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Water conveyance, return flows and technology choice[1]

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Abstract

This paper develops a spatial conjunctive use model of an irrigation project in which the regulatory agency determines investments in the centralized distribution system and farmers decide the level of on-farm technology in the field. Irrigation return flows are assumed to recharge the groundwater aquifer. It is shown that there is specialization in production with upstream farmers using surface water and downstream farmers pumping from the aquifer. An empirical model suggests that the proportion of return flows has a significant effect on the level of investments in water distribution as well as in the field. For example, if return flows are relatively high, it may be optimal to allow for significant water losses from the canal and the fields. It suggests that the project pricing and technology adoption policies may need to be tempered by consideration of the basinwide impacts of water diversions.

Keywords: Irrigation; Spatial water allocation; Conjunctive use; Return flows; Conveyance; On-farm technology

1. Introduction

In recent years the severe competition for limited water resources between urban, environmental and agriculture uses has created a pressing need to improve water efficiency in agricultural projects not only to improve productivity of the water but more importantly, to release the saved water for alternative uses[2]. It is now well known that water policies need to facilitate market-based approaches to water allocation and commercialization of agriculture (Rosegrant et al., 1995). Water policies that encourage a shift from high water intensity, low valued crops to high-valued crops that use limited water supplies more efficiently are expected to create a market for tradable water rights, as demonstrated successfully in several countries such as Chile, Mexico and California in the United States.

However, as is well known, unlike other commodities, trading in water rights pre-supposes a well established network of distribution canals and control infrastructure and a management system that is able to measure a possible third party impacts from reduced return flows. In the absence of a consistent framework for the analysis of the relationship between water pricing mechanisms, technology choice on the farm,

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[2]According to a study by the International Rice Research Institute, in a rice field with porous subsoil, about 60% of the water applied will flow into cracks in the field, 30% of which seeps down and recharges the aquifer and the remaining 70% is lost through drainage (IRRI, 1996).

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investment in the distribution system and return flows, many regulatory agencies have employed easy-to-use definitions on what constitutes tradable water that is not created at the expense of other rights holders (Rosegrant and Binswanger, 1994).

In this paper we develop a model that examines the spatial relationship between investment in the distribution system and differences in return flow characteristics in a water project. The model determines optimal public investment in canals as well as private on-farm choice of irrigation technology. For the sake of simplification, we assume that a certain portion of the lost water can be pumped up for groundwater irrigation. Conditions for technology adoption and canal investments are determined as a function of the seepage rate. The optimal allocation of irrigated area between surface and groundwater irrigation is determined. A simulation model with California data shows how these choice variables are affected by the assumption on the proportion of return flow. For example, if the soil seepage rates are relatively high, our results suggest that it may be optimal to allow to charge relatively 'low' surface water prices and allow for high water losses in the distribution system and on the farm. This would ensure significant third party benefits. On the other hand, when return flows are low, the project could benefit through an improved distribution system.

The model proposed here follows the approach taken by Chakravorty and Roumasset (1991); Chakravorty et al. (1995) although they do not incorporate return flows. Thus the results in terms of the spatial allocation of resources and the choice of technology turn out to be quite more complex than in the earlier work. For example, on-farm investment is not only a function of water prices but also of the shadow price of returned water and the proportion of water returned by the system. Section 2 develops the conjunctive use model with return flows. Section 3 explains the data and the functional forms used in the empirical model. Section 4 discusses the results from simulation and Section 5 concludes the paper.

2. The model

The model in this paper is similar to that developed by Chakravorty et al. (1995) appropriately modified to include reuse of water lost in distribution. Fig. 1 shows the schematic layout. A central planner or a water utility supplies water to farms located along both sides of a canal. Farms are assumed to locate in a continuum in the project area and are identical in all respects except their distance from the head of the canal. Let the distance of any given farm from the head of the canal be denoted by x. Farms withdraw water from the canal for irrigation. We assume that a single crop[3] is grown over one cropping season. Part of the water flowing through the canal and on individual fields is lost during distribution due to seepage and percolation, and the lost water recharges the groundwater aquifer underlying the project area. The amount of water lost can be reduced by investing in conveyance (i.e., lining the canal) and in on-farm water efficiency (such as drip irrigation) while the recharge can be pumped up by individual farmers for supplemental on-farm irrigation at any location. We abstract from the uncertainty of water supply at the head and other dynamic phenomena such as storage of water in the aquifer. We implicitly assume that water lost in distribution is instantaneously available for pumping, although in reality, the time lag between water loss and recovery may be significant.

The utility chooses the initial stock of surface water $z_s(0)$ at the source ($x=0$) flowing into the canal. Let the subscripts s and g denote surface and groundwater, respectively. Let $g(z_s(0))$ be the total cost of generating water at the source of the canal. This includes annualized capital costs and the cost of operation and maintenance of the headworks per cropping season. The cost of water generation is assumed to be an increasing, twice differentiable and convex function with $g'(z_s(0))>0$ and $g''(z_s(0))>0$. Thus the larger the initial stock of surface water the greater the marginal cost of generating water at the source. Since water is withdrawn for use in farms at each location and some of it is lost in transit, we define $z_s(x)$ to be the residual stock of water flowing in the canal which decreases with 'x'. Let the fraction of water lost in the canal at any location x be denoted by $a(x)$ with $a(x)\geq 0$. The volume of surface water withdrawn from the canal per unit land area at any location is given by $q_s(x)$ so that the change in the residual stock of water in the

[3]The model can be extended to multiple crops by indexing on crop type.

