Modeling Conjunctive Use Operations and Farm Decisions with Two-Stage Stochastic Quadratic Programming

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Abstract: This paper applies two-stage stochastic quadratic programming to optimize conjunctive use operations of groundwater pumping and artificial recharge with farmer's expected revenue and cropping decisions. The two-stage programming approach allows modeling of water and permanent crop production decisions, with recourse for uncertain conditions of hydrology, annual crops, and irrigation technology decisions. Results indicate potential gains in expected net benefits and reduction in income variability from conjunctive use, with increase in high value permanent crops along with more efficient irrigation technology.

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Introduction

Agricultural production often depends on uncertain water supplies. Water supply variability and uncertainty can reduce average economic returns and farmer welfare, and may ultimately limit agricultural development. Surface water reservoirs provide storage to reduce variability, but must also meet other competing demands (e.g., environmental, flood control, and hydropower) limiting their operation for agricultural uses.

Agricultural water users have long employed groundwater to supplement surface supplies or as a primary water supply. In California, direct groundwater exploitation became intense with pumping and well drilling technology improvements in the last hundred years (Coe 1988; Walker and Williams 1982). The existence of vast, relatively available groundwater supplies and the common lack of groundwater regulation contributed to this development. A supplemental groundwater supply often stabilizes agricultural benefits when paired with stochastic surface water as discussed by Tsur (1990) and Tsur and Graham-Tomasi (1991).

Groundwater development also has undesired effects in many regions where it began early and proceeded intensively, including land subsidence, saline intrusion, increase in groundwater pumping costs, reduction in stream flows, and soil salinization. Lee and Lacewell (1990) evaluated 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 reduced profitability as costs increase and yields decline. To keep groundwater exploitation sustainable in many regions it must be managed with surface supplies, taking advantage of each supply source's storage capacity, development cost, seasonal availability, and recharge times (Harou and Lund 2008).

Coordinated, conjunctive use, may include a broad range of temporal patterns, management and operational decisions (Pulido et al. 2003), and benefit from different infrastructure depending on specific objectives. Agricultural users in many regions depend largely on groundwater and can benefit greatly from this management, which has motivated studies with diverse approaches. Schoups et al. (2006a) investigated conjunctive use management to alleviate drought for irrigated agriculture with a spatially distributed simulation-optimization model including agronomic, hydrologic and physical components. Other studies explore optimal groundwater operations with stochastic surface water (Burt 1964; Young and Bredehoeft 1972; Provencher and Burt 1994; Azaiez and Hariga 2001; Gillig et al. 2001). In Schoups et al. (2006b) a multiobjective interannual optimization model generates Pareto curves to evaluate trade-offs between sustainable agriculture and optimal reservoir operation, which were analyzed for many equally probable streamflow series in a Monte Carlo approach.

The approach presented in this paper simulates coordinated farmer decisions on permanent and annual crops, water application, irrigation technology, artificial recharge, and groundwater pumping using two-stage stochastic optimization model for cropping decisions (Marques et al. 2005). The model maximizes the net expected benefit of allocating land and water to various permanent and annual crops, with optimized conjunctive use operations involving artificial recharge and groundwater pumping. 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 recharged in other years. Although this is a simple approach to groundwater modeling, it provides an upper bound on benefits and prevents overdraft in the long run with probabilistic surface

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water availability. The model and analysis presented in this paper contribute to existing knowledge by evaluating the benefits and implications of conjunctive use operations integrated with cropping, water and irrigation technology decisions using a more detailed quadratic economic profit function driven by market conditions. The model is calibrated to observed acreages with a PMP (positive mathematical programming) approach (Howitt 1995) and it replicates observed crop diversification without additional constraints or bounds.

This paper is organized as follows. The literature review describes general conjunctive use operations and reviews models developed to simulate and optimize conjunctive use operations for improved benefits and agricultural use. This section is 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 objectives, including controlling effects of pumping on surface streams, managing regional operations aimed at improving water supply reliability and cost, reducing environmental impacts such as salt water intrusion, soil salinity due to shallow water tables and land subsidence. The operations discussed in this paper address the management problem of improving water supply reliability and cost.

Infrastructure involved in 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 (Schwartz 1980) when surface infrastructure is not yet fully developed, or more balanced operations that alternate 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 economic usefulness to overcome seasonal water imbalances and droughts, while maintaining groundwater sustainability.

