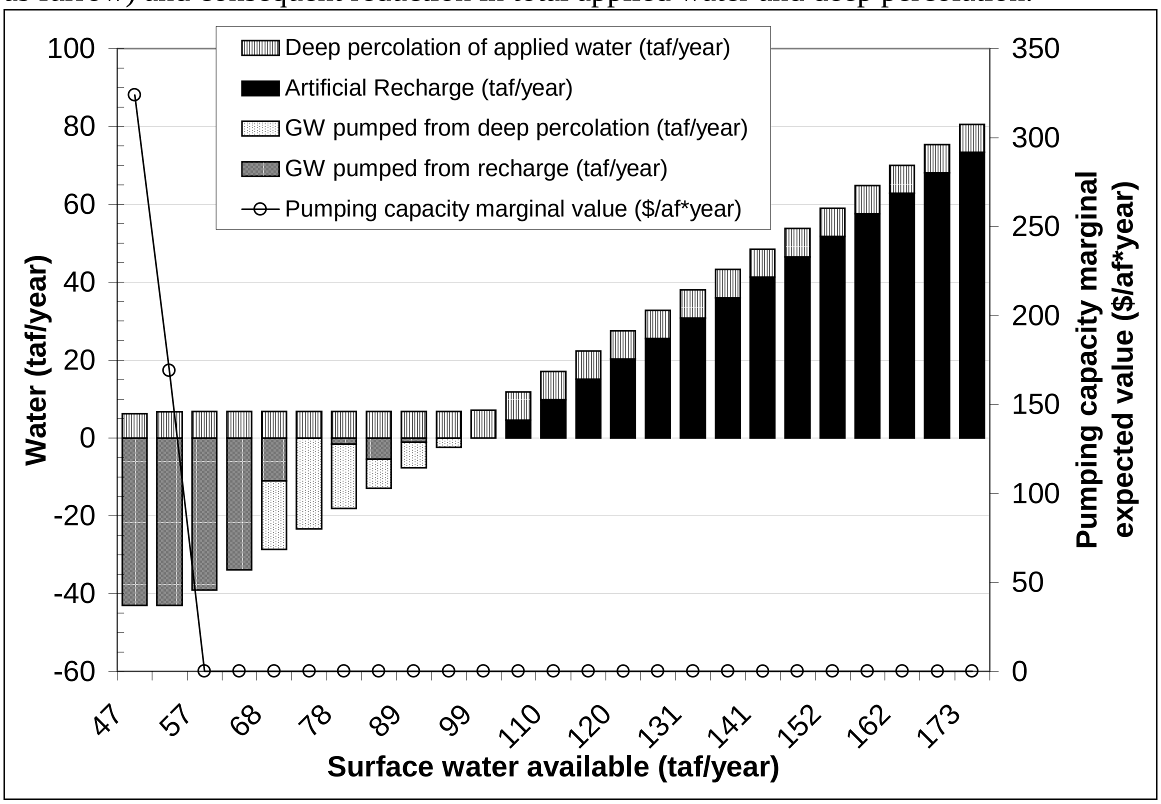

Figure 2. 1 – Conjunctive use operations

Positive marginal values for pumping capacity indicate potential gains in expanding groundwater pumping infrastructure (43 taf/year pumping capacity) in the two driest years. When groundwater is available expected total water use increases from 86.3 taf/year to 101.3 taf/year, and the reallocation of water from wet to dry years reduces the standard deviation in the total water use from 10.5 taf/year to 3.5 taf/year. This increase in both supply availability and reliability translates into slightly higher and largely less variable returns (Figure 2.2). The range of probable outcomes (net economic returns) is significantly narrowed (standard deviation on total net return reduced from $3.4 million to $80 thousand) with the total return with a 100% exceedance probability in any given increasing from $19.8 million to $46 million. The probability of having a net revenue that exceeds $49 million increases from 58% to 96%. These rather optimistic results are largely due to the large surplus of surface water in very wet years and large groundwater pumping capacity and storage capacity available to allow water be moved from wet to dry years, despite the pumping and artificial recharge costs.

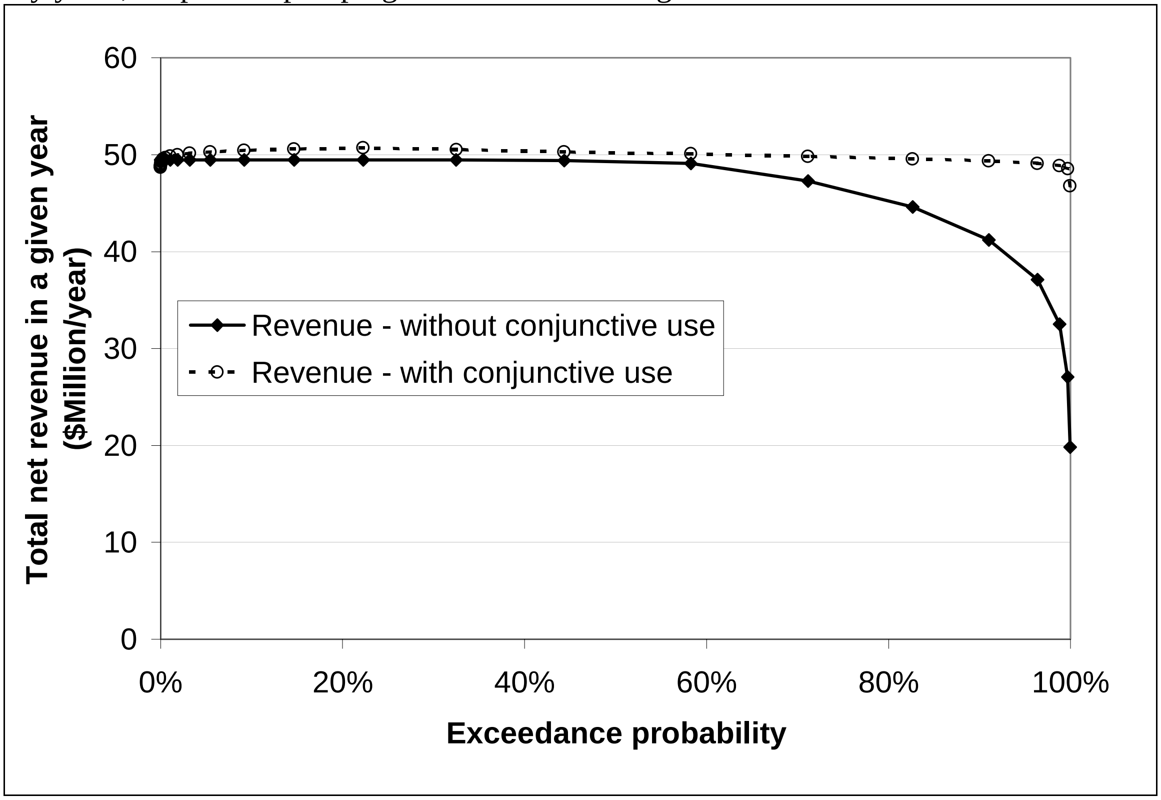

Figure 2. 2 – Revenue reliability curve. Probabilities of return for operation with and without conjunctive use

The increase in water availability and reliability results in more land being used for crop production. In the example, land remains a slack resource in both CU and no CU runs with zero marginal value. Where land is a binding constraint, its marginal value could be used to evaluate the opportunity cost of land considering artificial recharge and crop production decisions.

With conjunctive use improving water supply, stress irrigation is reduced and remains only in the two driest events. This contributes to the lower water marginal expected value (Figure 2.3) for the conjunctive use model run, compared to the no conjunctive use run. The water marginal expected value is still high for the two driest years ($408/af at 46.7 taf/year and $251/af at 52 taf/year of surface water available), however it drops to $83/af for year types from 57.2 taf/year to 93.9 taf/year of surface water available, and to $10/af for year types with higher surface water up to 173 taf/year (Figure 2.3). Groundwater pumping occurs in year types with 46.7 to 93.9 taf/year, and the water marginal expected value of $83/af reflects the groundwater pumping cost of $45/af and the artificial recharge cost of aprox. $28/af. At this point users are willing to pay for additional water what it costs to recharge and pump it from the aquifer. The higher water marginal expected value for the two driest years reflect both the pumping cost, the marginal costs for pumping capacity expansion, and the production foregone due to stress irrigation. Marginal expected water values represent the benefits of additional water in a given year divided by the probability of water availability in that year.

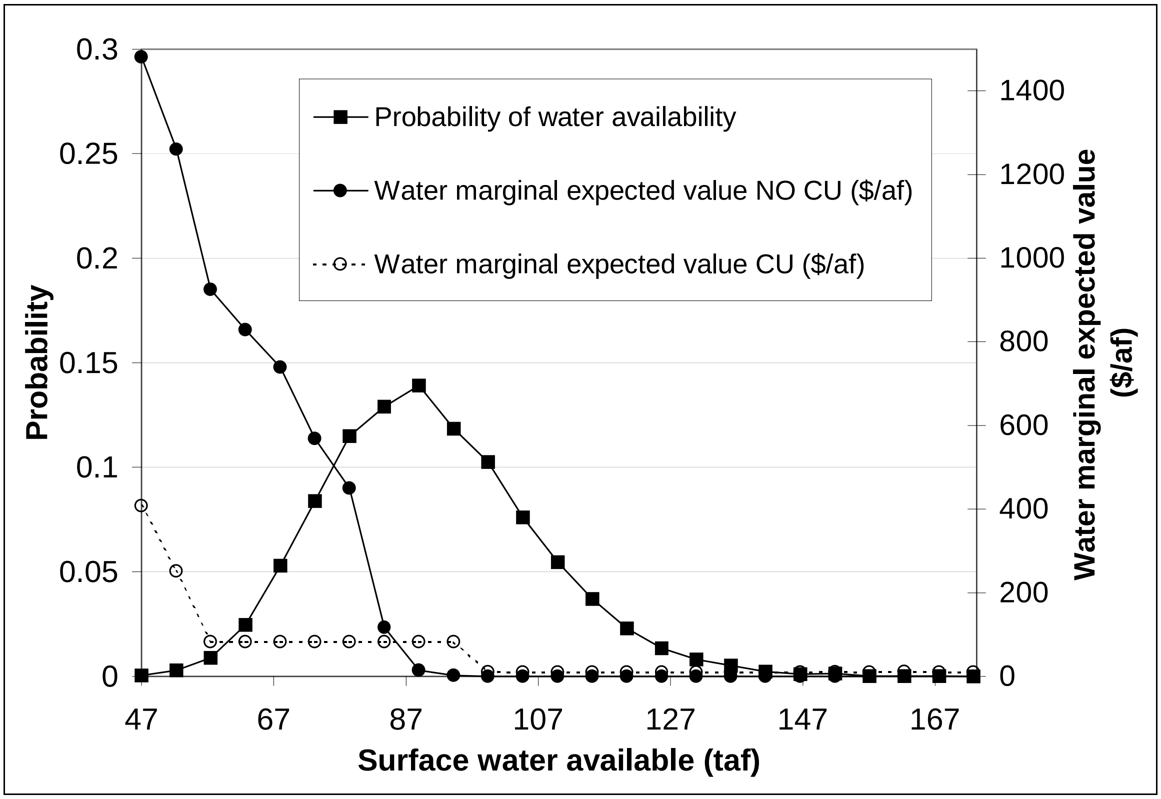

Figure 2. 3 – Water marginal expected values

This result seems to corroborate Schuck and Green (2002) findings in a study of supply-based water pricing in a conjunctive use system. Schuck and Green (2002) point out that the water user may face a “u-shaped” cost function, with high costs when supplies are low and large quantities are pumped from groundwater, and also when supplies are high and high quantities are recharged. Users are willing to pay more for additional water either when it can be used to supply crops in scarce water conditions, or when there are potential benefits in using it to recharge groundwater aquifers for later use in dry years.

Under average and wet surface supply conditions, from 88.6 taf/year and above, the water expected marginal value is higher with conjunctive use than without it (Figure 2.3). This difference is the value of the added supply reliability to the users (how much more they are willing to pay to increase supply and supply reliability).

Irrigation technology choice is affected by groundwater availability through deep percolation losses and artificial recharge. Less efficient irrigation increases aquifer recharge and consequently the supply available for groundwater pumping in other years.

However, the higher water consumption with less efficient technology also means less water available for artificial recharge, and lower productivity in very dry years when water is scarce. Thus, the final balance also depends on surface water availability in a given year. This results in some variation in irrigation technology use for annual crops as seen in Figure 2.4. The long horizontal portions on the chart of Figure 2.4 are in accordance with the relatively low rate of change in the technology use expected for annual crops. Although some change is bound to occur every few years, large equipment used in some irrigation technologies offer limitations in terms of storage, are more costly to assemble/disassemble and may remain in use while the crops around it may change. This aspect can be represented with more fidelity in the model by adding a constraint that holds the acreages irrigated with a given technology constant across all the years. One good example is sprinkler irrigation, which may include large central-pivot equipment, not expected to be disassembled very often.

Figure 2.4 depicts the greater use of high efficiency (drip) than lower efficiency (furrow) technologies in the dry years, and the opposite in most of the wet years. This is motivated by both water availability and deep percolation. To separate the effect of deep percolation the model was run with it disabled (but still allowing artificial recharge and groundwater pumping). Results present about the same amount of annual crops irrigated with low efficiency technology (furrow irrigation) as in the run with deep percolation enabled for the dry years. However, during wetter years the acreages of crops irrigated with low efficiency are higher with deep percolation than without it. The curves of acreages for both situations (CU runs with and without deep percolation) in Figure 2.4 "separate" exactly when groundwater pumping starts being cut and it is partially replaced by less expensive surface water (in this example, when surface water available reaches 99 taf/year). At this point water conservation through efficient irrigation is less important than aquifer recharge provided by deep percolation, since water is less expensive, and the area irrigated with low efficiency technology will expand even more if water deep percolated can be pumped back in other years. Without deep percolation, the acreage of low efficiency irrigation is lower than high efficiency technologies acreages in very wet years, given that more water conservation is necessary to supply increased artificial recharge that replaces recharge from deep percolation.

Without groundwater pumping annual crops will not be grown unless at least 78 taf/year is available, while with conjunctive use the additional supply allows annual crops to be planted in much drier years. Higher efficiency drip irrigation predominates over furrow irrigation in this period given the increased cost of the water. Under conjunctive use operations, the higher value placed on the water given the benefits of artificial recharge, acreages of crops furrow irrigated suffer the highest reduction among the technologies available, to maximize water conservation and increase water availability for artificial recharge.