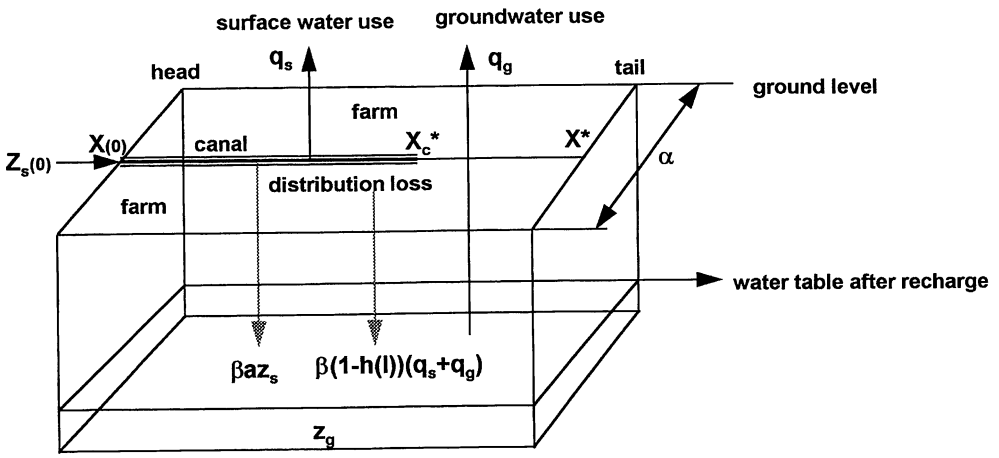

Fig. 1. Box diagram of water project area.

canal can be expressed by the differential equation:

$$z_s'(x) = -q_s(x)\alpha - a(x)z_s(x) \tag{1}$$

where 'α' is the constant width of the rectangular irrigated area, and $q_s(x)\alpha$ and $a(x)z_s(x)$ represent the water applied in the field and lost in the canal at any location 'x', respectively.

The fraction of water loss in the canal, $a(x)$, depends on $k(x)$, conveyance expenditure per unit surface area of the canal, which is determined by the model and may vary with location x. This water loss function is given by:

$$a(x) = a_0 - m(k(x)),$$
$$a_0 \in [0,1]\ m \in [0, a_0),\ a(x) \in (0,1] \tag{2}$$

where a_0 is the constant base loss rate that would result when no investment in canal lining is made, i.e., k=0. Conveyance investment, on the other hand, reduces the base loss a_0 by the factor $m(k(x))$, which is assumed to be an increasing, twice differentiable function exhibiting decreasing returns to scale with respect to k, i.e., $m(k) \in [0, a_0); m'(k) > 0; m''(k) < 0; \lim_{k\to\infty} m(k) = a_0;\ \lim_{k\to 0} m'(k) = \infty$. Therefore, investment in conveyance will decrease the water loss rate, i.e., $a(x) \leq a_0$. Since $m(k)$ approaches the base loss rate, a_0 only at the limit, the fraction of water lost becomes zero in the limit. The limit of $m'(k)$ is assumed to be infinite so as to avoid a corner solution and ensure non-zero conveyance expenditures.

The total volume of water applied on unit land area at any location is the sum of surface water and groundwater applied, $q_s(x)+q_g(x)$, where $q_g(x)$ is the groundwater applied per unit area at location x. On-farm water efficiency from the farm-gate of the canal to the root zone of the plant is represented by an increasing, concave function $h(I(x))$ where $I(x)$ is investment in on-farm technology for water conservation (e.g., furrow, sprinkler and drip irrigation) at location x. If no on-farm investment is made, i.e., I=0, farmers choose furrow irrigation, for which $h(0)$=0.6. In that case, 60% of the water applied (q_s+q_g) is used for evapotranspiration by the plant and the remaining 40% is lost from the system. However, if farms invest in improved on-farm technology such as sprinkler or drip irrigation, $h(I)$ may approach unity and the proportion of applied water lost is significantly lower. This concept of 'effective water' (see Caswell and Zilberman (1985) for the original definition) represents the actual amount of water e used by the crop and is given by $e(x) = (q_s(x) + q_g(x))h(x)$. The crop production function per unit land area is then defined by y=$f(e(x))$ where y is the agricultural output. The production function is assumed to be increasing, twice differentiable with decreasing returns to scale with respect to effective water, i.e., $f(e)$>0; $\partial f/\partial e > 0$; $\partial^2 f/\partial e^2 < 0$.

Let us assume that a proportion, β of the aggregate water lost from the system (canal and individual

fields) seeps down into the groundwater aquifer and is available for pumping. Further, assume that there is no change in the level of the aquifer over time since the amount of water flowing into the aquifer is instantaneously used up by pumping. This model can be considered as a static approximation of a dynamic problem where the water level in the aquifer reaches a steady-state. We abstract from considering any natural recharge into the aquifer. If $\beta=1$, all the water lost is available as groundwater. If $\beta=0$, water seeping through cannot be re-used and is therefore lost to the system. These are of course, polar cases and in reality, the actual value of β, which can be thought of as the permeability of the soil, may lie somewhere between these two extremes, $0<\beta<1$.