This alternating pattern of conjunctive use increases groundwater storage during wet periods to improve availability 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 applied water and natural runoff replenish groundwater, 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. 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 (Pulido et al. 2003). 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. High transaction costs can be a challenge (Sahuquillo and Lluria 2003; Marino 2001), as conjunctive use operations often depend on elaborate water transfers, exchange programs, and infrastructure operation (Brown et al. 2001; Jones 2003).

Conjunctive Use Modeling

Many simulation and optimization models have been proposed to design effective conjunctive programs and operations, including approaches with detailed representation of physical stream/aquifer interaction (Gorelick 1983,1988; Peralta et al. 1995; Fredericks et al. 1998; Belaineh et al. 1999) and combined operating decisions involving surface reservoir spill minimization (Schoups et al. 2006a,b). These methods provide important understanding of how surface and groundwater interact, and the management implications of this interaction. However, application to support regional management still faces limitations in representing users' decisions behind water demands, especially with economically valuable agricultural regions. Peralta et al. (1995) developed a simulation/optimization model with embedded groundwater flow equations to calculate optimal water-use strategies. Their model was run for different scenarios, each characterized by time series of up and lower bounds on water use. Results showed 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. To properly identify alternative water-use strategies depending on water conservation, a more detailed approach is necessary to model the water demand, including its variation and behavior as consequence of the users' decisions on how to use the water and the available groundwater operations.

Bredehoeft and Young (1983) assessed 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 writers assume the necessity of augmenting 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 their model. Burt (1964) and Philbrick and Kitanidis (1998) included recharge operations in stochastic dynamic programming approaches to identify optimal extraction and recharge rates in wet and dry periods. The 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, without the effects of pumping and recharging decisions on future pumping lifts. Marques et al. (2006) represented more detailed water use decisions with monthly penalty functions reflecting each irrigation district's willingness-to-pay for water in a simulation model driven by economics with variable pumping cost. In Schoups et al. (2006b) a single profit-maximizing decision-maker approach is used to drive the agricultural water demands, using historical bounds to incorporate market conditions not explicitly accounted in the model.

By combining a quadratic economic profit function with a two-stage programming approach, the model presented in this paper simulates the farmers' cropping and technology decision structure under uncertain surface water supplies. The results are useful in identifying potential gains of conjunctive use operation and implications to farm cropping and irrigation technology decisions.

Model Formulation

The model formulation builds on cropping and irrigation decision modeling work in Marques et al. (2005) to investigate benefits of conjunctive use operations by including decisions and constraints representing artificial recharge and pumping. The model uses a two-stage quadratic programming approach, and represents permanent crop decisions in the first stage and annual crop decisions in the second stage, based on the probability distribution of surface water available in a given year. Irrigation technology decisions are made in both stages to represent combinations of crop type and technology type. The model allows stress irrigation and crop yield reduction under dry scenarios for added flexibility, and it is run for a set of possible hydrologic events, each with a given amount of surface water available (interval lower bound) and its respective probability of occurrence. The objective function maximizes net expected economic benefits from crop, technology use, water application and conjunctive use decisions. The decision variables are acreages of permanent and annual crops, amount of water applied, irrigation technology, groundwater recharge, pumping and pumping capacity investment. The objective function includes permanent crops establishment costs $(INI \times X_1)$, irrigation technology investment (IR) and groundwater pumping infrastructure costs $(IPC \times c_{pc})$ in the first stage. In the second stage, the objective function includes revenues from crop production (quadratic functions in terms of Y_1 and X_2), penalty for lost crops $(K_1 \times CA_1)$, artificial recharge costs $(XR_2 \times RC)$ and groundwater pumping costs $(UR+UPD) \times PC$. All terms in the second stage are multiplied by the probability of the given hydrologic event j (p_j). A more detailed description of the decision variables is listed in the following section.

Conjunctive use operations are represented by groundwater artificial recharge and pumping, combined with surface water use. A set of constraints maintains long-term sustainability by limiting groundwater pumping to the amounts recharged.

The stochastic nature of surface water availability is modeled with an empirical probability distribution of yearly surface water deliveries. Each hydrologic year is a realization of a stochastic process resulting in a given amount of water available for the whole year. Based on observed data, a group of possible hydrologic years j (hydrologic events, or simply "events") was assembled each one with a probability of occurrence p_j and a quantity of surface water available a_j. On each possible event, different decisions may be made (second stage) and an economic return is calculated. The model is run considering all possible events, and calculates the maximum expected economic return to agricultural production. There is no explicit definition for the optimization time horizon. Instead, the model results are valid for as along as the permanent decisions remain "permanent." This could be as long as 15 or 20 years.