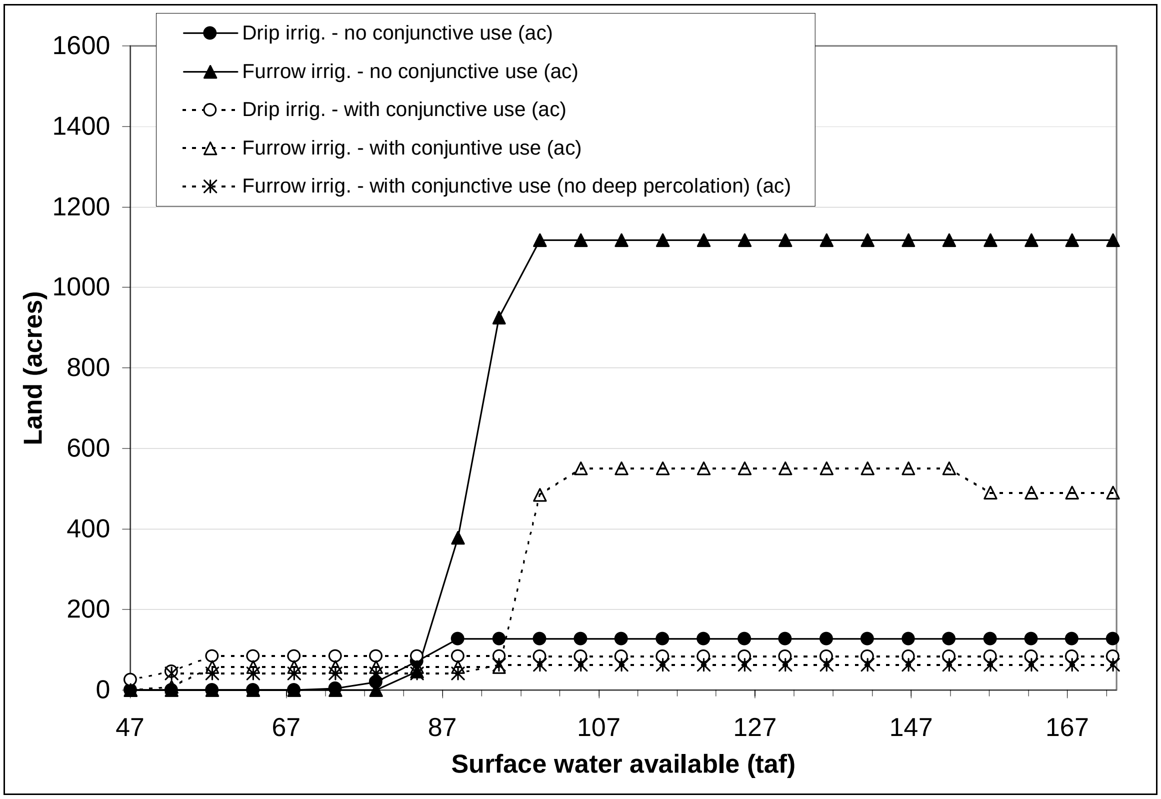

Figure 2. 4 – Irrigation technology applied to annual crops in CU and no CU scenarios

As the permanent crop acreage increase with conjunctive use, the percentage of crops irrigated with the highest efficiency technology (drip) increase (Table 2.2), from 21.7% to 23.4% of the total planted. This indicates that to improve the water supply and reliability in the system with groundwater programs higher efficiency irrigation technologies are economically preferred, notably because most of the improvement occurs in dry years when water is scarce.

Table 2. 2 – Permanent crops irrigation technology choice for CU and no CU runs

Irrigation technology	No CU run		CU run	
	Used (ac)	% from total permanent crops grown	Used (ac)	% from total permanent crops grown
Furrow	4,608	25.9%	5,165	25.6%
Sprinkler	4,674	26.2%	5,179	25.6%
LEPA	4,672	26.2%	5,136	25.4%
Drip	3,863	21.7%	4,731	23.4%

The use of groundwater to mitigate water supply uncertainty reflects the users' risk averse behavior. Risk aversion motivates users to invest in income variability reduction. This may include over-application of irrigation water and even expansion of groundwater pumping capacity beyond a point of maximum expected income (Bredehoeft and Young, 1983; Willis and Whittlesey, 1998). Despite the smaller uncertainty in groundwater availability compared to surface water, especially when supported by a conjunctive use program with planned recharge and pumping, it will not fulfill its role in improving supply reliability if the users are unable to pump it when demanded. Thus users may be willing to invest in a pumping capacity large enough to partially or totally replace surface water during drought periods. Exactly how much pumping capacity investment depends on production value and well costs. The positive marginal values for expanding pumping capacity verified in the model results indicate this behavior.

To further explore this issue, the model is run for different pumping capacities and later modified to include groundwater pumping capacity as a first stage decision variable to evaluate optimal investment in pumping infrastructure. The user would invest in a given capacity in the first stage, and then pump the desired amount in the second stage, based on crop water demands and surface water availability. This would model pumping capacity as a "permanent" decision (like the permanent crops in the model) without further expansion recourse in the future. Despite this limitation, the approach is still reasonable in the short/medium term.

Groundwater pumping infrastructure cost is based on a cost of $25,000 per well placed, and a 3,000 gpm well pumping capacity. The model was run for different total pumping capacities (taf/month) on the right hand side of equation 2.9 and for each total pumping capacity an infrastructure cost was deducted in the objective function. As expected, the result is an expected total benefit that peaks at the optimal pumping capacity and starts to decline for higher investments in groundwater pumping infrastructure (Figure 2.5).

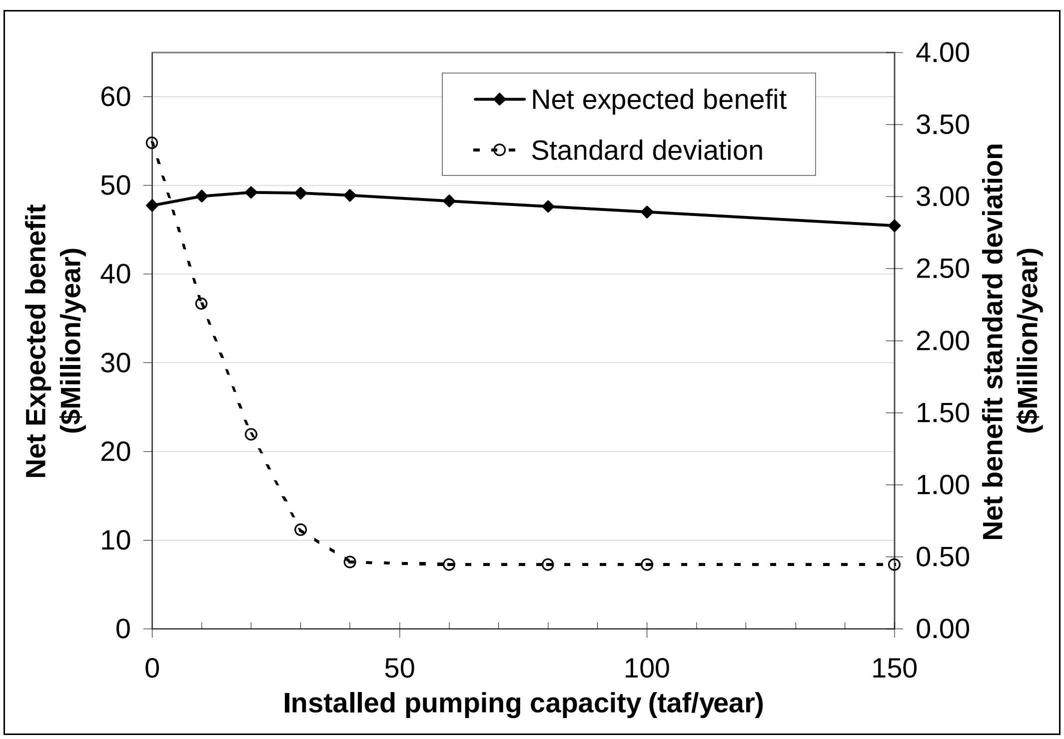

Figure 2. 5 – Total net expected benefit for different levels of pumping capacity

Pumping capacity maximizes expected net benefit and quickly reduces net benefit standard deviation (more reliability) when expanded up to around 20 taf/year, indicating the double benefit of installing sufficient pumping infrastructure. A similar result is also found in Bredehoeft and Young (1983). Around the optimal capacity (20 taf/year) the net expected benefit curve is relatively flat, indicating that a broader range of installed pumping capacity will result in a benefit close to optimal. This translates into more flexibility in infrastructure investment. The further reduction in the net benefit standard deviation beyond the optimal pumping capacity at the cost of reduction in the expected net benefit shows the trade-off between expected benefit and reliability. In this example, it would cost the farmers about $900,000 in reduced net expected benefit to bring the standard deviation from about $1.35 million/year to $450,000/year. After this level of reliability additional groundwater pumping (beyond 60 taf/year) will bring no further advantage, and only adds investment costs. Trade-off decisions depend on user's risk aversion.

By substituting the right hand side of equation 2.9 with an additional decision variable representing pumping capacity an optimal groundwater pumping capacity of 22.3 taf/year (for a maximum net expected benefit of $49.2 million) was found.

Limitations

The model does not track groundwater storage explicitly and relies on assumptions of large aquifer storage and small fluctuations in water table to hold the pumping cost constant across different hydrologic events. The fact that the model balances out pumping and recharge across the horizon of events considered prevents continuous overdraft situations and subsequent impacts on the pumping cost. However the possibility of having a high number of dry years occurring sequentially (probability of a very long drought) could result in variations in the groundwater pumping cost too large to be ignored. As a multi-stage stochastic model, there is no sequential time line for the hydrologic events to occur. This limits modeling of decisions on groundwater pumping capacity expansion, since once built or deepened; a given well capacity will be available in the next event. Consequently, groundwater pumping infrastructure decision is modeled in the first stage, without recourse on the second stage other than pumping (i.e. capacity cannot be changed in the second stage). For longer term planning, expansion on pumping capacity occurring during very dry years must be taken into account.

Nevertheless, the proposed model does allow a wide range of irrigation decisions (including use and recharge of groundwater) to be represented and explored. Such groundwater operations are often undertaken by farmers and irrigation districts in a context of external probabilistic surface water quantities provided to an irrigation district under contract.

Conclusions

Availability of groundwater improves significantly the economic benefits of irrigated agriculture. Results indicate that this can be attained by conjunctive use programs aimed at taking advantage of differences between surface and groundwater supplies, notably temporal variability and storage volumes. The development of a conjunctive use program will maintain groundwater exploitation sustainable in the long run avoiding overdraft related problems. Despite the additional cost and resources necessary to implement the program (e.g. artificial recharge cost and land used for recharge facilities) the benefits are still significantly higher. Some specific conclusions are:

1) Conjunctive use increases not only supply reliability but also availability.
2) There is marginal value for water also in very wet events, consequence of demand for artificial recharge.
3) Deep percolation and aquifer recharge affects technology choice, notably for low efficiency technologies and higher consumptive demand crops.
4) Groundwater pumping capacity can be expanded to optimize total net expected return.
5) Expansion on pumping capacity not only maximizes total expected return, but also reduces return variability.
6) The gains in income reliability are considerably higher than the increase in the expected net benefit. With conjunctive use the net expected benefit increase by only 4.8%, however the revenue reliability curve (Figure 2.2) is almost flat with conjunctive use, indicating significant increases in the probability of having high returns exceeded.

Groundwater availability; price and conjunctive use operations affect significantly crop and irrigation technology decisions. Some specific conclusions on this point are:

1. The stabilizing effect of groundwater supply increases permanent crops acreage.
2. Groundwater supply also allow for expansion of annual crops in dry years, but limits it in the wet years when pumping is cutback.
3. Supply availability and price affect technology and crop decisions. Annual crops with high consumptive demand are not supplied with expensive water through low efficiency irrigation technology. As groundwater supply is cutback in wet years surface supply is diverted to permanent crops and the acreages of annual crops are reduced.
4. Artificial recharge is preferred in very wet years, to take most advantage of the investment in recharge infrastructure. In these periods most of the surface water available is used for artificial recharge and acreage of annual crops is significantly reduced.
5. While more water is available with conjunctive it is also more expensive due to operating costs. This shifts irrigation technology use towards more efficient technologies.

The last analysis of investment in groundwater pumping capacity gains in reliability/net returns provide some helpful insight to support decisions on investment on system capacity expansion:

6. The net revenue curve (Figure 2.5) in flatter close to optimal solution indicating that there is flexibility in investment decisions.
7. There is a clear trade-off of net revenue for added income reliability. This information can be used to evaluate user's willingness-to-pay for insurance according to user's risk aversion.
8. Even though users may be willing to expand investment in groundwater pumping capacity at the expense of some of the total net return gains, there is a maximum groundwater pumping capacity investment beyond which no benefits either in reliability or in net expected returns are verified.

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ECONOMICALLY-DRIVEN SIMULATION OF REGIONAL WATER SYSTEMS: FRIANT-KERN, CALIFORNIA

Abstract

Most water is used for economic activities where water users can make substantial water conservation and allocation decisions. Yet regional models often represent water demands non-economically as requirements or strict priorities. For systems dominated by economic water uses, it may be more useful and effective to represent water uses as economic demands, simulating how water users conserve water, select supply sources, and make water exchange and market decisions in response to changes in water costs, availability, infrastructure and technology. This paper develops an economically driven simulation model for California's Friant-Kern system, characterized by diverse groundwater and surface water sources employed predominantly for irrigated agriculture. For this system, high surface water prices cause farmers to pump more groundwater, disturbing an existing conjunctive use system and aggravating regional groundwater overdraft.

Introduction

Water resources systems are operated to provide water, food, power, transportation, recreation, and environmental protection. Water users who produce these outputs are organized predominantly as business activities such as farms, commercial enterprises, households, and industries operating under market relationships for economic objectives. In many regions, development of these economic activities has been intense and water is perceived as scarce, necessitating efficient management.