Let $z_g(x)$ denote the amount of water available for pumping at any location x. Initially, we assume that there is no groundwater stock at the source of the canal and $z_g(0)=0$. The change in the groundwater stock at location x, $z_g'(x)$, can be expressed as follows:

$$z_g'(x) = \beta a(x) z_s(x) + \beta(1 - h(I(x)))(q_s(x) + q_g(x))\alpha - q_g(x)\alpha \tag{3}$$

where $\beta a(x)z_s(x)$ and $\beta(1-h(I(x)))(q_s(x)+q_g(x))\alpha$ represent the recharge from the canal and from the field, respectively, and $q_g(x)\alpha$ is the extraction of groundwater at any location x.

2.1. Optimization problem

Let p denote the constant unit output price of the crop. This price-taker assumption may be appropriate when the crop is characterized by a relatively high elasticity of demand, such as a commercial or export-oriented crop, for example. The fixed cost of irrigated farming per unit area is given by F and w is the variable pumping cost per unit of water, which is assumed to be uniform over the project regardless of the depth of the aquifer. The social planner maximizes net consumer plus producer surplus in a two-stage procedure as follows: first, given an initial fixed stock of surface water, $z_s(0)$, the social planner or utility is assumed to choose $q_s(x)$, $q_g(x)$, $k(x)$, $I(x)$, and X, the boundary of the project area; second, the utility optimizes over the value of $z_s(0)$ taking into account the cost of freshwater generation. The first stage can be written as follows:

$$\underset{q_s,q_g,k,I,X}{\text{Maximize}}\ \mathrm{NB}(z_s(0)) = \int_0^X \{[pf[(q_s + q_g)h(I)] - I - F - wq_g]\alpha - k\}\,\mathrm{d}x \tag{4}$$

subject to the two state constraints Eqs. (1) and (3). Let $\lambda_s(x)$ and $\lambda_g(x)$ be the co-state variables for the surface and groundwater resource stocks, respectively. The Hamiltonian for this optimization problem can be written as follows:

$$H(q_s, q_g, k, I, \lambda_s, \lambda_g) = [pf[(q_s + q_g)h(I)] - I - F - wq_g]\alpha - k - \lambda_s[q_s\alpha + az_s] + \lambda_g[\beta az_s + \beta(1 - h(I))(q_s + q_g)\alpha - q_g\alpha] \tag{5}$$

where $z_s(x)$ and $z_g(x)$ are state variables, and $q_s(x)$, $q_g(x)$, $k(x)$, and $I(x)$ are control variables. Let $q_s^*(x)$, $q_g^*(x)$, $k^*(x)$, $I^*(x)$, $z_s^*(x)$, $z_g^*(x)$, and X^* denote the corresponding optimal functions for this problem. Assume that the Hamiltonian is concave in $q_s(x)$, $q_g(x)$, $k(x)$, $I(x)$, $z_s(x)$, $z_g(x)$ and that the appropriate sufficiency conditions are met. Then the necessary conditions for optimality are given as follows:

$$pf'h \le \lambda_s - \lambda_g\beta(1 - h) \quad (= \text{if } q_s > 0) \tag{6}$$

$$pf'h \le w + \lambda_g[1 - \beta(1 - h)] \quad (= \text{if } q_g > 0) \tag{7}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \le 1 \quad (= \text{if } k > 0) \tag{8}$$

$$pf'(q_s+q_g)h'(I) \le 1 + \lambda_g\beta(q_s+q_g)h'(I) \quad (= \text{if } I > 0) \tag{9}$$

$$\lambda_s'(x) = a(\lambda_s - \beta\lambda_g) \tag{10}$$

$$\lambda_g'(x) = 0 \tag{11}$$

where $\lambda_s'(x)$ and $\lambda_g'(x)$ are derivatives with respect to x. The transversality condition for a free terminal problem states that the Hamiltonian at the terminal point X^* is zero, and there is no restriction on the shadow price of resources at X^*, $\lambda_s(X^*)$ and $\lambda_g(X^*)$:

$$[H(q_s, q_g, k, \lambda_s, \lambda_g)]_{x=X^*} = 0 \tag{12}$$

The necessary conditions Eqs. (6)–(11) are interpreted as follows. In Eq. (6), the left hand side represents the value of marginal product of surface water which is less than or equal to its shadow price

net of its value in return flow, i.e., the term $\lambda_g\beta(1-h)$ denotes the shadow price of groundwater times the fraction that seeps into the ground and recharges the aquifer and is available for pumping. Hence the marginal benefit from crop production is equal to the marginal cost of surface water net of the positive externality of distribution loss.

Eq. (7) can be similarly interpreted by rewriting it as follows:

$$pf'h \leq w + \lambda_g - \lambda_g\beta(1-h) \quad (= \text{if } q_g > 0) \quad (13)$$

which shows that the marginal value product of groundwater is less than or equal to the sum of the unit pumping cost and the shadow price of groundwater net of the value of the groundwater that goes back into the aquifer for reuse. Thus for both surface and groundwater, the price of water that may be charged by the utility (net shadow price, i.e., shadow price net of the externality) is strictly less than the private cost of water at each location, given by λ_s and $\lambda_g + w$, respectively. Under groundwater use, the net supply price, i.e., the sum of the pumping cost and the net shadow price of groundwater (given by the right-hand side of Eq. (7), is the marginal cost of water for firms.