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 other events f will be available for pumping in event j through decision variable UR_{fj}, subject to pumping costs PC. The term $\Sigma_{f=1}^{g} UR_{fj}$ then gives the total water pumped in a given event j, given the artificial recharge made in all other events $f(f \neq j)$. The same reasoning is used for water artificially recharged in event j, represented by R_{jf} which accounts for the water available for pumping in the other events f. The term $\Sigma_{f=1}^{g} R_{jf}$ then represents the sum 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. The maximum amount of water available through deep percolation is calculated by the state variable PD_{jf}. The amount of water that is actually pumped from deep percolated irrigation is calculated by the decision variable UPD_{jf} which is the water pumped in a given hydrologic event j, available due to deep percolation in other hydrologic events $f(f \neq j)$.

More realistic deep percolation calculations require specific irrigation efficiency characteristics and 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 also rely on vadose zone thickness and soil's field capacity. For simplicity and given the annual representation of water availability, a single factor is used to estimate the percentage of water applied that deep percolates.

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 (1) groundwater storage is large enough to not constrain the transfer of water from one hydrologic event to the other; (2) the hydrologic event's time scale of one year is long enough that water recharged in one event will have time to reach any other event; and (3) that variation in the water table does not significantly affect pumping costs or stream aquifer interaction.

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. Events with higher probabilities occur more times, on average, in the same time period. For example, if a fixed amount of water is recharged in an event with $p=0.05$, the average interval (return period T) among recharges is 20 years $(T=1/p)$, resulting in five recharge occurrences in a period of 100 years, on average. If this same fixed amount of water is recharged in an event with $p=0.02$, the result is only two recharge occurrences in the same 100-year interval, on average (return period $T=50$ years). Thus, more water is effectively being recharged if the event has higher probability.

Groundwater withdrawals and recharge are thus balanced in the long run by probabilistic mass balance constraints to prevent overdraft [Eqs. (11) and (12)]. 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 p_j/p_f to account for the difference in the number of recharge and pumping occurrences, effectively reducing (or increasing) the water available for pumping depending if it is recharged in a hydrologic event with lower or higher probability than the event where it is pumped.

The objective function and model constraints are presented as follows. The constraint set includes water balance (2), land (3), second stage permanent crops (4), stress irrigation (5), stress irrigation threshold (6), irrigation technology (7), artificial recharge (8), groundwater pumping capacity (9), deep percolation (10), probabilistic mass balance [(11) and (12)], and nonnegativity (13). Additional detail in Constraints 4–7 is presented in Marques et al. (2005)

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

subject to

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

$$\sum_{i=1}^{m}\sum_{k=1}^{h} X_{1ik} + \sum_{l=1}^{n}\sum_{k=1}^{h} X_{2jlk} + XR_{2j} \leqslant L, \ldots, \forall j \tag{3}$$

$$Y_{1jik} \leqslant X_{1jik}, \ldots, \forall j, \forall i, \forall k \tag{4}$$

$$Y_{1jik} = \frac{1}{AW_{1jik}} TAW_{1jik}, \ldots, \forall j, \forall i, \forall k \tag{5}$$

$$K_{1jik} \geqslant X_{1ik} - \xi_i TAW_{1jik}, \ldots, \forall j, \forall i, \forall k \tag{6}$$

$$\sum_{i=1}^{m} X_{1ip}IC_{ip} + \sum_{l=1}^{n} X_{2jlp}IC_{lp} \leqslant IR_p, \ldots, \forall j, \forall p \tag{7}$$

$$\sum_{f=1}^{g} R_{jf} \leqslant XR_{2j}\mathrm{RCAP}, \ldots, \forall j, f \neq j \tag{8}$$

$$\sum_{f=1}^{g} UR_{fj} + \sum_{f=1}^{g} UPD_{fj} \leqslant IPC \times \mathrm{Wcap}, \ldots, \forall j, f \neq j \tag{9}$$

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

$$UR_{fj} \leqslant \frac{p_f}{p_j} R_{fj}, \ldots, \forall j, \forall f, f \neq j \tag{11}$$

$$UPD_{fj} \leqslant \frac{p_f}{p_j} PD_{fj}, \ldots, \forall j, \forall f, f \neq j \tag{12}$$

$$IR_k, TAW_{1jik}, X_{1ik}, X_{2jlk}, XR_{2j}, UR_{fj}, R_{jf}, UPD_{jf}, IPC, Y_{1jik} \geqslant 0, \ldots, \forall j, \forall f, f \neq j \tag{13}$$