Simulation models commonly are employed to improve management, representing storage and conveyance operations, as well as physical, chemical and biological processes. Models designed to simulate sector behavior have included price-quantity relationships (price endogenous) in early economic studies with linear and quadratic programming (Samuelson, 1952; Takayama and Judge, 1964). These models investigate problems of spatial allocation of inputs by competitive markets and are able to identify demand and supply functions for inputs. In water management, this theory allows the improvement of simulation and optimization models by representing water use decisions driven by price-endogenous economic demands, rather than by fixed water demands.

However, representation of water demands as fixed, priority-based is still common in traditional engineering water allocation an simulation models, even when those demands are subject to localized water management decisions driven by economic objectives. In contrast, economic demands have water as an input with economic value, with water users reacting to variations in water cost, availability, reliability and technology. Water users usually make decisions on water use quantity and supply sources, and in some regions users interact in water markets and exchanges for mutual profit and benefit.

This work applies mathematical modeling to simulate water resource systems and enable engineers and water planners to (a) better understand the system and (b) analyze the efficacy and impacts of water management policies in a system driven by user economic decisions. The methods are applied to the Friant-Kern agricultural region of California's Central Valley. The objective of the chapter is to present economically-driven simulation of regional water systems applied to Friant-Kern's water system focusing on implications for conjunctive use operations, water scarcity and scarcity costs when subject to variations in surface water and groundwater prices.
The chapter begins with a review of regional water system modeling approaches, followed by theory of water system simulation driven by economics and application to the Friant-Kern agricultural region in California's Central Valley. Friant–Kern is predominantly occupied by irrigated agriculture and water users have historically employed multiple water sources and engaged 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 Using Mathematical Programming

Two main factors contribute to the difficulties in managing water systems successfully. First, some interconnections of the system's components are often unknown or ignored, and may propagate the effects of actions and operations negatively (or positively) towards other parts of the system. For example, surface and groundwater are frequently managed as separate resources even though they are closely connected in most cases. Also, users make decisions on what and how much to produce based on the availability and price of water, compared to the economic value of the production. The water demands are influenced by economic forces. Second, the multiplicity of water demands with different spatial and temporal patterns often results in conflicting objectives where the identification of compromise management alternatives is difficult.

To develop and operate water systems it is necessary to understand their dynamics and interactions among their components. When this understanding is systematically organized in mathematical models and database systems, it is possible to draw valuable insights about water system responses to inputs like operation rules, institutional arrangements and legal constraints.

Simulation models provide such capability and their utilization is not new (Hufschmidt and Fiering, 1966; Humphrey and Allan, 1959). Simulation models allow analysts to represent water system components and operations and support evaluation of different proposed operational strategies (Labadie, 1997). Real systems operate based on goals and objectives driven by diverse arrangements, including water rights, environmental laws and economic relationships. System operations generally take the form of operating rules. For system simulation, computer models often represent those idiosyncratic rules either explicitly or implicitly by using mathematical programming to operate and allocate water according to a set of operational priorities. Simulation models based on mathematical programming can connect multiple components of the system in a single model, and easily represent diverse goals that drive the system operation through priority schemes. With priority-based penalties assigned to elements such as demands and reservoir storage pools, a mathematical programming model can flexibly seek predetermined operational targets, and evaluate the penalty of different operational setups when targets cannot be met.

Early attempts to apply mathematical programming to simulation of water systems took advantage of network flow programming due to its convenient graphical description, ability to represent multiple components of large systems, and efficient solution methods. A water resources system resembles a transportation network where water is moved between *nodes* through *arcs.* Nodes may represent demand points, junctions, turnouts, or reservoirs; and arcs may represent streams, conveyance infrastructure and carry-over storage; and may have transportation costs, gains and losses to represent pumping costs, system priorities for water allocation and seepage losses. The model is set as a minimum cost network flow problem with an objective function that minimizes the total cost in allocating the water available to the demands for a given time period.

Goals can be represented with priorities on operations and demands 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 and simulate a large multireservoir system. Penalties were assessed on deviations from ideal, predefined conditions. A large California system was simulated similarly (Chung et al, 1989) to estimate water availability for transfers in a priority-based water rights framework. To simulate more elaborate systems where users have different rights depending on the water source, Andrews et al (1992) applied a network flow 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).

The priority scheme in these approaches must be able to represent the desired operations under varied conditions with multiple users, a difficult task for large systems where operations involving gains and losses in the network (i.e., canal losses, return flows) are present. Labadie (1995) developed a generalized network flow model that avoids the problem by considering gains and losses indirectly in a separate, iterative flow calculation algorithm. Israel and Lund (1999) proposed a generalized linear programming algorithm for determining priority unit costs for network flow models with gains so the desired priority system and water allocation are correctly reproduced.

Other complex operations, such as water transfers, water quality management and conjunctive use pose limitations for simulation with network flow programming. Although iterative approaches may reduce such limitations, a mixed-integer linear programming (LP) solver can also represent gains, losses and a variety of constraints explicitly. This approach models system components and connections with constraints that perform mass balance at nodes and set limits for flows according to physical and institutional configurations, while priority coefficients define operational goals' in the objective function. Randall et al (1997) applied an LP solver with a priority-based objective function to simulate detailed diversion and water blending operations for water quality. These operations were added as direct constraints into the model structure, simplifying building of the model while maintaining a robust structure. Kuczera and Diment (1988) used a generalized LP model (WASP) with multiple constraints representing reservoir target curves. Similar approaches were used to model a large system in California through generalized LP and MILP solvers, including OASIS (Meyer et al, 1999) and CALSIM (Munevar and Chung, 1999). LP solvers 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.

Representing longer-term operations in a simulation model also requires use of penalties or constraints to persuade the model to follow operations for which benefits occur in subsequent time steps. These penalties may be artificial values with the sole purpose of setting a priority scheme for execution of pre-defined operational rules, but ideally they should represent future value of operations so that the system could be operated optimally. This approach would use an optimization model to develop optimal operational rules represented by carryover value functions, and then use those functions in a model with higher level of detail to *simulate optimized operations*.

When demands are economically modeled, additional alternatives that include water transfers and re-allocations within the system can be explicitly represented. In intensely developed systems where water is scarce, such as California's Friant-Kern system, complex conjunctive use operations, water transfers and exchanges already exist, and traditional modeling techniques should adapt to simulate the driving forces behind these operations. Initial approaches in optimizing water operations with simulation of price-endogenous water demands include stochastic dynamic programming in Burt (1964), sequential linear programming in Young and Bredehoeft (1972) and mixed-integer linear programming in Gillig et al (2001).

The continuous development of data collection and management systems, refinement of mathematical methods, and expansion of computer processing power have enabled simulation models to address increasingly complex problems. Traditional priority-based approaches with network flow and LP priority-based models present an effective representation of different goals driven by institutional frameworks, agreements and environmental regulations. However, some components, such as water demands, usually driven by economic relationships, may not be adequately represented in traditional priority-based approaches. When economic demands are predominant, a priority-based approach will mimic predefined rules, rather than the users' dynamic behavior and decisions, and may be limited in evaluating performance of management alternatives.

This study employs traditional representation of surface and groundwater storage components and the conveyance network, but with water allocation driven by economic demands. Such economically-driven *simulation* extends now-common mathematical programming based simulation and should be useful in the developing models to evaluate system behavior when users optimize water use based on economic value.

Economic modeling

Water's economic value guides the decisions regarding its use on productive processes and it is directly related to the value of the goods being produced and water availability. Operation of regional water systems where economic uses are predominant should consider the economic value of the water if a broader range of management alternatives is to be evaluated. To Howe (1976), economic modeling is aimed at relating decisions on the use of scarce resources and providing criteria for ranking different policies for management and development. These policies should provide guidelines for efficient water allocation.

Economic models representing agricultural production as a function of inputs can provide solutions that address economic efficiency and simulate decisions of water users seeking to maximize profit subject to exogenous prices (price taker). They are particularly useful in water management given the large amount of water usually demanded by the agriculture sector. If a water plan will affect farmers, it is important to evaluate the impact of the plan in farmer decisions with some degree of detail other than merely assuming fixed demands.

Economic models can be static or dynamic and optimize a production function subject to a set of constraints representing limitations in input resources availability, infrastructure capacities and legal and institutional framework. Static models find a point solution for resource allocation given a fixed structure defined by the constraint set. Common techniques include linear production function and linear constraints (linear programming) and quadratic production function and linear constraints (quadratic programming). Examples of these approaches include the Central Valley Production Model (CVPM), developed to investigate effects on agricultural production as result of reallocation of water supplies for environmental purposes in California's Central Valley (ref); and the Statewide Water and Agricultural Production Model (SWAP), an economic optimization model that identifies demands for water in agricultural regions based on water's marginal value (ref). In cases where uncertainties relative to the constraints are considered important, a chance-constraint approach can be used.

Dynamic models assess how decisions affect present and future states of the system and find a set of actions over time that optimizes resource allocation with possibility of recourse. These models can be implemented with dynamic programming techniques that decompose the sequential decision structure of the problem into simpler sub-problems and find an optimal solution for each time step, or *stage* (Labadie, 1997). This process is based on Bellman's *Principle of Optimality* that states that regardless of the initial stage and state of the system in a sequential decision process, there exists an optimal policy from the current stage and the ending stage. For Kennedy (1986) these models may be better suited in solving intractable problems usually lacking analytic solutions; they can be specified with non-linear and stochastic functions, integer variables and constraints on state and decision variables. However, they may become dimensionally intractable as the number of possible ways to describe the state of the system increases exponentially with the number of state variables. This problem is termed by Bellman and Dreyfus (1962, p.323) as “curse of dimensionality”. Methods to alleviate this limitation may increase the coarseness of the discretization grid of system states or restrict the state-space to a strip around a given solution. The latter is the concept of discrete differential dynamic programming algorithms Hiedari et al (1971). Further detail in techniques to solve dynamic optimization problems can be found in Kennedy (1986) and Miranda & Fackler (2002).

Critical information provided by such models includes the *dual variables* or *Lagrange multiplier* results (for quadratic programming). These variables measure the unit worth of resources, or, in other words, how better off the system would be if one more unit of the given resource were available or a given constraint were relaxed by one unit. The willingness to pay for additional resources (or additional system capacity) can be inferred through the dual variables, also be referred to as *marginal values* or s*hadow prices* due to its economic meaning.

Efficient allocation of water in a market system whose users are price takers and seek profit maximization presupposes existence of well defined property rights, homogeneous information, and homogeneous access to water. In these circumstances users can exchange water according to production value and reach equilibrium where the marginal value of additional water is the same for all users. Ideally, this equilibrium occurs in a *perfect competition* scenario. Existence of positive and negative externalities, usual for common pool resources like the water also limit the efficiency of market based allocation. Lastly, equity issues are not addressed. A more detailed discussion on market failures in water allocation is found in Livingston (1995).

Economic Demands in Simulation – Concepts and Theory

Water use operations and allocations are often guided by water’s economic value. Water users face decisions on how much to produce using water as an input with varying price and availability. Under these circumstances water demands reflect users’ decisions and are not static. Water has a high value when it is scarce, and as more water becomes available, other aspects may hinder production and the value of the next unit of water supply (marginal value) diminishes. Based on this economic value, the user decides which supply sources and how much water to use, not resorting to expensive supply sources without production value. The idea behind an economically-driven simulation model is to represent this behavior with penalty curves derived from water’s economic value (or user’s *willingness to pay* for water) (Figure 3.1). If at a given supply level the cost of the cheapest additional supply exceeds the user’s marginal economic benefit, the user will not apply additional water to production. If this happens at a delivery quantity where the marginal use value exceeds zero we have a situation of *scarcity*, where water may be available, but at a cost that is not economically worthwhile. This scarcity provides a measure of economic loss when a user receives less than the maximum demand (where marginal production cost equals price).

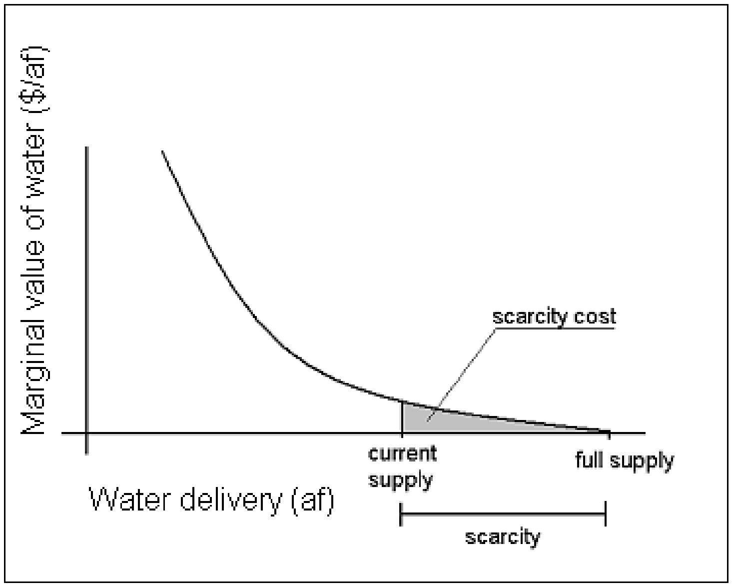

Figure 3. 1 - Economic (demand) function and water scarcity

Economic models exist for most common economic water uses. They can be used to develop economic penalty functions for many water uses. 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.

Some user decisions reflect trade-offs between future and current water use, such as carry-over storage, hedging, and may not be captured in simulation models with a short optimization horizon. These operations can be simulated with a priority-based scheme or be driven by economic storage value functions that reflect optimal system operation in the long run (Draper and Lund, 2004).

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 reflecting higher-than-economic objectives 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 alternatives in terms of the marginal and total values of water in the system.

Application – Friant-Kern System, California

An economically-driven simulation model was developed for the Friant-Kern system, in California's Central Valley (Leu, 2001; Marques et al, 2003). The system is composed primarily of irrigation districts with access to surface waters and groundwater. Groundwater is important for the region and its intensive use has led to aquifer overdraft, land subsidence, saline intrusion, increase in groundwater pumping costs, and migration of groundwater with undesirable quality to higher quality storage areas (CDWR, 2003). Historically this overdraft has provided water supply for the Central Valley's economic development and most recently storage space for water banking programs and conjunctive operations with surface water (Brown et al, 2001). However, this exploitation pattern will increase adverse impacts if groundwater use is not considered in water management efforts. This problem motivated development of a model to simulate the behavior of the water users in the region, how they react to system, policy and cost changes, and to evaluate overall effects on system operation.