Eq. (8) indicates that the marginal value of water saved (net of the return flow) is equal to its marginal cost which is the unit cost of conveyance. The left hand side of Eq. (9) shows the marginal benefit of increasing on-farm investment by one unit while the right hand side shows the marginal cost. An additional term, $\lambda_g\ \beta(q_s + q_g)h'(I)$, reflects the value of foregone marginal benefit of the groundwater resource resulting from employing one more unit of on-farm investment in water efficiency. Thus, although increased on-farm technology improves water efficiency, it reduces the amount of groundwater recharge and increases the marginal cost of water. Eq. (10) represents the change of shadow price of water with location. The shadow price increases with the conveyance loss rate since the latter makes it more costly to transport water to a given location but it decreases because of return flows. That is, the higher the seepage rate, the lower the increment in shadow price over distance. Thus a high seepage rate would reduce shadow price differentials across location. Eq. (11) indicates that the shadow price of groundwater is constant over space. This is because of the assumption of a uniform pumping cost over space. Finally, the transversality condition Eq. (12) suggests that at the boundary of the project area, X^*, the net benefit from the project (i.e., total revenue less investment on conveyance) is exactly offset by the shadow value of water at the tail.

Let us define the optimal net benefit function given the initial stock of surface water $z_s(0)$ as derived from the above program as $\text{NB}^*(z_s(0))$. In the second stage of the optimization process, the optimal net benefit from the first stage net of the cost of water generation at the source is maximized with respect to the initial stock of water as $z_s(0)$, as follows:

$$\text{Maximize NB}^*(z_s(0)) - g(z_s(0))z_s(0) \quad (14)$$

which gives the necessary condition, $\text{NB}^{*\prime}(z_s(0)) = g'(z_s(0))$ that determines the optimal stock of water $z_s^*(0)$. From the first stage, partial differentiation of NB^* with respect to the given optimal initial stock of surface water $z_s^*(0)$ gives:

$$\frac{\partial \text{NB}^*}{\partial z_s^*(0)} = \lambda_s^*(0) \quad (15)$$

which implies that the shadow price of surface water at the source, $\lambda_s^*(0)$, is equal to the marginal benefit evaluated at the optimal initial stock of surface water, $z_s^*(0)$. Eqs. (14) and (15) also yield:

$$\lambda_s^*(0) = g'(z_s^*(0)) \quad (16)$$

Hence, the shadow price of surface water at the source in the optimal solution is also equal to the marginal cost of generating water at the source.

Finally, quasi-rents per unit land area, R_L, which accrue to firms at location x are given by the relationship

$$\begin{aligned} R_L(x) = \{&pf[(q_s(x) + q_g(x))h(I(x))] \\ &- [\lambda_s(x) - \lambda_g\beta(1 - h(I(x)))]q_s(x) - (w + \lambda_g(x) \\ &[1 - \beta((1 - h(I(x)))])q_g(x) - I(x) - F\} \end{aligned} \quad (17)$$

where the right-hand side represents returns per unit water net of fixed and variable costs.

The optimal allocation provides a corner solution for this problem. Using the necessary conditions, it is straightforward to show that upstream farmers use surface water and downstream farmers use groundwater for production. Fig. 2 shows the spatial distribution of shadow prices, water use, on-farm

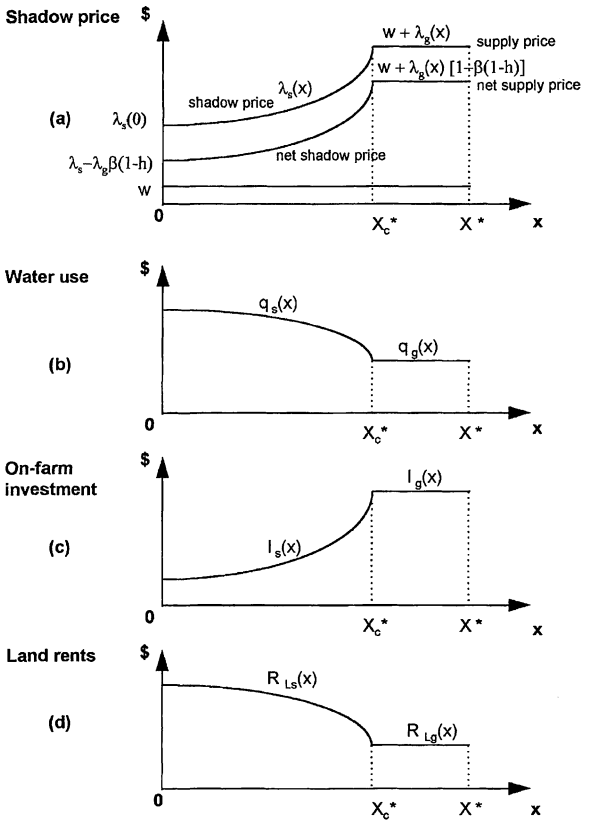

Fig. 2. Spatial distribution of shadow prices, water use, on-farm investment, and land rents.

investment and land rents. Panel (a) shows the gross shadow prices of surface water and groundwater and the net shadow prices, i.e., the prices that take into account the positive externality effects of return flows. These net shadow prices may be charged by the utility for implementing the optimal water allocation. Let X_c denote the boundary of the canal (distinct from the boundary of the project). For firms located from 0 to X_c, surface water is cheaper than groundwater and therefore they only withdraw surface water from the canal (panel (b)). On the other hand, firms from X_c to X^* pump groundwater for irrigation. Thus groundwater emerges as an endogenous 'backstop' technology in this model. The price of surface water increases away from the source and is bounded above by the price of groundwater. Higher prices of water induce higher investment in on-farm technology and lead to lower quasi-rents from land (panels (c,d)).