Where model parameters are:

α_{1ik}	Supply function slope for permanent crop i and irrigation technology k(\$/ha × ha)
γ_{1ik}	Supply function intercept for permanent crop i and irrigation technology k(\$/ha)
α_{2jlk}	Supply function slope for annual crop l in year type j with irrigation technology k(\$/ha × ha)
γ_{2jlk}	Supply function intercept for annual crop l in year type j and irrigation technology k(\$/ha)
ξ_i	Stress irrigation threshold for permanent crop i (acre/acre-ft)
a_j	Water available in year type j(million m^3/year)
CA_{1i}	Annualized reestablishment cost for permanent crop i(\$/ha)
IC_{ik}, IC_{lk}	Irrigation capital value to supply an acre of permanent crop i or annual crop l with technology k (\$/ha)
INI_i	Annualized establishment costs for permanent crop i(\$/ha)
L	Land available (ha)
p_j	Probability of hydrologic event (year type) j
RE_{1j}	Annualized gross revenue of permanent crop i in year type j(\$/ha)
PC	Pumping costs (\$/m^3)
c_{pc}	Pumping infrastructure average cost (\$/well)
RC	Artificial recharge costs (\$/ha)
RCAP	Recharge capacity (m^3/ha × year)
Wcap	Average well capacity, in m^3/year × well
ϕ	Deep percolation aquifer recharge parameter
AW_{1jik}	Water requirement for permanent crop i irrigated with technology k in hydrologic event j(m^3/ha)
AW_{2jlk}	Water requirement for annual crop l irrigated with technology k in hydrologic event j(m^3/ha)
RE_{2l}	Annualized gross revenue of annual crop l(\$/ha)

The model decision variables are:

IR_k	Annualized first stage investment in irrigation technology k(\$)
TAW_{1jik}	Water supply to permanent crop i with technology k in year type j(m^3)
X_{1ik}	Area of permanent crop i established with technology k(ha)
X_{2jlk}	Area of annual crop l irrigated with k in year type j(ha)
XR_{2j}	Area of land allocated to artificial recharge in event j(ha)
UR_{fj}	Water pumped in event j, available through artificial recharge in other hydrologic event f(m^3)
R_{jf}	Water artificially recharged in event j, that will be available in other hydrologic event f(m^3)
UPD_{jf}	Water pumped in event j, available due to deep percolation in other hydrologic event f(m^3)
IPC	Installed pumping capacity (number of wells with an average capacity of 981,460 m^3/year each)
Y_{1jik}	Area of permanent crop i irrigated with technology k in year type j(ha)

The model state variables are:

PD_{jf}	Maximum amount of water available in event j through deep percolation in other hydrologic event f(m^3)
K_{1jik}	Area of permanent crop i lost in year type j due to excessive stress (ha)

Table 1. Crop Data and Input Costs

Crop	Prices ($/t)	Yields (t/ha)	Land and capital ($/ha)	Water ($/m^3)
Citrus	747	22.7	8,658	0.04
Grapes	900	21.0	7,860	0.04
Nuts	3,400	3.2	1,959	0.04
Cotton	1,400	1.5	1,014	0.04
Field crops[a]	500	3.5	453	0.04
Truck crops[b]	533	22.2	9,822	0.04
Alfalfa	116	15.7	465	0.04
Miscellaneous grains[c]	130	14.8	341	0.04

[a]Wheat.

[b]Melons.

[c]Beans.

Constraint (2) includes the recharge (R_{jf}) and pumping (UR_{fj} and UPD_{fj}) terms for water balance. Constraint (4) limits the second stage irrigation of permanent crops to the area established in the first stage. Constraint (5) limits the area of permanent crop i irrigated in a given year $jY1_{jik}$ to a given amount of water $TAW1_{jik}$. The ratio $1/AW1_{jik}$ (hectares per m^3 of water) indicates how many acres of $Y1_{jik}$ can be grown for a given quantity of water $TAW1_{jik}$. Constraint (6) limits stress irrigation based on a stress threshold ξ_i, representing the area of permanent crop i that can be maintained per unit of water, and calculates the variable K_{1jik}, the area (ha) of permanent crop i lost in year type j due to excessive stress. K_{1jik} is a state variable and it is not directly controlled by the farmer, but a consequence of water application decisions. Constraint (7) limits the use of each irrigation technology in the second stage to the investment made in the first stage IR_p.