The Friant system

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 one million acres 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 (San Joaquin River), the Friant-Kern Canal, and the Madera canal (Figure 3.2 and Table 3.1)). 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.

Table 3. 1 – Main Friant Division Infrastructure and Characteristics

Infrastructure	Size	Obs.
Friant Dam	Height: 319 ft Surface area: 4,900 acres Capacity: 520,528 acre-feet	Concrete gravity
Friant Kern Canal	Length: 151.8 mi Capacity: 5,000 cfs to 2,000 cfs	85% concrete-lined aprox.
Madera Canal	Length: 35.9 mi Capacity: 1,250 cfs to 625 cfs	79% earth-lined

Source: USBR

Supply contracts with the USBR classify the water by reliability. The first 800,000 acre-feet are termed *class 1* water and are the most reliable, followed by the next 1,400,000 acre-feet (class 2). Supplies beyond class 2 (usually winter surplus or flood control releases) are delivered upon availability. Class 1 water is contracted currently at $44/acre-foot and class 2 at $34/acre-foot. Forecasts of annual runoff are made in March and updated through 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 zeroed (Leu, 2001). Contractors include 36 irrigation districts and water districts.

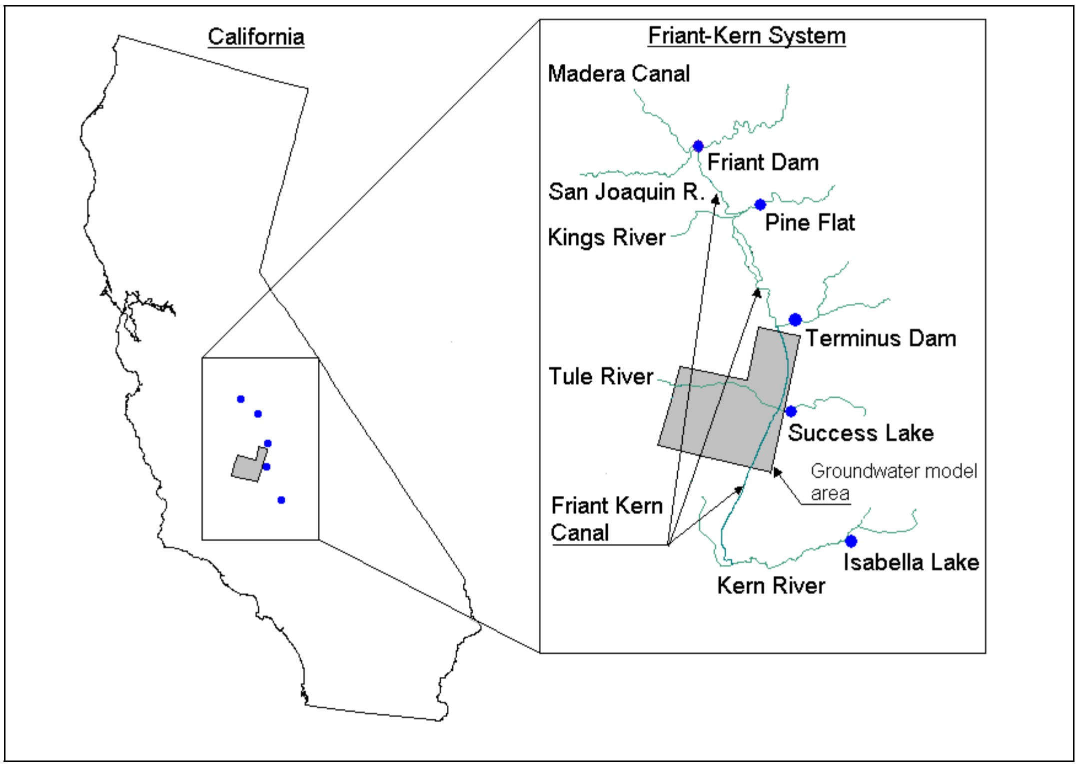

Figure 3. 2 – Friant-Kern System, California

Model Concept and Methods

The Friant-Kern system is modeled as a network flow optimization that simulates operations of water allocation driven by economic decisions at the irrigation district level. The model includes the physical system of canals, reservoirs, streams and demand points, and the institutional framework of water contracts. 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. MODSIM uses a capacitated network flow approach for simulation and optimization of water systems that finds the least cost network sequentially for each time step, with results used as initial conditions for the following time step. The software has been applied with success to simulate diverse river basin systems (Dai and Labadie, 2001; Fredericks and Labadie, 1998). Three other models were used externally to provide information regarding groundwater flow, economic values and water demands based on crop evapotranspiration. 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. The model uses a monthly time step.

Demands are represented with piece-wise linear economic value functions developed through parametric analysis with the Statewide Agricultural Production (SWAP) model. SWAP is a farm optimization model that maximizes economic benefit within land, water and capital constraints, based on data on crop prices, yields and elasticities (Howitt et al, 1999). The marginal value for each demand level in the function is represented in MODSIM as a benefit (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 is represented by a link in the network. To minimize cost, water is delivered first through the lowest cost link available, representing 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). For this problem economic-based penalties represent farmer water source use decisions from among various surface and groundwater sources and supply contracts. The Friant system network model appears on Figure 3.3.

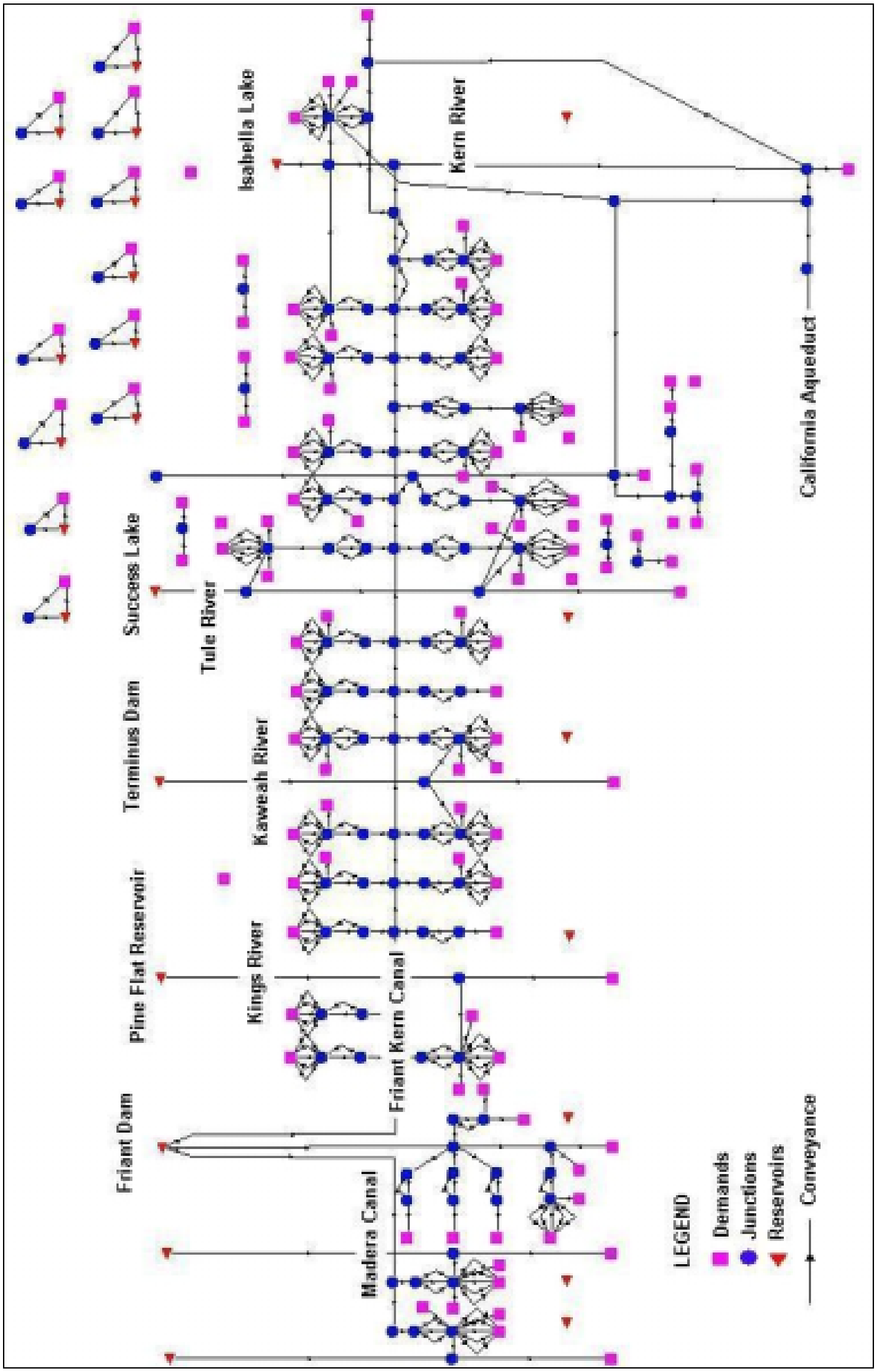

Figure 3. 3 - Friant system representation as a network flow model (MODSIM)

To generate water demand functions, the SWAP model requires input on applied water and evapotranspiration of applied water for all irrigation districts. The LAIUZ (Land-Atmosphere Interface and Unsaturated Zone) model, developed by Naugle (2001) to compute water budget over the land surface and unsaturated zone, was used to provide applied water demand over each land unit of the project area. Land units are defined by their respective landuse type and were later aggregated into irrigation districts. Mass balance is performed in LAIUZ based on precipitation, irrigation applications, water demand, consumptive use, percolation, recharge, excess irrigation and groundwater pumping (Naugle, 2001).

Evapotranspiration of applied water (ETAW) refers to the portion of ET supplied by irrigation, i.e. excluding water already present in the soil (soil moisture) and precipitation water. LAIUZ is originally configured to output demand for applied water based on ET. Thus some adjustments were introduced in the model to separate the required ETAW.

On the adjustments, the effective precipitation Peff is initially calculated as

$$Peff = \begin{cases} (ETa + fc - \phi'), & Pe > (ETa + fc - \phi') \\ Pe, & Pe \le (ETa + fc - \phi') \end{cases} \qquad \textbf{(3. 1)}$$

Where ETa is the evapotranspiration in a given month, Pe is the precipitation; fc is the field capacity and ϕ’ is soil moisture content. Equation 3.1 sets the amount of space available in the soil to store water as the summation of evapotranspiration plus the field capacity, minus water already present (ϕ’). If precipitation in a given month exceeds this amount, then the effective precipitation is (ETa + fc - ϕ’), otherwise the effective precipitation Peff equals the precipitation. Effective precipitation may increase the amount of water stored in the soil and this effect is carried to the next month with an accounting storage variable Speff0. The evapotranspiration of applied water ETAW is then calculated as (3.2)

$$ETAW = \begin{cases} 0, & ETA < (Speff\,0 + Peff) \\ (ETa - Speff\,0 - Peff), & ETA > (Speff\,0 + Peff) \end{cases} \qquad \textbf{(3. 2)}$$

Equation 3.2 adds soil water content from the previous month (Speff0) to the effective precipitation on the present month and compares the total with the evapotranspiration ETa in the present month. If ETa is smaller, all water used by crops is being provided by effective precipitation and soil moisture and in this case ETAW is zero. If ETa exceeds (Speff0 + Peff) then a portion of the ETa will be provided by irrigation applied water. This portion is the ETAW and it is calculated in equation 3.2 as (ETa – Speff – Peff). Whenever ETAW is zero, the amount of water over ETa is carried to the next month in the variable Speff0.

One important aspect that limits this approach is the temporal distribution of ETa and precipitation. The calculations are performed monthly and all ETa is lumped at the end of the month. In a more detailed temporal scale, precipitation and evapotranspiration can vary and the actual amount of water stored in the soil as effective precipitation will not be same as the monthly total calculated in (3.1). Sequences of days with low evapotranspiration, paired with a higher precipitation, may result in monthly totals of effective precipitation considerably lower than the lumped monthly sum of equation 3.1, for the same monthly totals of precipitation and evapotranspiration. Overestimated effective precipitation will result in underestimates for ETAW.

The groundwater representation is designed to calculate and update water table elevations every monthly time step based on changes in storage due to pumping, artificial recharge and deep percolation losses. The water table at the end of a time step is used to calculate the groundwater pumping cost for the next time step. The aquifer geologic characteristics also vary spatially, meaning that the same stress may cause different responses in different places.

In an unconfined porous media, one way to link the water table to storage is through the s*pecific yield* or drainage porosity. Specific yield is the ratio of the volume of water that is drained by gravity forces over the bulk media volume Charbeneau (2000). This means that by lowering the water table by an amount Δh over an area A, the volume of water drained from an unconfined porous media is given by:

$$V_{drained} = Sy * A * \Delta h \qquad \textbf{(3. 3)}$$

Equation 3.3 allows estimation of a variation in head when water is removed or added to an unconfined aquifer, provided that the section considered is small enough so that the specific yield can be assumed as homogeneous. Specific yield information available for part of the project area is based on GIS maps developed in Ruud et al (2002) for a three-dimensional groundwater simulation model (Figure 3.4).