Let us now compare water allocation in the conjunctive use model for low and high values of β, the permeability coefficient of the soil that determines the proportion of water available for return flow. In Fig. 3(a), the superscripts '1' and '2' denote, respectively, low and high values of permeability. In the extreme case when permeability is zero, the conjunctive use model developed above reduces to a model with no groundwater recharge as in Chakravorty et al. (1995). When permeability is high, for any given initial stock of surface water, project benefits are going to be higher since a higher proportion of the water will be re-used. Thus the net shadow price of the system with high permeability is higher at the source than the shadow price under low permeability. This also implies that since water is used more efficiently under high permeability, the aggregate stock of water will be greater when soil permeability is higher.

With a higher initial stock of water and a higher shadow price of water, one might intuitively suspect that there is less surface water use in the system with high seepage. However, the externality effects of seepage are higher when more water is reused, hence the net shadow prices under high permeability are smaller than when permeability is low. That is, a system with high water reuse will also allow farmers to withdraw more water, since that also means more water is available for pumping. Fig. 3 compares water allocation under different soil types. Irrigation technology use will be lower and land rents will be higher in permeable soils.

2.2. *Conjunctive Use under sub-optimal conveyance*

Let us now compare surface and ground water use when there is sub-optimal conveyance. This comparison is helpful because most water projects not only in developing countries but also in developed countries are characterized by poor maintenance, unlined canals and lack of proper control structures. The no-conveyance scenario is mostly similar to the previous case except that without centralized investment in the canal, seepage rates are higher and the difference between the amount of water available for pumping is driven solely by the permeability of the soil. Shadow

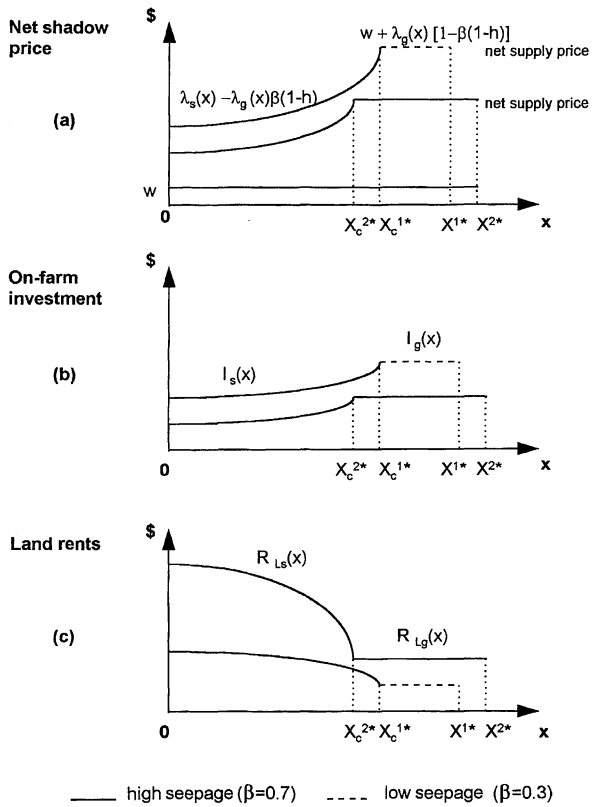

Fig. 3. Spatial distribution of net shadow prices, on-farm investment, and land rents for different soil permeabilities.

prices also rise faster with distance since it is costly to move water when losses are higher. However, it seems obvious that with optimal conveyance, gross shadow prices for groundwater must be higher when permeability is more, but net shadow prices must be smaller with higher seepage because it is cheaper to use more water when a bigger proportion of it can be reused. However, when conveyance is sub-optimal, the relatively steep shadow price gradient between head and tail may offset this result and net shadow prices may be larger when permeability is low.

When the recharge rate is high, it is likely that the area irrigated by surface water will be small since more water is now available for groundwater pumping. However, with a higher recharge, more water is now available to the project, which in turn will increase the surface area irrigated. The net result is not indeterminate although a larger proportion of area must be in groundwater irrigation under high permeability.

3. Data and method of simulation

The above cases are illustrated in this section by using secondary data on cotton production from Western U.S. agriculture.

3.1. Data

The production function for cotton is defined as a quadratic function of effective water. It yields a maximum of 1500 lb with 3.0 acre-feet of effective water and 1200 lb with 2.0 acre-feet of effective water. The revenue function in US$ is given by the following function:

$$Pf(e) = -0.2224 + 1.0944 \cdot e - 0.5984 \cdot e^2 \quad (18)$$

where the output price of cotton is taken as US$ 0.75 per lb and the effective water, e, is in m^3 (Zilberman et al., 1994). Partial differentiation of Eq. (18) with respect to e provides the value of marginal product function:

$$Pf'(e) = 1.0944 - 1.1968 \cdot e \quad (19)$$

On-farm water conservation at each location is a function of on-farm investment. The conservation function is estimated from available data on expenditures in irrigation technologies in California (University of California, 1988). It is constructed such that we assume that in the case of traditional furrow irrigation, no investment is made, i.e., I=0 and the proportion of water delivered to the field for use in production, $h(0)$ is 0.6. Increasing the level of on-farm investment increases the efficiency which approaches unity in the limit. The investment function is defined as follows:

$$h(I) = 0.6 + 21.67 \cdot I - 333.3 \cdot I^2 \quad (20)$$

where $\partial h/\partial I > 0$ and $\partial^2 h/\partial I^2 < 0$ and I is in US$/$m^2$. For example, in case of modern technology, sprinkler (h=0.85) and drip (h=0.95) irrigation require on-farm investment of US $0.015/$m^2$ and US$ 0.030/m^2, respectively (Caswell and Zilberman, 1986). A fixed cost of US$ 0.107/m^2 (US$433/acre) is assumed and is taken to be a constant regardless of

the level of on-farm technology[4] (University of California, 1988).