Artificial recharge constraint (8) limits the amount recharged in event j to the recharge area allocated in jXR_{2j} times a recharge capacity RCAP in m^3/ha·year. Groundwater pumping capacity (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 Eq. (9) since they are limited by different decisions. UR_{fj} depends on artificial recharge decisions, while deep percolation UPD_{fj} depends on both water and irrigation technology decisions used in other hydrologic events, according to Eq. (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 transfer Eqs. (11) and (12) to account for the effect of different hydrologic event probabilities.

Model Data and Area of Study

The model runs use production and hydrologic data from irrigation districts in California's Central Valley (Table 1). The model simulates the decisions of a single irrigation district with a total area of 18,500 ha and access to a major surface water supply source and groundwater. The optimization package GAMS-General Algebraic Modeling System (Brooke et al. 1998) is used to solve the model.

Crop prices and input costs are pre based on surface reservoir releases operated by The U.S. Bureau of Reclamation (USBR) and Friant Kern canal division. The sample of hydrologic years (events) was obtained by generating a histogram (Fig. 1) of a long time series of water deliveries to the irrigation district such as might be derived from historical data or outputs from another water resource system model (Marques et al. 2006). The water available values in the histogram represent the lower bound of each interval.

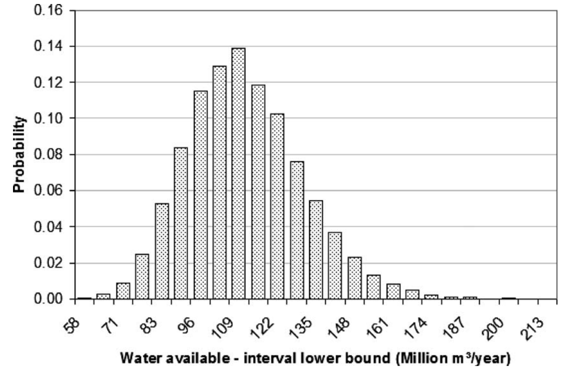

Fig. 1. Histogram of surface water availability

Two initial runs were executed for this analysis—a base run without groundwater pumping (no CU) and one run with groundwater pumping and artificial recharge (CU). The conjunctive use (CU) run allows groundwater pumping from deep percolation and artificially recharged water. The CU run has groundwater pumping capacity initially fixed as a model parameter, with Wcap$\times IPC$ term in Eq. (9) replaced by a fixed value for groundwater pumping capacity (Table 2). This is simulates conditions in a system where groundwater infrastructure capacity is already in place and no significant changes are expected. Another model run presented later in this paper modifies this to add groundwater pumping capacity as a first stage decision to evaluate optimal investment in pumping infrastructure. Conjunctive use operational data appears on Table 2, with more detail on model data and parameters in Marques (2004).

Results and Discussion

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 (Fig. 2). This increases total net expected benefit by 4.8% (from $47.8 to $50.1 million/year) comparing to the base run without groundwater pumping (no CU). The separation between deep percolation and artificial recharge in Fig. 2 is made only to illustrate the relative importance of each; in practice there is no distinction in the groundwater available for pumping. Deep percolation occurs in all events with some minor

Table 2. Conjunctive Use Operational Data

Element	Unit	Value
Capacities		
Artificial recharge	10^3 m^3/ha.year[a]	1,099
Groundwater pumping	10^3 m^3/year	53,039
Costs		
Artificial recharge	$/ha	2,471
Well establishment	$/well	25,000
Groundwater pumping	$/m^3	0.04

[a]Volume of water per unit area of land allocated to recharge ponding.

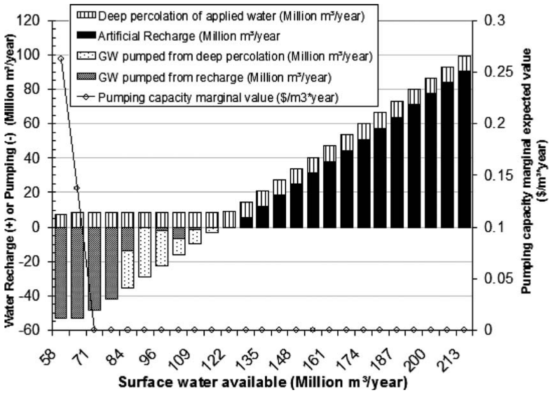

Fig. 2. Conjunctive use operations

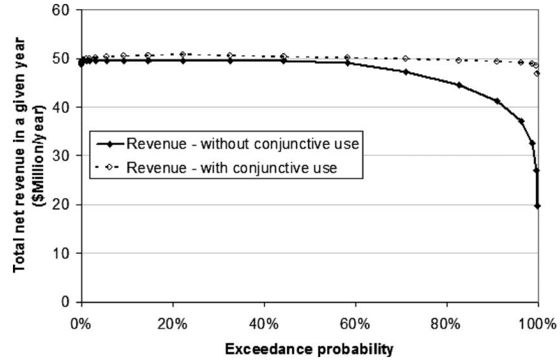

Fig. 3. Revenue reliability curve. Probabilities of return for operation with and without conjunctive use.