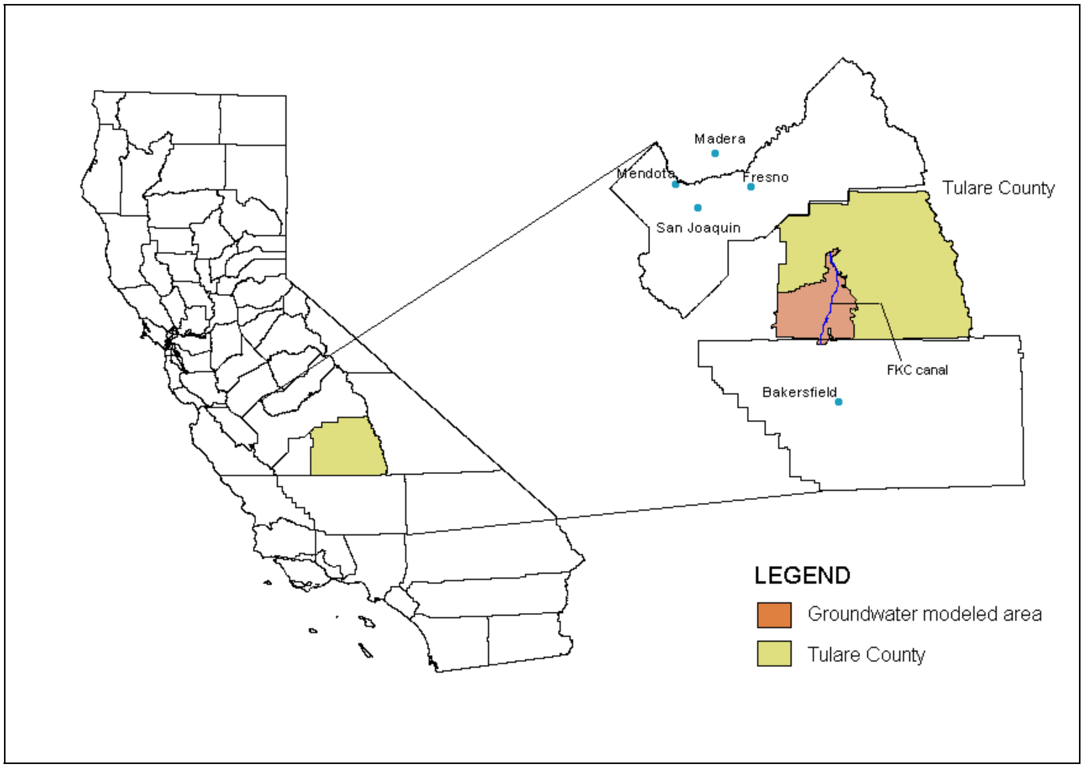

Figure 3. 4- Area included in the groundwater model

Another important aspect is the presence of subsurface fluxes that occur as heads vary spatially and hydraulic gradients are established. Darcy law is applied to establish a linear relationship between flux and the hydraulic gradient defined by the difference in head between two adjacent cells. This relationship is presented in equation 3.4.

$$Q_{ij} = C_{ij}^{eff} * \Delta h_{ij} \tag{3. 4}$$

Where Q_{ij} is the flux between sections i and j, Δh_{ij} is the difference in head and C_{ij}^{eff} is the *effective conductance* between cells i and j. Areas with relatively homogeneous specific yield define the boundaries of the sections.

The 3D groundwater flow simulation model (Ruud et al, 2002) was used to estimate the conductance parameter (Figure 3.5). The groundwater flow model uses a finite differences approach (MODFLOW) and it was run for a number of years to produce the paired data Q_{ij} vs. Δh_{ij}, which was fit with a linear regression curve. The goodness of fit will depend ultimately on how the cell boundaries and specific yield values were devised and if those boundaries and values can capture the aquifer's behavior acceptably. If the cells are too large, the cell average specific yield value may become a meaningless representation of the aquifer's characteristics or, if it is too small, a given cell may suffer significative influence of other non-adjacent cells and the linear relationship among two adjacent cells described in equation 3.4 may not hold. Both situations result in poor fit. A few attempts were made with different sizes, boundaries, and specific yield values for the cells until acceptable fits for equation 3.4 were obtained. The cells are also referred to as groundwater *zones* and are treated as individual, interconnected, groundwater reservoirs. The final configuration of the groundwater zones appears in Figure 3.5.

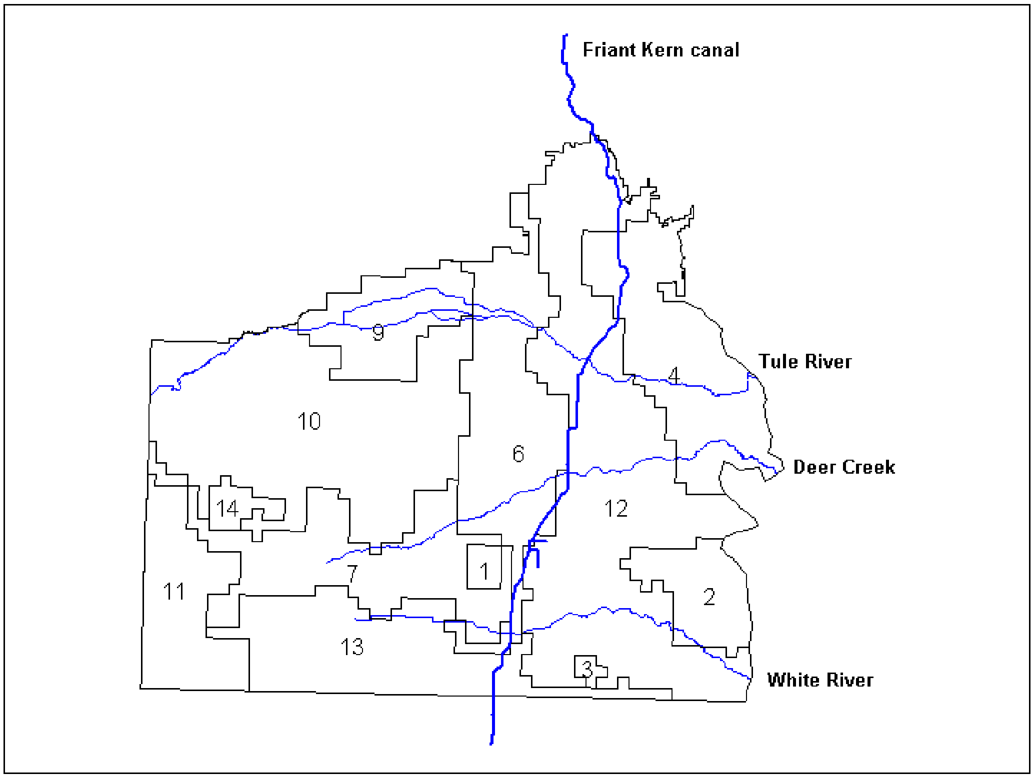

Figure 3. 5 - Groundwater zone definitions

The water table level for each groundwater zone is updated every time step based on storage variations of each zone. The groundwater zones are set in MODSIM's network as storage nodes. Storage will change as water is pumped, deep percolates, or flows from/to adjacent zones. At the end of each time step, heads are updated by the perl script routine and used to calculate the new pumping cost, which is used by MODSIM to solve flows for the next period. Variations in storage due to pumping and deep percolation are managed directly by MODSIM with the pump pattern percentages and deep percolation distribution set in the model's interface. Subsurface Darcy fluxes are calculated separately in the Perl subroutine using equation 3.4, the conductance parameters and the difference in head between the zones. The operation is repeated for all adjacent zones and the fluxes are accumulated to obtain the final net volume that a given groundwater zone will exchange with the adjacent zones in the present time step. The net volumes are added to the groundwater zones node through a set of artificial inflow and demand nodes.

After the MODSIM solver converges to the optimal solution, the heads are updated in the perl subroutine based on the difference between the optimal storage and the previous storage (equation 3.5)

$$h_i^{t+1} = h_i^t + \frac{\Delta S_i}{Sy_i * A_i} \quad \textbf{(3. 5)}$$

Where h_i^{t+1} is the updated head at groundwater zone i, h_i^t is the initial head, ΔS_i is the storage change, Sy_i and A_i are respectively the specific yield and area of groundwater zone i.

Pumping cost is calculated based on the energy required to pump water over the total head, considering head losses due to well and pump inefficiencies. The term "total head" includes the regional water table level *h*, plus the local drawdown *s* generated during pumping. Calculation of drawdown is based on aquifer transmissivity and storage coefficient data and can be made using the *Thiem* equation, for confined aquifers, or *Theis* equation, for unconfined aquifers. Thiem equation (3.6) estimates steady-state drawdown for confined and semi-confined aquifers and is used here as an initial approach. A necessary assumption to use this equation is the existence of a small drawdown relative to the aquifer saturated thickness.

$$s = \frac{Q_{well}}{2\pi T} \ln \frac{r_{eff}}{r_{well}} \quad \textbf{(3. 6)}$$

Q_{well} is the well pumping rate, based on typical well flow capacity T is the aquifer transmissivity, defined as the integral of the hydraulic conductivity over the aquifer saturated thickness, r_{eff} is the effective radius, and defines the distance from the well bore at which there is no drawdown effect, and r_{well} is the well bore radius.

The *input power* IP_j [kw] required to pump water over the total head $(s + h)$ [ft] in a given groundwater site and at a given pumping rate Q_{well} [gpm] can be calculated through the expression 3.7 (Harter, 2001).

$$IP_j = \frac{Q_{well} * (2 * s + h_{reg_j}^{\ t}) * 0.735}{3{,}960 * e_o} \quad \textbf{[kw]} \quad \textbf{(3. 7)}$$

A 50% efficiency for both well and pump (e_o) is assumed. The *energy consumed* E_{well} [kw-hr] by a well operating at these conditions during a period of time t_p [hr] is then (3.8):

$$E_{well\ j} = IP_j * t_p \quad \textbf{[kw-hr]} \quad \textbf{(3. 8)}$$

The volume of water V_{well} [gal] extracted after time t_p is given by 3.9.

$$V_{well} = Q_{well} * t_p * 60 \text{ [gal]} \qquad (3.9)$$

The energy required to pump a unit volume of water E_o [kw-hr/gal] is:

$$E_{o\,j} = \frac{E_{well\ j}}{V_{well}} = \text{ [kw-hr/gal]} \qquad (3.10)$$

As seen, the energy required does not depend on the pumping time, nor on the well pumping rate Q_{well}. Now, defining the energy cost as *c* [$/kw-hr], one can finally obtain the unit pumping cost per volume PC_j [$/af] as:

$$PC_j = \frac{E_{o\,j} * c}{n} = \frac{(2 * s + h_{reg\ j}^{\ t}) * 0.735 * c}{3{,}960 * e_o * n} \text{ [\$/af]} \qquad (3.11)$$

Where *n* (3.069E-06) converts US gallons to acre-feet.

Although some variations on the pumping cost may occur within a time step, they are assumed to be negligible and the pumping cost is only re-calculated at the beginning of a given time step, using the end-of-period head from the previous time step. This assumption seems reasonable since groundwater flow is rather slow and the impact of pumping on water depth may take some time to develop.

Model Results

Model results explore the effects of surface water prices on conjunctive use and groundwater sustainability, and the effects of representation of variable head and groundwater pumping cost and implications for system management. Model runs include variable groundwater pumping (VP), and fixed head pumping cost (FPhigh and FPlow) for comparison purposes. The VP run models the 11 districts included in the groundwater model with variable pumping head.

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 by altering the balance between surface water and groundwater use, which can be captured by a simulation model driven by economics. This section analyses effects of surface water contract prices changes on the system, subject to variable groundwater pumping costs.

The run period was 73 years based on historical inflow data to the surface reservoirs. The forecast for class 1 and class 2 deliveries to Friant was correlated with annual inflows at Millerton 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 this sort of statistical analysis; a longer record of class 1 and class 2 deliveries should be used in future model improvements.

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, change pumping patterns, operating costs and end-of-period groundwater storage. Contract water prices have been increased recently due to increasing operation and maintenance costs (Leu, 2001) and environmental regulation. To simulate the effects of surface water price changes in the Friant system, ten runs were made with surface water prices varying from $24/af and $14/af to $204/af and $194/af (class 1 and class 2 respectively) across the runs.

Increase in surface water prices results in users switching to groundwater use and intensifying aquifer overdraft. This effect accumulates and is felt in later years where the volumes pumped actually drop when groundwater becomes too expensive. Higher surface water prices cause higher groundwater pumping in the first years. At the highest surface water prices the aquifer is so intensely exploited in the first years that groundwater pumping declines after 1961 and is pumped in much less quantity during the 1976-1977 drought compared to scenarios with lower surface water price (Figure 3.6). At this high surface water price there is a large economic impact and drought conjunctive use operations are compromised.

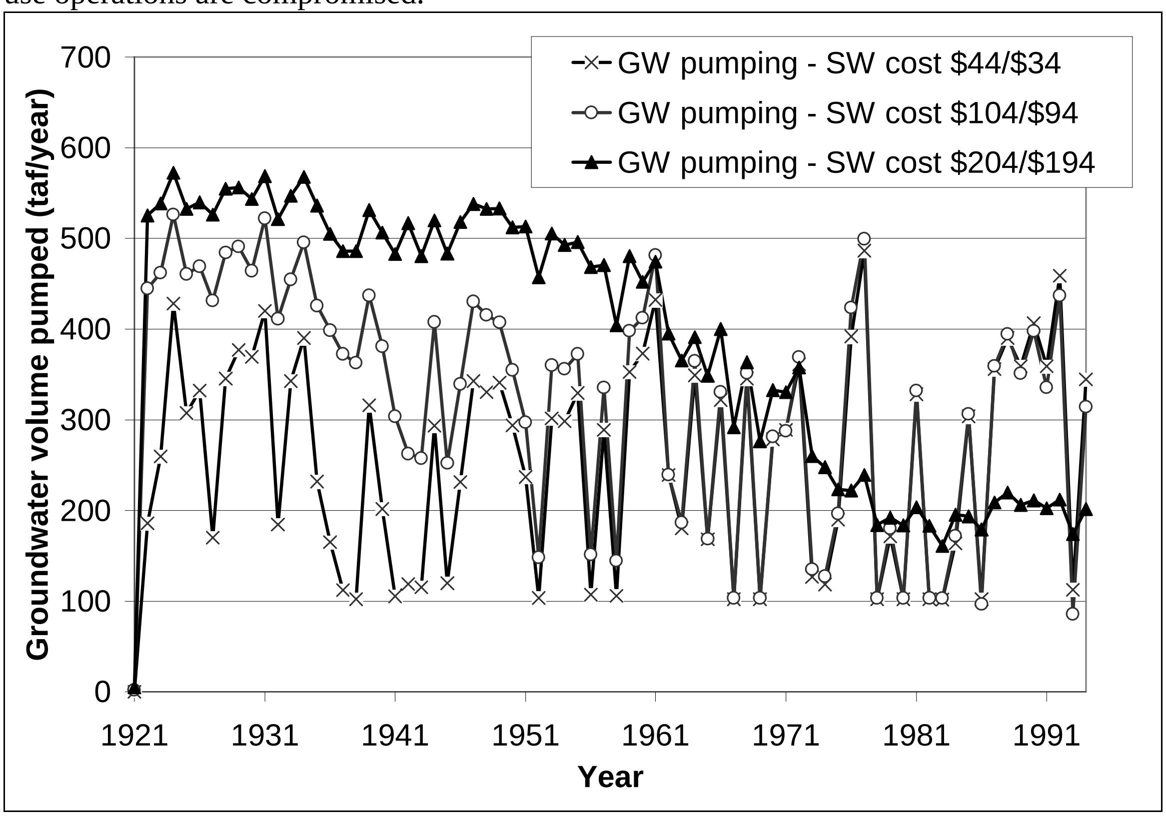

Figure 3. 6 – Groundwater pumping under different scenarios of surface water pricing

Economic impact appears in Figure 3.7 (scarcity costs related to surface water prices and End-of-Period cummulative overdraft). Reduction of supply options caused by significant increase in surface water prices leads to penalties over $35 million/year with severe overdraft conditions in parts of the system.