The water loss function is a quadratic function of conveyance expenditures that was constructed from data on average lining and piping costs in 17 states in the western United States. For example, a piped canal with a conveyance expenditure of US$ 200/m length of canal is assumed to result in zero conveyance loss. An investment of US$ 100/m in concrete lining gives a total loss rate of 10^{-5}/m with a conveyance loss rate of 0.1 for a 10 km length of the canal, or a conveyance efficiency of 0.9 per 10 km. If there is no conveyance expenditure, no reduction in loss is achieved. Then the loss rate is equal to the base loss rate, 4×10^{-5}/m, which gives a conveyance loss rate of 0.4 per 10 km or a conveyance efficiency of 0.6 per 10 km. The water loss function at each location x is:

$$a(x) = 4 \times 10^{-5} - (4 \times 10^{-7} k - 10^{-9} k^2) \quad (21)$$

where base loss $a_0=4\times10^{-5}$, and the loss reduction function is:

$$m(k) = 4 \times 10^{-7} k - 10^{-9} k^2,\ 0 \leq k \leq 200 \quad (22)$$

which is increasing at a decreasing rate with respect to conveyance expenditure k, i.e., $\partial m/\partial k \geq 0$; $\partial^2 m/\partial k^2 \leq 0$.

The long-run marginal cost function for water supply was estimated from the average cost of water supply in 18 irrigation projects in the western United States and is given as:

$$g'(z_s(0)) = 0.003785 + (3.785 \times 10^{-11} z_s(0)) \quad (23)$$

where marginal cost is in US$ and the initial stock of water $z_s(0)$ is in m^3.

For convenience, the width of the project area α is assumed to be 10^5 m, although our results are independent of the project width. For the seepage rate β which represents permeability of the soil, Gisser and Mercado (1973); Gisser and Sanchez (1980) use a return flow coefficient of 0.27 for the Pecos River Basin in New Mexico. Kim et al. (1989) use 0.20 for irrigated production in the Texas High Plains. In this model, high and low seepage rates of 0.7 and 0.3 were assumed. So under furrow irrigation, where 40 % of the water is lost, the recharge rate is 0.28 (0.7*0.4) for a seepage rate of 0.7 and 0.12 (0.3*0.4) for a recharge rate of 0.3.

In many groundwater studies, the marginal cost of water is approximated by the pumping cost of water and is defined as a linear function of pumping lift (Burt, 1964; Gisser and Mercado, 1973; Gisser and Sanchez, 1980; Gisser, 1983; Kim et al., 1989). Caswell and Zilberman, 1985, 1986 also specify marginal pumping cost as a function of lift. They assume that the marginal cost of pumping does not depend on the amount of water extracted. For simplicity, the same assumption of constant marginal cost of pumping is adopted here. The marginal pumping cost, US$ 0.0128/m^3 (US$ 15.80/acre-feet) as estimated by Negri and Brooks (1990), excludes the cost of pressurization and is considered appropriate for this model in order to separate pumping cost from on-farm investment.

3.2. Method of simulation

A computer algorithm was written to solve the above model. First, we guess the initial stock of surface water, $z_s(0)$, and $\lambda_s(0)$ is computed from the salvage value condition Eq. (16). The initial stock of groundwater z_g at x=0 is zero. Next we guess λ_g, which is constant, and condition (Eq. (8)) gives $m'(k)$ at x=0. The marginal reduction function derived from Eq. (22) defines the conveyance expenditure $k(0)$ and by substituting it into Eq. (21), we next compute the water loss from the canal $a(0)$. Given $\lambda_s(0)$ and λ_g, condition (Eq. (6)) yields $q_s(0)$, and $q_s(0)$ which then is used to compute $I(0)$, $h(0)$, $e(0)$, $y(0)$ and $R_L(0)$ for surface water use at x=0.

In the next cycle when x=1, $a(0)$, $\lambda_s(0)$, and λ_g are substituted into Eq. (10) to give $\lambda_s(1)$. The residual stock of surface water $z_s(1)$ is obtained from the state constraint Eq. (1) by subtracting the surface water use and water loss in the canal in the previous location x=0. The residual groundwater stock $z_g(1)$ is estimated from Eq. (3). Given $\lambda_s(1)$ and $z_s(1)$, the previous cycle is repeated to yield $q_s(1)$, $I(1)$, $h(1)$, $e(1)$, $y(1)$ and $R_L(1)$. This procedure for the surface water-irrigated region is repeated at x=2, 3, ... and is terminated when one of the following conditions is satisfied: (1) the shadow price of surface water is greater than the shadow price of groundwater, (2)

[4]Zilberman et al. (1994) showed varying fixed costs of irrigation technology for California cotton production according to the type of technology adopted.