fluctuations from changes in acreages of annual crops and irrigation technologies across the year types. Artificial recharge increases toward the very wet events to satisfy probabilistic mass balance [Eqs. (11) and (12)]. Overall results indicate 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. Although the model focuses on identifying potential gains of conjunctive use operation and implications to farm cropping and irrigation technology decisions, optimal operating policies can be devised by observing the results for a given hydrologic event.

For example, in Fig. 2, if the irrigation district has a forecast of water availability within the 71 million m^3 interval (71 is interval's lower bound) they should pump approximately 53 million m^3 of groundwater and grow an annual crop area with irrigation technologies presented in Fig. 5. Fig. 2 also shows that in any given year with more than 135 million m^3 of surface water available, no pumping should occur and recharge should take place, with the amount varying depending both on the amount of surface water available and the probability of that year (hydrologic event) occurring.

Positive marginal values for pumping capacity indicate potential gains in expanding groundwater pumping infrastructure (53 million m^3/year pumping capacity) in the two driest events. When groundwater is available, expected total water use increases from 106.4 million m^3/year to 124.9 million m^3/year, and the reallocation of water from wet to dry events reduces the standard deviation in total water use from 13 million m^3/year to 4.3 million m^3/year. This increase in both supply availability and reliability leads to slightly higher and significantly less variable returns (Fig. 3). The range of probable outcomes (net economic returns) is significantly narrowed (standard deviation on total net return reduced from \$3.4 million to \$80,000) with the total return with a 100% exceedance probability in any given increasing from \$19.8 million to \$46 million. The probability that net revenue exceeds \$49 million increases from 58 to 96% (Fig. 2). 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 to be moved from wet to dry years, despite pumping and artificial recharge costs. However, this is an upper bound on potential gains, since other constraints limiting the groundwater availability (e.g., environmental and hydrogeologic limitations) are not modeled here.

With conjunctive use improving water supply availability and reliability, more land is used for crop production, while stress irrigation is reduced and remains only in the two driest events. This lowers the expected marginal value of water (Fig. 3) compared to the no conjunctive use (no CU) run. Water's expected marginal value is still high for the two driest years (\$0.33/m^3 at 57.6 million m^3/year and \$0.2/m^3 at 64.1 million m^3/year of surface water available), but drops to \$0.07/m^3 for events ranging from 70.6 million m^3/year to 115.8 million m^3/year of surface water available, and later to \$0.01/m^3 for events with more surface water up to 213.4 million m^3/year (Fig. 4). Between 109.4 and 115.8 million m^3/year, the water's expected marginal value is higher with conjunctive use operations, reflecting added benefits of expanding conjunctive use infrastructure, not available in the no CU run.

Groundwater pumping occurs in years with 57.6 million to 115.8 million m^3/year of surface water availability. The water's expected marginal value of \$0.07/m^3 reflects the groundwater pumping cost of \$0.04/m^3, the artificial recharge cost of \$0.02/m^3 plus a residual value of \$0.01/m^3. This residual value represents the marginal value of overdrafting the aquifer, reflecting the opportunity cost of water in other events.

The higher expected marginal value of water 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. Expected marginal water values represent the benefits of additional water in a given year divided by the probability of water availability in that year.

This result corroborates Schuck and Green (2002) findings in a study of supply-based water pricing in a conjunctive use system. They point out that the water user may face high costs when