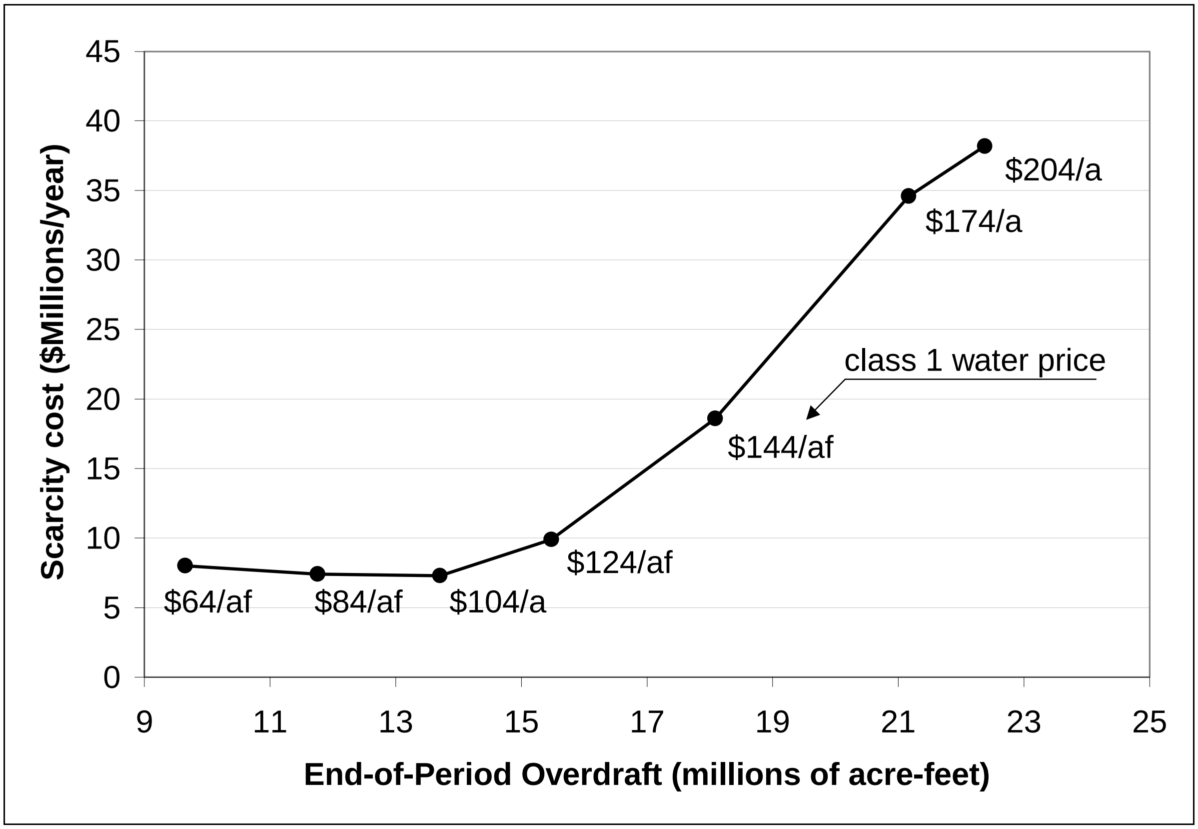

Figure 3. 7 – End-of-Period overdraft and scarcity costs

Figure 3.8 presents end-of-period (EOP) groundwater storage for some of the variable head modeled groundwater reservoirs (GW01 to GW06) and different contract prices for Friant water. EOP storage is strongly affected 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.

GW06 is shared by most districts and suffers a high overdraft as surface water price increases (Figure 3.8). GW04 is also affected but not until the surface water price surpasses $124/af. Most water in GW04 is used by irrigation districts with high value crops.

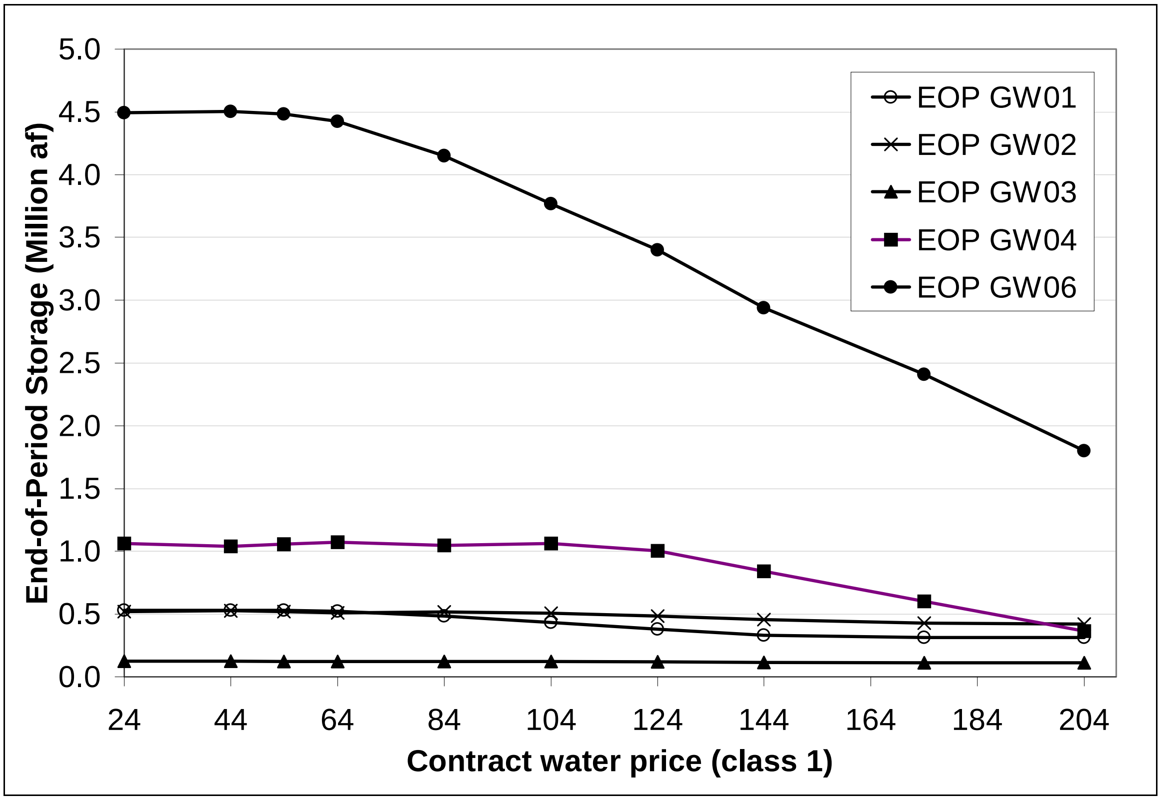

Figure 3. 8 – End-of-Period groundwater storage for varying surface water price

Increases in surface water costs raise scarcity and scarcity costs, but some distortions in model behavior are found. For increases in contract price up to $109/af class 1 and $94/af class 2, scarcities are reduced for some districts (Tables 3.2 and 3.3). For lower contract water prices, surface water is used whenever there is demand. During the drier, high demand months, a district will not have enough contract water available and resort 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 further increases in contract water prices, the model’s behavior is consistent and scarcity and scarcity costs increase for most districts.

Table 3. 2 – Average scarcity volumes for 11 variable pumping cost districts for varying surface water prices.

		Scarcity (taf/year)									
Friant contractor	class1/class2 Price ($/af)	14/ 24	34/ 44	44/ 54	54/ 64	74/ 84	94/ 104	114/ 124	134/ 144	164/ 174	194/ 204
Delano-Earlimart	DEID	5.7	6.3	6.3	5.2	3.8	2.1	13.9	35.6	47.0	47.7
Kern-Tulare WD	KTWD	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
Lindmore	LIID	1.2	1.3	1.3	1.3	1.3	1.3	0.9	1.5	12.3	14.3
Lindsay-Strathmore	LSID	7.3	7.3	7.3	7.3	7.3	7.3	7.2	6.6	5.8	10.0
Lower Tule River	LTID	14.8	14.9	13.4	12.0	9.9	9.3	14.2	46.4	106.9	112.5
Pixley	PXID	0.0	0.0	0.0	0.0	0.0	1.4	6.5	11.8	15.5	15.9
Porterville	POID	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.7	5.9	7.0
Rag Gulch	RGWD	1.0	1.0	0.9	0.9	0.9	0.9	0.5	0.2	0.1	0.1
Saucelito	SAID	0.9	1.0	1.0	1.0	0.9	1.3	2.7	5.3	14.1	20.6
Tea Pot Dome	TPWD	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0
Terra Bella	TBID	0.1	0.1	0.1	0.1	0.1	0.1	0.1	2.6	6.6	6.6
Total (taf/yr)		**32.7**	**33.6**	**31.9**	**29.4**	**25.8**	**25.2**	**47.7**	**112.2**	**215.4**	**236.0**
Total all contractors (taf/yr)		**142**	**119**	**97**	**105**	**152**	**192**	**254**	**340**	**454**	**476**

Table 3. 3 - Average scarcity costs for 11 variable pumping cost districts for varying surface water prices.

		Scarcity cost ($1,000/year)									
Friant contractor	class1/ class2 Prices ($/af)	14/ 24	34/ 44	44/ 54	54/ 64	74/ 84	94/ 104	114/ 124	134/ 144	164/ 174	194/ 204
Delano-Earlimart	DEID	928	1062	1062	870	626	342	1782	4826	6880	7010
Kern-Tulare WD	KTWD	669	669	669	669	669	669	669	669	669	669
Lindmore	LIID	204	215	215	215	215	215	152	255	2082	2469
Lindsay-Strathmore	LSID	3747	3750	3750	3750	3750	3750	3696	3411	2022	2372
Lower Tule River	LTID	2044	2060	1846	1664	1369	1278	1958	6429	16375	17368
Pixley	PXID	0	0	0	0	0	179	877	1606	2141	2197
Porterville	POID	37	44	34	31	31	24	21	111	951	1153
Rag Gulch	RGWD	557	569	541	523	523	520	304	97	45	41
Saucelito	SAID	136	144	144	144	134	202	406	820	2333	3819
Tea Pot Dome	TPWD	70	71	71	71	71	71	46	15	6	2
Terra Bella	TBID	17	18	18	18	18	18	18	401	1108	1134
Total ($million/yr)		**8.4**	**8.6**	**8.4**	**8.0**	**7.4**	**7.3**	**9.9**	**18.6**	**34.6**	**38.2**
Total all contractors ($million/yr)		**26.2**	**24.0**	**21.8**	**22.1**	**25.6**	**29.4**	**36.7**	**48.2**	**65.7**	**69.6**

Energy prices changes

Given the high groundwater use in the system, energy consumption is a significant part of supply operating costs and is susceptible to changes in energy prices. Energy prices have increased from around $0.06/kwh in the early eighties to about $0.1/kwh at the present (AECA, 2002). In the other hand, some irrigation districts can stabilize power costs by developing power plants, long-term power contracts, and shifting irrigation schedules to off-peak hours (FWUA /MWDSC,2001).
This section investigates some potential impacts in the Friant division from changes in energy price. The impact is evaluated in terms of groundwater operating costs. Three energy cost scenarios are evaluated, 0.08$/kwh, 0.1$/kwh and 0.12$/kwh. The 0.1$/kwh is the cost used in all previous runs and model analysis so far. The model is presently capable of running with energy cost varying per Friant contractor and per month, if data is available to do so.

A reduction of 20% in energy cost, from $0.1/kwh to $0.08/kwh has a relatively small effect on pumping, about 2% increase overall with Delano Earlimart (DEID) and Rag Gulch (RGWD) presenting the highest increases (approximately 4% and 6% respectively) (Table 3.4). The impact on operating costs as expected is noticeably higher, 17% overall reduction. The increase in the amount pumped is expected to lower the water table, increasing the pumping lift and the energy consumption per unit volume of water extracted. This effect causes a small reduction in the gains from pumping with cheaper energy.

Table 3. 4 - Groundwater pumping and operating cost for energy cost scenarios for the 11 VP districts

	Avg. GW pumping (af/yr)			Avg, GW operating cost (k$/yr)		
Energy cost scenario	0.08$/kwh	0.1$/kwh	0.12$/kwh	0.08$/kwh	0.1$/kwh	0.12$/kwh
Contractor						
DEID	20,491	19,673	19,607	1,294	1,529	1,818
KTWD	0	0	0	0	0	0
LIID	20,252	20,252	19,829	2,051	2,552	2,979
LSID	1,245	1,245	1,245	133	166	198
LTID	103,937	99,657	98,926	7,015	8,261	9,806
POID	6,401	6,707	5,065	654	851	761
PXID	93,458	92,334	91,479	6,255	7,527	8,894
RGWD	1,641	1,542	1,542	145	174	208
SAID	13,396	13,396	12,994	1,191	1,468	1,693
TBID	454	454	357	48	60	56
TPWD	1,998	1,998	1,998	209	261	312
Totals	**263,273**	**257,258**	**253,042**	**18,996**	**22,849**	**26,726**

An increase of 20% in energy costs causes a similar effect in the opposite direction. The reduction in the amount pumped and the higher water tables alleviate part of the impact on the operating costs.

Further effects on scarcity costs appear in Table 3.5. Reducing energy cost from $0.1/kwh to $0.08/kwh does not result in significant changes, but an increase to $0.12/kwh heavily affects irrigation districts where the demand is smaller and groundwater is a significant portion of the total district water supply, such as Pixley (PXID) and Porterville (POID). Other districts with higher value crops such as Lindsay (LIID) and Lindsay Strathmore (LSID) face smaller or zero effects on water use.