Table 1
Simulation results with endogenous conveyance and on-farm technology

Variable	Unit	A	B	C	D
		Conjunctive use model			
		Endogenous conveyance		No conveyance	
		β=0.7	β=0.3	β=0.7	β=0.3
Total net benefit	(10^8US$)	4.10	3.58	3.00	2.05
Area irrigated	(10^3ha)	520	510	340	210
Length of canal (X_c^*)	(km)	43	49	18	17
Length of project area (X^*)	(km)	52	51	34	21
Initial surface water stock $z_s(0)$	(10^8 m^3)	42.1	41.9	32.7	23.7
Groundwater stock z_g	(10^8 m^3)	7.5	0.45	14.1	2.82
Aggr. output	(10^8US$)	14.02	13.79	9.32	5.95
Aggr. land rent	(10^8US$)	0.552	0.177	0.87	0.87
Shadow price of surface water (head)	(US$/m^3)	0.1631	0.1624	0.1276	0.0935
	[US$/AF]	[201.3]	[200.4]	[157.5]	[115.4]
Shadow price of surface water (tail)	(US$/m^3)	0.1639	0.1628	0.1461	0.1443
	[US$/AF]	[202.3]	[200.9]	[180.3]	[178.1]
Net shadow price of surface water	(US$/m^3)	0.1392	0.1579	0.0838	0.0854
$\lambda_s - \lambda_g\beta(1-h)$ (head)	[US$/AF]	[171.8]	[194.8]	[103.4]	[105.3]
Supply price of groundwater	(US$/m^3)	0.1706	0.1629	0.1693	0.1457
$w+\lambda_g$	[US$/AF]	[210.5]	[201.0]	[208.9]	[179.8]
Shadow price of groundwater	(US$/m^3)	0.1578	0.1501	0.1565	0.1329
λ_g	[US$/AF]	[194.7]	[185.2]	[193.1]	[164.0]
Net supply price of groundwater	(US$/m^3)	0.1499	0.1584	0.1487	0.1414
$w + \lambda_g - \lambda_g\beta(1-h)$	[US$/AF]	[185.0]	[195.5]	[183.5]	[174.5]
Surface water use (head) $q_s(0)$	(m^3/m^2)	0.9773	0.8531	1.330	1.0337
Surface water use (tail) $q_s(X_c^*)$	(m^3/m^2)	0.9767	0.8527	1.087	0.8786
Groundwater use (tail) q_g	(m^3/m^2)	0.9362	0.8526	0.938	0.8772
Investment in canal (head) $k(0)$	(US$/m)	197.74	198.98	0	0
Investment in canal (tail) $k(X_c^*)$	(US$/m)	106.17	155.00	0	0
Water loss rate (head) $a(0)$	(10^{-3}/km)	0.0051	0.0010	40.0	40.0
Water loss rate (tail) a(X_c^*)	(10^{-3}/km)	8.8044	2.0246	40.0	40.0
Land rent at head	(10^6US$/m^2)	1.1682	0.3437	5.1486	6.6870
Land rent at tail	(10^6US$/m^2)	0.4448	0.3007	0.5563	1.7473
On-farm investment at head $I_s(0)$	(US$/m^2)	0.010	0.020	0	0.011
On-farm investment at tail $I_s(X_c^*)$	(US$/m^2)	0.010	0.020	0.006	0.019
On-farm investment at tail I_g	(US$/m^2)	0.012	0.020	0.012	0.019
On-farm water efficiency at head $h_s(0)$		0.7834	0.9001	0.6	0.798
On-farm water efficiency at canal tail $h_s(X_c^*)$		0.7834	0.9001	0.718	0.891
On-farm water efficiency at tail h_g		0.8120	0.9001	0.812	0.891

Note: Supply price of groundwater is the sum of the shadow price of groundwater and pumping cost; AF = acre-foot; the values at X_c^* and at the tail are to the nearest kilometer.

the land rent is negative, or (3) the residual surface water z_s is exhausted.

On completion of the above sequence, the extraction of groundwater begins. The groundwater cycle repeats the same process with the values of $z_g(X_c)$ and λ_g from above. It terminates when the residual groundwater stock is exhausted or when either land rents or net benefits at any location are nonpositive. Finally, aggregate net benefit, output and land rents from surface and groundwater production are computed by summing over the entire project.

The above procedure is repeated with new guesses of $z_s(0)$ and λ_g. The optimal $z_s(0)$ and λ_g are those that maximize the total net benefit for the project, i.e., the

aggregate net benefit less the cost of generating surface water at the source given by (Eq. (14)).

4. Simulation results

Simulations were run to examine the effect of soil type as well as conveyance investments on conjunctive use of surface and groundwater. The results are presented in Table 1. The first two columns (A and B) compare projects with different soil types and with optimal distribution systems. The last two columns (C and D) compare projects with distribution problems. The results are summarized as follows:

(1) It is clear from looking at the aggregate net benefits that soil type differences matter more when distribution systems are malfunctioning. Net benefits in project C are nearly 50% more than in D, while the difference is less than 20% between A and B. This is because if both projects have unlined canals, higher permeability allows a higher percentage of reuse. More importantly, comparison between A and C and between B and D suggests that canal maintenance plays a larger role when soils are less permeable.

(2) When permeability is high, a significant portion of the area is irrigated by groundwater. Under no conveyance, this ratio is approximately 47% while under endogenous conveyance, it is about 17%. However, with low permeability, the area under groundwater use is small.

(3) On an absolute level, land rents are several times higher in projects with poor distribution systems mainly because of the smaller cost of water generation. However, in projects with proper maintenance, land rents are higher under high seepage, because each firm gets an incentive for using more water, since that translates into groundwater stock available for pumping. As columns A and B indicate, this is measured by the differential between the gross and the net shadow price of surface water at each location.

(4) It is interesting to observe the differences in irrigation investments between columns A and B, and between C and D. With high seepage, on-farm investments are relatively much lower. This suggests that policies that promote adoption of on-farm irrigation technology must consider the alternative uses of the lost water. When seepage is low, or in situations where the lost water is not retrieved, it may pay to achieve high on-farm efficiency. Thus unlike in earlier models such as Chakravorty et al. (1995) where shadow prices alone determined the choice of conservation technology, seepage rates are an important factor in this more general framework.