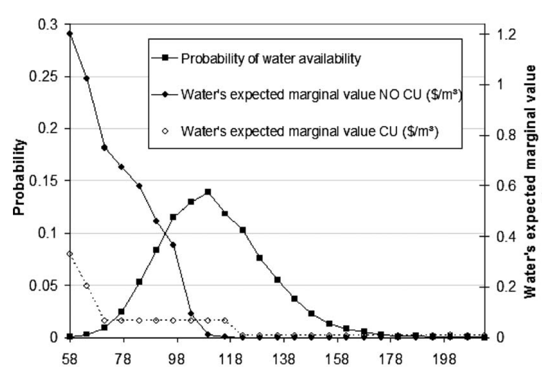

Fig. 4. Water's expected marginal values

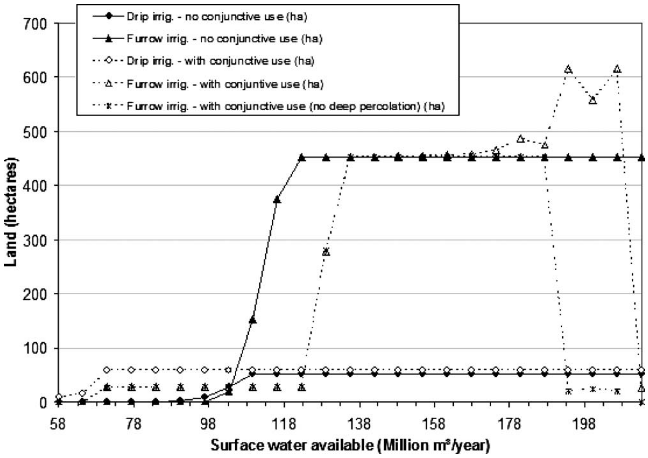

Fig. 5. Irrigation technology applied to annual crops in CU and no CU scenarios

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 from recharging groundwater for later use in dry years.

Under average and wet surface supply conditions, from 109.36 million m^3/year and above, water's expected marginal value is higher with conjunctive use (Fig. 4). This difference is the value of the added supply reliability to users (their willingness to pay to increase supply and supply reliability).

Irrigation Technology

Irrigation technology choice is affected by water supply availability and reflects on 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, although it also reduces productivity in very dry years when water is scarce. This results in some variation in irrigation technology use for annual crops as seen in Fig. 5. The flat portions in Fig. 5 reflect the few changes in technology use expected for annual crops, especially for technologies other than furrow irrigation. Although some change is bound to occur every few years, capital equipment used in some irrigation technologies have limitations in terms of storage, are more costly to assemble/disassemble, and may remain in use while crops change.

Fig. 5 depicts the greater use of high efficiency (drip) than lower efficiency (furrow) technologies in dry years, and the opposite in most of the wet years, which is motivated by both water availability and deep percolation. To separate the effect of deep percolation, it was disabled in an additional model run (but still allowing artificial recharge and groundwater pumping) and the results are plotted in Fig. 5. The same amount of annual crops irrigated by furrow occurred when comparing to the run with deep percolation enabled for the dry years. However, during the wettest years the acreages of crops irrigated with furrow are higher with deep percolation. As more (and less expensive) surface water becomes available, it starts to replace groundwater pumping. 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

Table 3. Permanent Crops Irrigation Technology Choice for CU and No CU Runs

	No CU run		CU run	
Irrigation technology	Used (ha)	Percentage from total permanent crops grown (%)	Used (ha)	Percentage from total permanent crops grown (%)
Furrow	1,865	25.9	2,090	25.6
Sprinkler	1,892	26.2	2,096	25.6
LEPA	1,891	26.2	2,079	25.4
Drip	1,563	21.7	1,915	23.4

with furrow technology will expand more if deep percolated water can be pumped back in other years. Without deep percolation, furrow irrigation acreage is eventually reduced to less than drip irrigation acreages in very wet years. This is because more water conservation is needed to increase artificial recharge that replaces recharge from deep percolation.

Without groundwater pumping, annual crops will not be grown unless at least 96.2 million m^3/year is available (the rest of the water goes to high value permanent crops), 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 drier years given the increased cost of the water.

The permanent crop acreage also increases with conjunctive use. The percentage of crops irrigated with the highest efficiency technology (drip) increases (Table 3), from 21.7 to 23.4% of the total area planted. To improve water supply and reliability in the system with groundwater programs, higher efficiency irrigation technologies are economically preferred, because most improvement occurs in dry years when water is scarce.

Groundwater Pumping Capacity

The use of groundwater to mitigate water supply uncertainty may also be affected by the users' risk averse behavior. Although not modeled here, risk aversion motivates users to invest in income variability reduction. This may include overapplication 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 with planned recharge and pumping, conjunctive use will not improve supply reliability if users cannot pump water when demanded. Thus users may be willing to invest in enough pumping capacity to partially or totally replace surface water during droughts. Exactly how much pumping capacity investment depends on production value and well costs, as well as crop water demands and irrigation technology. The positive marginal values for expanding pumping capacity indicate that further economic benefit is possible with more infrastructure.