Table 3. 5 - Scarcity costs for energy cost scenarios

	Avg. Scarcity cost (k$/year)		
Energy cost scenario / Contractor	0.08$/kwh	0.1$/kwh	0.12$/kwh
DEID	1050.7	1062.2	1062.2
KTWD	669.2	669.2	669.2
LIID	215.0	215.0	283.8
LSID	3749.9	3749.9	3749.9
LTID	1792.1	2059.9	2173.6
PXID	0	0	65.3
POID	34.2	44.3	184.9
RGWD	533.9	568.9	568.9
SAID	143.6	143.6	203.5
TPWD	70.5	70.5	70.5
TBID	17.7	17.7	33.8
Total ($Millions/year)	**8.3**	**8.6**	**9.1**

Groundwater Pumping Costs – management implications

To evaluate the effect of groundwater pumping cost changes two model runs with fixed pumping costs were made in addition to the VP version. One uses original groundwater pumping costs (FPlow), and the second uses recalculated groundwater pumping costs based on VP model initial conditions, which rely on more detailed water table information provided by Ruud et al (2002). The groundwater pumping costs recalculated in this version are held fixed during the run period. This model version is named FPhigh. Original pumping costs are found in Leu (2001). Districts outside the detailed groundwater model used in VP run were assigned the same pumping costs as in the FPlow run.

Variations in groundwater pumping costs affect the balance of the supply mix of surface water and groundwater, and may facilitate or restrict conjunctive use and other operations in the region. Impacts on water supply and water allocation are evaluated through changes in operations such as surface and groundwater use, and in the system state, characterized by groundwater storage and heads. Groundwater pumping costs for each model run appear in Table 3.6.

Table 3. 6 – Groundwater Pumping Costs for 11 variable pumping costs districts.

Irrigation District	Irrigation District name	FPlow run ($/af)	FPhigh run ($/af)	VP run average[1] ($/af)	VP run minimum[1] ($/af)	VP run maximum[1] ($/af)
DEID	Delano-Earlimart	45	59	75	58	97
KTWD	Kern-Tulare WD	45	96	96	60	119
LIID	Lindmore ID	45	122	128	113	142
LSID	Lindsay-Strathmore ID	45	132	133	125	147
LTID	Lower Tule River	45	73	87	52	120
PXID	Pixley ID	45	45	81	45	112
POID	Porterville ID	45	114	127	113	139
RGWD	Rag Gulch WD	45	61	91	60	136
SAID	Saucelito ID	45	78	110	78	130
TPWD	Tea Pot Dome	45	117	130	117	143
TBID	Terra Bella ID	45	117	130	117	142

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

The higher groundwater pumping cost used in FPhigh reduces the groundwater volume pumped (73-year average) by over 50% (with the exception of LTID, 32%) compared to the FPlow run for the 11 VP districts. Terra Bella irrigation district (TBID) presents a reduction of 97% in groundwater pumping as the cost is updated from $45/af in FPlow to $117/af in FPhigh. This operation is followed by an increase in class 1 TBID water use from 8.4 kaf/yr to 24.3 kaf/yr, on average.

With higher groundwater pumping costs, irrigation districts switch to cheaper sources to maximize net revenue and avoid scarcity costs, 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), which has its Tule River supply reduced from 17.3 kaf/yr to 12.8 kaf/yr, on average. These results demonstrate the effect of each district's operations on water allocation in the system when users make economically-based decisions on water supply sources.

When groundwater costs start at a higher value than other surface supply sources, further increase in groundwater costs has little effect on pumping until the pumping cost exceeds the district's marginal willingness to pay for additional water. Class 1 and class 2 water are also constrained by contract amounts (the districts cannot trade USBR contract water among themselves in the model) limiting the representation of system's flexibility to cope with increases in groundwater costs by switching to other surface water supplies. These factors explain the relative unresponsive pattern of groundwater pumping to fluctuations in pumping cost.

Groundwater pumping costs calculated in the VP run are higher than the other runs and present an increasing trend in time, resulting in less groundwater use and higher scarcity. Of the 164 taf/yr average reduction in groundwater use, 138 taf/yr is replaced by contract water (Table 3.7), and the remaining 26 taf/yr are scarcity increase. This difference between modeling scenarios indicates that the region can operationally accommodate variations in groundwater pumping cost.

Table 3. 7 - Overall results, 73 year average – 11 VP districts

	Fixed pmp cost **FPlow run**		Variable pmp cost **VP run**	
Totals (taf/yr avg)		% Total		% Total
Demand	794	100.0%	794	100.0%
Total Supply	786	99.0%	760	95.7%
Scarcity	8	1.1%	34	4.3%
Surface contract supply	272	34.6%	410	53.9%
Surface other supply[2]	93	11.8%	93	12.2%
GW supply	421	53.6%	257	33.8%

[2]Excluding artificial recharge

Minor differences from FPhigh to run VP are limited to irrigation districts highly dependent on groundwater supply, like Pixley irrigation district. 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 pumping cost varying, a second factor is introduced and some change is perceived in the pumping pattern (Figure 3.9). 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 $125/af for the last portion of supply and since pumping costs increase up to $109/af there is no cutback in GW pumping due to scarcity in run VP, meaning that it remains economically attractive to use groundwater supply at the margin

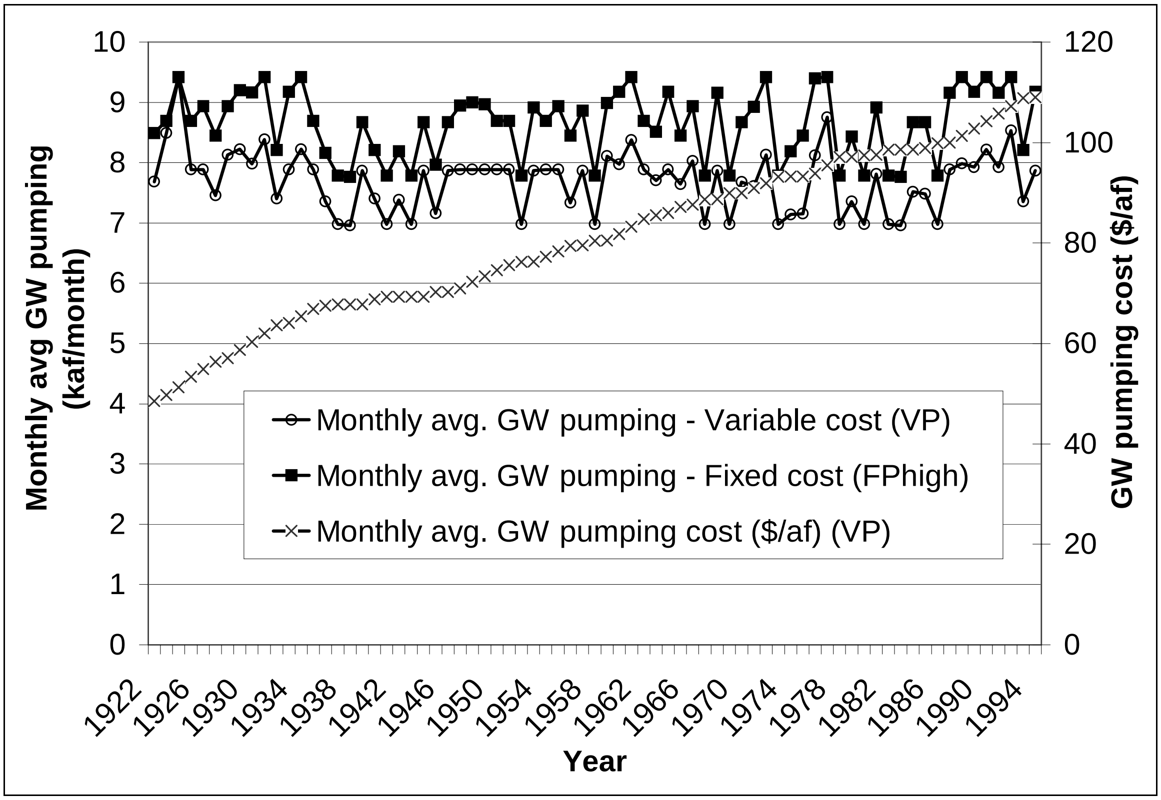

Figure 3. 9 - Groundwater pumping in Pixley (PXID) irrigation district

Conjunctive use operations in the region are present in Figure 3.10, which depicts time series of pumping heads and respective pumping costs for groundwater zone GW12 including the droughts of 1976-1977 and 1987-1992. These operations include:

A) *Seasonal operations.* Use of groundwater and surface water alternates within the year. Typically groundwater pumping is concentrated in the dry months, and artificial recharge undertaken in the wet months with surplus floodwater. Results in Figure 3.10 show the effects of seasonal and multi-year operation in the groundwater pumping cost and heads, with groundwater pumping concentrated in the "jump" sections of the chart, and surface water and artificial recharge in the flat sections.

B) *Drought management*. The distinct heads and groundwater pumping costs pattern in Figure 3.10 presents groundwater pumping concentrated in dry years (steeper head and cost increases during the dry years of 1976-1977) and reduced groundwater use on wet years (minimal head and cost increase during the wet years of 1978-1984).

C) *Continuous overexploitation.* The overall trend is of increasing pumping costs and heads, indicating that the historical overdraft continues. According to the economic framework of the model, it may still be economically worthwhile to maintain current groundwater pumping volumes for most irrigation districts, despite the increase in the pumping cost. A more informed conclusion on this issue depends on further knowledge of other impacts, such as land subsidence, and externalities such as groundwater pumping cost increases from neighboring groundwater use. Economically, the model considers this impact as a "transfer" of water to an irrigation district with higher willingness to pay, so that overall economic gains are higher. However the third party effect of this transfer to the neighboring user (increase in pumping costs) must be considered. 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 necessary for successful conjunctive use programs.

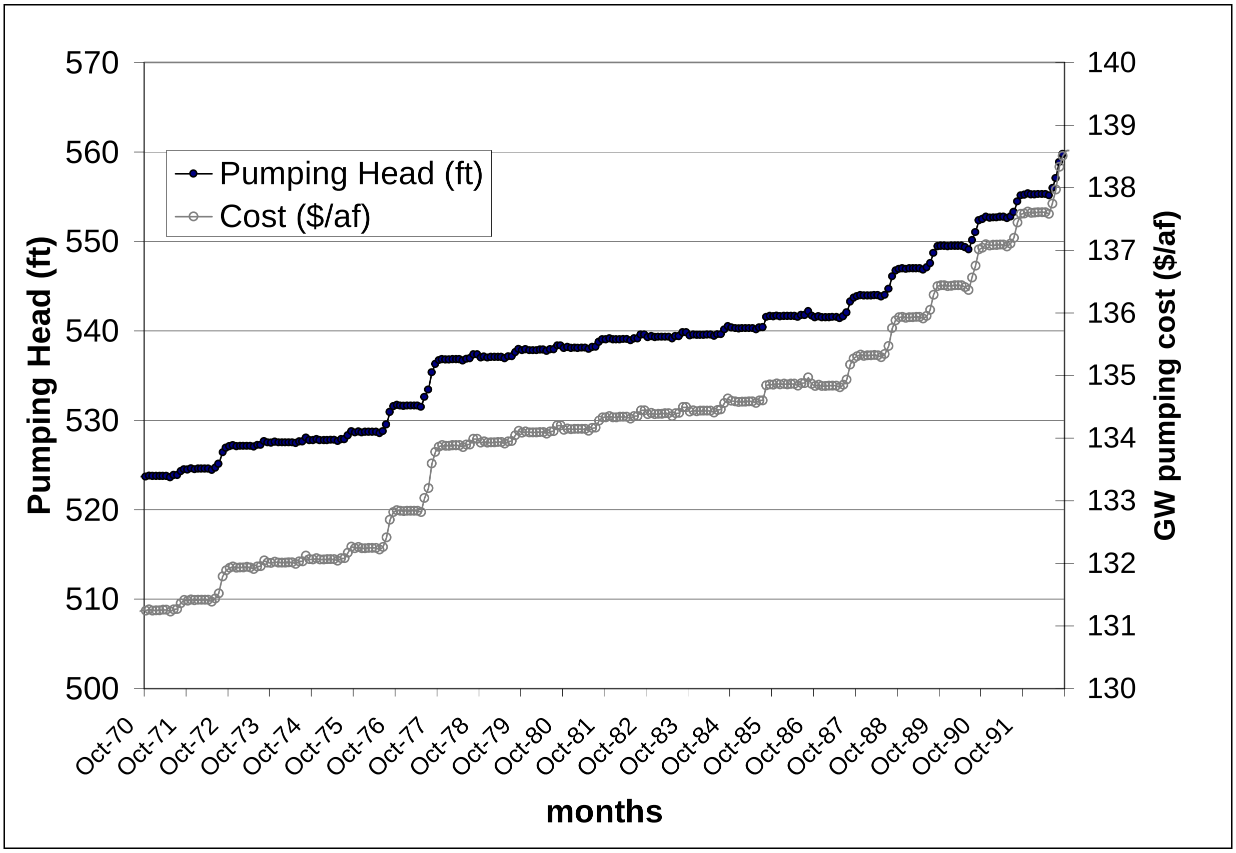

Figure 3. 10 - Groundwater site GW12 heads and pumping costs for 1970-1991

Further effects of reduced groundwater pumping are end-of-period (EOP) storage increases of about 34% from FPlow to FPhigh run, and of 1.6% from FPhigh to the variable pumping VP run, over the 73-year period (Figure 3.11). However, a reduction in aquifer overdraft raises average annual scarcity from 8 taf to 34 taf, comparing FPlow to FPhigh runs. This increase in scarcity is attenuated by reduction in pumping expenses.