(5) Water use per acre is highest in model C because it is cheap and it makes sense to accumulate recharge. With optimal conveyance, however, water use is less concentrated in the upstream regions since low canal losses allow water applications to be more dispersed.

5. Conclusions

This paper extends the standard spatial model of water use to include the conjunctive use of irrigation water. It assumes that water lost in distribution recharges the groundwater aquifer and is available for pumping. The results suggest that both seepage rates and investments in water distribution have a critical role to play in the spatial organization of production. Differences in seepage rates are much more critical in projects with high distribution losses than in those where these losses are small. Unlike in previous models where the choice of on-farm technology is guided solely by the shadow price of water, high seepage in our model induces high water losses on the farm, thus replenishing the groundwater aquifer.

These results have important consequences for water policies based on conventional wisdom that encourages investments in distribution canals and in better on-farm irrigation technology. For example, if seepage rates were significant, attempts at reducing water losses on the farm through improved technology adoption may be of little benefit. In that case even investments in upgrading distribution canals may have marginal impacts and limited agency resources spent on technology extension or canal upgrading and management could be diverted elsewhere. On the other hand, where seepage rates are low, the project could benefit significantly from improved conveyance. These issues also point to the need for integrated decision-making systems for the entire watershed or

river basin that will then take these externalities into account, rather than management on a project-by-project basis. This emphasis on basin-wide management and concepts of water efficiency that incorporate water reuse are currently being proposed by several researchers (e.g., Seckler, 1996).

Some of the simplifying assumptions of our model could be relaxed in future work. For example, one needs to think further on the types of monitoring and enforcement mechanisms that could induce the spatial specialization of surface and groundwater irrigation. In the present formulation, if farmers are charged net shadow prices, there would be no incentive for instance, for upstream firms to pump groundwater. However, alternative pricing policies could distort these incentives. In a decentralized framework, there may be opportunities for upstream and downstream farmers to engage in water trading where upstream farmers divert water and use water-intensive irrigation that increases recharge and benefits downstream users. Under some conditions, such as a high water table or low pumping costs, transfer of water between locations through a centralized distribution system may be costlier than through the groundwater aquifer.

The separation of the investment decision between centralized conveyance investments and decentralized on-farm investments raises some interesting political economy issues and can be explored further in a future work. For instance, the decision of the regulatory agency or the water manager to invest in the distribution system can have differential impacts on surface and groundwater users. The manager's weighted welfare function with say, the wealthy, landowning farmers located upstream and poor, landless farmers, situated downstream, having different weights, may affect the conveyance decision. Similarly, the choice of technology by upstream farmers would have direct welfare consequences for groundwater pumpers.

Finally, although the quality of the recharge water is assumed away, in reality, there may be chemical and salt accumulation. This would affect shadow prices of the reused water in the downstream region. Similarly, stochastic supplies can be explicitly modeled by using the aquifer for storage. Variable pumping costs as a function of aquifer depth can be introduced.

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References

Burt, O.R., 1964. The Economics of Conjunctive Use of Ground and Surface Water. Hilgardia 36, 31–111.

Caswell, M., Zilberman, D., 1985. The Choices of irrigation technologies in California. Am. J. Agric. Econ 67, 224–234.

Caswell, M., Zilberman, D., 1986. The effects of well depth and land quality on the choice of irrigation technology. Am. J. Agric. Econ. 68, 798–811.

Chakravorty, U., Hochman, E., Zilberman, D., 1995. A spatial model of optimal water conveyance. J. Environ. Econ. Management 29, 25–41.

Chakravorty, U., Roumasset, J., 1991. Efficient spatial allocation of irrigation water. Amer. J. Agric. Econ. 73, 165–173.

Gisser, M., 1983. Groundwater: Focusing on the real issue. J. Polit. Econ. 91, 1001–1027.

Gisser, M., Mercado, A., 1973. Economic aspects of groundwater resources and replacement flows in semiarid agricultural areas. Amer. J. Agric. Econ. 55, 461–466.

Gisser, M., Sanchez, D.A., 1980. Competition versus optimal control in groundwater pumping. Water Resour. Res 16, 638–642.

IRRI, Newsletter, May 1996.

Kim, C.S., Moore, M.R., Hanchar, J.J., 1989. A dynamic model of adaptation to resource depletion: Theory and an application to groundwater mining. J. Environ. Econ. Management 17, 66–82.

Negri, D.H., Brooks, D.H., 1990. Determination of irrigation technology choice. West. J. Agric. Econ. 15, 213–223.

Rosegrant, M.W., Binswanger, H.P., 1994. Markets in tradable water rights: Potential for efficiency gains in developing country water resource allocation. World Development 12, 1613–1625.

Rosegrant, M.W., Scheleyer, R.G., Yadav, S.N., 1995. Water policy for efficient agricultural diversification: Market based approaches. Food Policy 20, 203–223.

Seckler, D., 1996. The new era of water resources management: From dry to wet water savings, IIMI Research Report 1.

University of California, 1988, Associated costs of drainage water reduction, Committee of Consultants on Drainage Water Reduction, Salinity/Drainage Task Force and Water Resources Center.

Zilberman, D., MacDougall, N., Shah, F., 1994. Changes in water allocation mechanisms for California agriculture. Contemporary Econ. Policy 12, 122–133.