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 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 permanent crops) without further

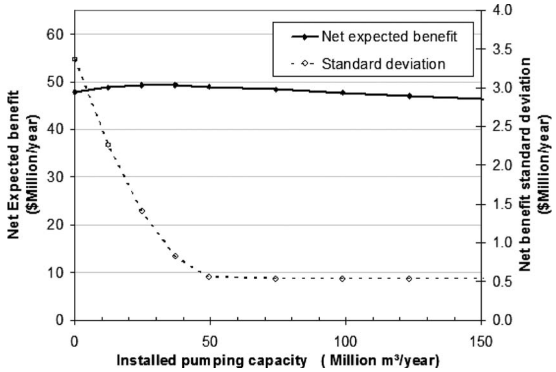

Fig. 6. Total net expected benefit for different levels of pumping capacity

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 $25,000 per well placed, and a 681-m^3/h well pumping capacity. The model was run for different total pumping capacities (million $m^3/year$) on the right hand side of Eq. (9) with additional pumping capacity infrastructure cost deducted in the objective function. The result is an expected total benefit that peaks at an optimal pumping capacity and starts to decline for higher investments in groundwater pumping infrastructure (Fig. 6).

Pumping capacity maximizes expected net benefit and quickly reduces net benefit's standard deviation (adding reliability), indicating a double benefit of installing pumping infrastructure. A similar result is also found by Bredehoeft and Young (1983). Near optimal pumping capacity, 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. Beyond this point, there is a trade-off between pumping capacity and expected benefit and reliability. In this example, it would cost farmers about $900,000 in net expected benefit to reduce the standard deviation from $1.35 million/year to $450,000/year. After this point, additional groundwater pumping above 50 million $m^3/year$ results in little reliability gain. Beyond 74 million $m^3/year$ pumping capacity there is no further benefit, only increase in investment costs. By substituting the right hand side of Eq. (9) with an additional decision variable representing pumping capacity, the exact value found for the optimal groundwater pumping capacity was 27.5 million $m^3/year$ (for a maximum net expected benefit of $49.2 million).

Limitations

The model does not track groundwater storage explicitly and relies on assumptions of large aquifer, never binding, storage, and small fluctuations in water table to hold the pumping cost constant across different hydrologic events. Balancing pumping and recharge across the range of events considered prevents long-term overdraft and subsequent long-term impacts on pumping cost. However the possibility of having many dry years occurring sequentially (very long drought) could cause variations in groundwater pumping cost too large to be ignored. As a two-stage stochastic model, there is no sequential time line for hydrologic events. 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 decisions are 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 of pumping capacity during very dry years might be considered.

Nevertheless, the proposed model allows 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

Groundwater availability can significantly improve the economic benefits of irrigated agriculture. Results indicate that this can be attained by conjunctive use programs that take 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 needed to implement conjunctive use (e.g., artificial recharge cost and land used for recharge facilities), the benefits are higher. Some specific conclusions for the example studied here are:

1. Conjunctive use increases both supply reliability and availability;
2. There can be positive marginal value for water in very wet years for artificial recharge;
3. Deep percolation and aquifer recharge affects irrigation technology choice, especially for low efficiency technologies and crops with higher consumptive use;
4. Groundwater pumping capacity can be expanded to optimize total net expected return. This expansion not only maximizes total expected return, but also reduces net benefit variability; and
5. The gains in income reliability are considerably greater than the increase in the expected net benefit. With conjunctive use the net expected benefit increased by only 4.8%, however with a significant increase in the probability of having high returns exceeded, as indicated by the flatter pattern on the revenue reliability curve. There is a clear trade-off of net revenue for added income reliability, and this information can be used to evaluate user's willingness-to-pay for insurance according to user's risk aversion. 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 occur in either reliability or net expected returns.

Groundwater availability, price, and conjunctive use operations significantly affect crop and irrigation technology decisions. The stabilizing effect of groundwater supply increases permanent crops acreage and allows for expansion of annual crops in dry years, limiting it in the wet years when pumping is cutback. Annual crops with high consumptive demand are not supplied with expensive water through low efficiency irrigation technology. As groundwater supply is reduced in wet years, surface supply is diverted to permanent crops and acreages of annual crops are reduced. To take most advantage of the investment in recharge infrastructure, artificial recharge is preferred in very wet years, using most of the surface water available and reducing the acreage of annual crops. Given that this additional water available through conjunctive use is also more expensive due to operating costs, irrigation technology shifts toward more efficient technologies.

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