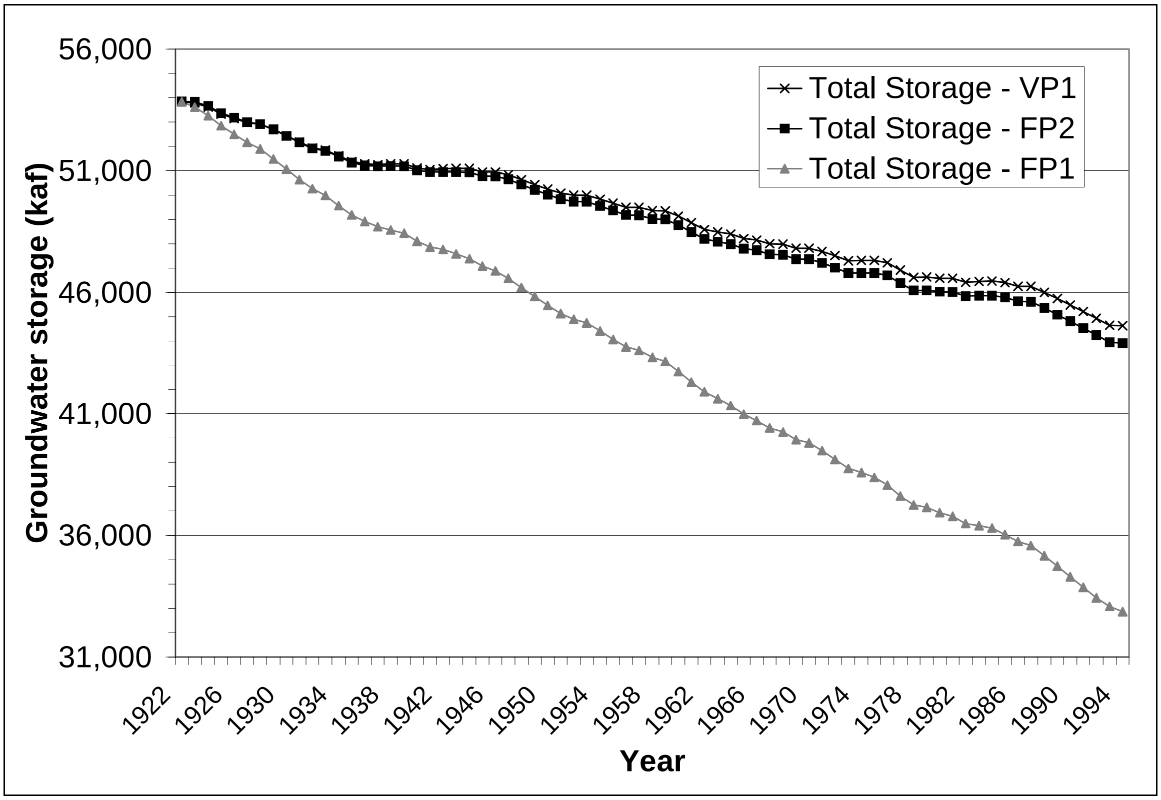

Figure 3. 11 – Groundwater storage

The lower groundwater pumping cost run (FPlow) results in 21 maf of total overdraft over 73 years and a $19 million/yr average penalty in scarcity costs. Avoiding this overdraft would require reducing groundwater pumping by either cutting back in production or acquiring supplemental non-local surface supplies averaging 288 kaf/yr. The groundwater pumping curtailment seen in the VP run could reduce the overdraft to 9.2 maf at a cost of $24 million/yr in scarcity costs, if no supplemental surface supply is available. To eliminate the 9.2 maf overdraft, an average of 126 kaf/yr of supplemental surface supplies would be needed.

Model Limitations and Promising Extensions

This is the first integrated system model developed for the Friant-Kern system, thus there are 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 (11 of 32 irrigation districts) has such a groundwater model. The method used to estimate total pumping lift does not account for overlapping cones of depression, which could further increase the pumping head.

Allocation of water resources to surface or groundwater storage is based on future benefits. To provide information such as worthwhile economic levels of groundwater recharge, future benefits must be identified. This would also remove the limitation of "zero-foresight" and the distortions seen in the results, since future benefits of operations can be used to drive early decisions. The identification of future economic benefits should be made considering the optimal operation of the system. This approach would require a model able to allocate the resource dynamically across the time. Carry-over storage penalty functions, like the ones developed in an optimization model in Draper (2001) could be used in this extension. Another alternative is to extend the optimization period over multiple time steps giving the model some foresight over future hydrology and operations.

Friant users operate a highly dynamic system in a closely coordinated manner 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 setup is still inflexible regarding contract water. Further model improvements should look at possibilities of contract water exchanges and its consequences for the system's water management, perhaps using a LP engine for the simulation.

Conclusions

An economically-driven simulation model was applied to a water system with predominantly economic water uses. The approach extends conventional use of priority-based penalty functions in simulation by representing demands with economic penalty functions based on individual users' willingness to pay for water. Results show that users change supply sources and quantities, and transfer water in reaction to variations in water price, economic value and availability. By capturing this behavior, the model provides insights about how management alternatives affect potential for water transfers, levels of surface and groundwater exploitation, and water scarcity and scarcity costs in the region. Further conclusions are:

1) Use of economic functions in the 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 import programs.

2) Where economic effects determine users' reactions to perturbations in the system, a water system populated by users with high production value will take more time to react to groundwater overdraft and increased pumping cost.

3) Simulation performance is affected by future operations and events. Actual water users have some foresight in making decisions and this 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.

Reduction of historical overdraft requires reduction of groundwater pumping. In terms of surface water this is equivalent to 33% of contract surface supplies. Without additional surface supplies, a 49% reduction in overdraft (9.8 maf) would cost $5 million/yr average in scarcity costs, a 26% increase.

The direct effect of surface water availability and prices on the supply balance between surface and groundwater has consequences for management programs including conjunctive use operations. Intensive groundwater pumping under high surface water prices resultes in aggravated overdraft conditions and considerably limits groundwater supply in dry seasons and dry years. With high surface water prices, the efficacy of conjunctive use programs relying on alternation between recharge in wet periods and pumping on dry periods is reduced.

Economically-driven simulation can be applied to other regions where water is a scarce resource with predominantly economic uses and data is available to calibrate supporting economic models. Other productive sectors, like 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 model 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 impact of proposed management alternatives is of interest.

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CONCLUSIONS

Water users engaged in economic activities will seek to optimize production with the water available, and will make decisions on land and water use, water supply source, application of technology to improve water use efficiency, and implement local operations, such as conjunctive use, to take advantage of water supply conditions. These decisions are affected by factors such as water availability, reliability, and price, according to each user's access to water supply sources and risk aversion.

This environment is often complex and with a breadth of operations to transfer, exchange and allocate the water using surface and groundwater infrastructure. Water management in these conditions requires increasing levels of understanding of how, and why, water users make decisions and how that affects their water demand. With this information one can better evaluate their reaction to modifications and fluctuations in the system and identify desirable water management solutions. This is especially important in regions where economic water uses are predominant and have large demands.

However, the consideration of water demands that lack detailed characterization of the user decision framework is still the norm, rather then the exception in simulation models designed to support regional water management. This dissertation presents two simulation models that address water users' decisions in different levels. A two-stage stochastic quadratic programming model with higher level of detail on crop, water, technology and groundwater operations focusing on individual decisions; and a network-flow, economically-driven model with decisions on production, water supply source and groundwater operations focusing on regional water allocation. Although not related, these models allow the identification of impacts on different user decisions and on different parts of the system. Both models were run for varying conditions of surface water availability, reliability and price. Lessons learned contribute to improved understanding of users' behavior and economic water demands in dynamic water systems with intense competition for scarce water. Major conclusions are:

1) A quadratic, PMP calibrated stochastic programming approach presented results that better match real observed conditions of crop diversification as compared to a linear approach. A basic PMP calibration process better calibrated for average and marginal conditions than an initial attempt to calibrate for supply elasticity data and average conditions.

2) The stochastic model is able to represent water supply as a stochastic variable and model a large number of decision variables (800 combinations of crop types/irrigation technologies/water years in the second stage, 1,200 variables representing conjunctive use operations of groundwater pumping and recharge, 16 variables representing first stage decisions, 750 variables representing stress irrigation operations for all combinations of permanent crops/irrigation. technologies/water years). The model solution takes a few seconds with the MINOS algorithm (GAMS platform).

3) Desirability for different levels of irrigation technology efficiency change with variations in water price and water availability. However, the desirability for more efficient irrigation varies with different conditions. Users will not employ low efficiency technology in scarce water conditions regardless of its price, while higher efficiency technologies will still be applied in abundant water supply conditions if water price is high enough (in this case $100/af).

4) Higher water supply reliability shifts production to average conditions. Permanent crop acreages are slightly increased to take advantage of more reliable water under average conditions at the expense of some stress irrigation in drier (and less probable) years.

5) Higher water supply reliability reallocates water from annual to permanent crops and motivates the use of more efficient technologies for annual crops irrigation given the scarcer water supply.

6) Conjunctive use increases both water supply availability and reliability. To take most advantage of investments in recharge infrastructure, users may be willing to pay for additional water in very wet years when artificial recharge takes place.

7) The added supply flexibility and reliability of conjunctive use motivate users to coordinate its use with cropping and irrigation technology decisions. The use of lower efficiency irrigation technologies (such as furrow irrigation) is increased in wet years to improve groundwater recharge, while more efficient technologies are prioritized in dry years to conserve water and offset higher operating costs (groundwater pumping and recharge).

8) With conjunctive use, the gains in income reliability are considerably higher than increases in expected net economic benefit. Despite the relatively small gain in expected benefit (5.2%), the probability of having high returns is significantly increased.

9) Groundwater pumping infrastructure investment decisions can be flexible, as indicated by the flatter net revenue curve close to the optimal pumping infrastructure.

10) A clear trade-off of net revenue for added income reliability indicates user's willingness-to-pay for added reliability (such as through crop insurance).

11) Even though users may be willing to increase groundwater pumping capacity to improve supply reliability at the expense of expected return gains, there is a maximum groundwater pumping capacity investment beyond which there are no benefits either in reliability or in net expected returns.

12) In regional, interconnected water systems the use of economic functions to drive users' decisions allow evaluation of economic losses when demands are not met.

This enables the model to evaluate economic feasibility of supply expansion projects and water import programs.

13) Where economic effects determine users' reactions to perturbations in the system, a water system populated by users with high production value will take more time to react to groundwater overdraft and increased pumping cost.

14) The direct effect of surface water availability and prices on supply balance between surface and groundwater has consequences for management programs including conjunctive use operations. Expensive surface water tends to shift supply towards groundwater and will limit the flexibility in developing conjunctive use operations based on the alternate use of both water supply sources.

15) Simulation performance is affected by future operations and events. Actual water users have some foresight in making decisions and this may not be captured in a simulation model unless present operations account for the value of the water being allocated in the future.

APPENDIX A1 – MODEL PARAMETERS

Table A1. 1 – Model parameters

Parameter	Unit	Value
Crop Prices		
Citrus	$/ton	747
Grapes	$/ton	900
Nuts	$/ton	3,400
Cotton	$/ton	1,400
Field crops[1]	$/ton	500
Truck crops[2]	$/ton	533
Alfalfa	$/ton	116
Misc. Grains[3]	$/ton	130
Crop Yields		
Citrus	ton/acre	9.2
Grapes	ton/acre	8.5
Nuts	ton/acre	1.3
Cotton	ton/acre	0.625
Field crops[1]	ton/acre	1.4
Truck crops[2]	ton/acre	9.0
Alfalfa	ton/acre	6.35
Misc. Grains[3]	ton/acre	6.0
Re-establishment costs		
Citrus	$/acre	5,043
Grapes	$/acre	11,457
Nuts	$/acre	6,344
Base observed calibration acreages[4]		
Citrus	ac	943
Grapes	ac	24,500
Nuts	ac	9,963
Cotton	ac	228
Field crops[1]	ac	1,214
Truck crops[2]	ac	319
Alfalfa	ac	2,233
Misc. Grains[3]	ac	421

1Wheat
[2] Melons
[3] Beans
[4] Delano-Earlimart Irrigation district

Table A1. 2 – Model parameters, cont.

Parameter	Unit	value	Metafata
Leontieff Coefficients - Land			
Citrus	ac/ac	1	
Grapes	ac/ac	1	
Nuts	ac/ac	1	
Cotton	ac/ac	1	
Field crops[1]	ac/ac	1	
Truck crops[2]	ac/ac	1	
Alfalfa	ac/ac	1	
Misc. Grains[3]	ac/ac	1	
Leontieff Coefficients - Water			
Citrus	af/ac*year	2.7	
Grapes	af/ac*year	2.8	
Nuts	af/ac*year	3.42	
Cotton	af/ac*year	3.10	
Field crops[1]	af/ac*year	2.97	
Truck crops[2]	af/ac*year	1.78	
Alfalfa	af/ac*year	4.30	
Misc. Grains[3]	af/ac*year	1.4	
Input costs - Land			
Citrus	$/ac	3,504	
Grapes	$/ac	3,181	
Nuts	$/ac	793	
Cotton	$/ac	410.3	
Field crops[1]	$/ac	183.4	
Truck crops[2]	$/ac	3,975	
Alfalfa	$/ac	188	
Misc. Grains[3]	$/ac	137.9	
Input costs – Surface water			
Citrus	$/af	44	
Grapes	$/af	44	
Nuts	$/af	44	
Cotton	$/af	44	
Field crops[1]	$/af	44	
Truck crops[2]	$/af	44	
Alfalfa	$/af	44	
Misc. Grains[3]	$/af	44	

Table A1. 3 - Model parameters, cont.

Parameter	Unit	value	Metafata
Stress Irrigation threshold			
Citrus	af/ac*year	2.5	
Grapes	af/ac*year	2.5	
Nuts	af/ac*year	2.5	
Goundwater			
Artificial recharge capacity	af/ac*year	36.06	
Artificial recharge cost	$/ac	1,000	
Groundwater pumping capacity	af/year	43,000	
Groundwater pumping cost	$/af	45	
Well establishment cost	$/well	25,000	
Well capacity	af/month	132	
Irrigation Technology			
Efficiency for consumptive use (eff = ETAW/AW)			
Furrow	0.4		
Sprinkler	0.7		
LEPA	0.8		
Drip	0.9		
Irrigation technology constant elasticity of substitution isoquant - parameters			
Parameter "a"			
Citrus, grapes, nuts		0.068	
Cotton		0.061	
Field crops[1]		0.081	
Truck crops[2]		0.190	
Alfalfa		0.098	
Misc. Grains[3]		0.190	
Parameter "b"			
Citrus, grapes, nuts		0.259	
Cotton		0.176	
Field crops[1]		0.263	
Truck crops[2]		0.561	
Alfalfa		0.419	
Misc. Grains[3]		0.564	
Parameter "ρ"			
Citrus, grapes, nuts		-0.392	
Cotton		-0.561	
Field crops[1]		-0.449	
Truck crops[2]		-0.217	
Alfalfa		-0.247	
Misc. Grains[3]		-0.215	