Efficient Spatial Allocation of Irrigation Water

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In the presence of conveyance losses, the efficient quantity of water applied falls with distance from the water source, but the amount of water “sent” (including conveyance losses) actually increases with distance from the source, except toward the tail end of the irrigation system. This implies that if marginal cost pricing were implemented, farmers at the middle and lower reaches of the system would have to pay more money for less water received. The model is illustrated and alternative financing schemes compared for an empirically derived demand function for irrigation water.

Key words: benefit taxation, conveyance losses, irrigation, spatial efficiency, water.

Despite massive public investments in irrigation infrastructure, ex post evaluations of irrigation projects in developed and developing countries indicate that actual benefits are substantially below projected levels. Considerable evidence suggests that these low benefits are largely the result of poor on-farm water use efficiencies and rent-seeking activities that result from water charges that are low and often unrelated to water use (Chaudhry, Repetto, Bowen and Young). For example, farmers near the system headworks are said to consume a disproportionate share of irrigation water, while tail farmers are left with scanty and unreliable residual supplies (Reidinger, Wade).

Many governments, faced with increasing political pressure to conserve water and reduce fiscal deficits are considering higher water charges to decrease waste and increase cost recovery from project beneficiaries. There is also increased awareness that low water charges and loosely enforced water rationing guidelines lead to environmental damages and excessive mining of groundwater resources. In general, the problems of water allocation and low user charges contribute to derivative problems in achieving efficiency, equity, fiscal stability, and environmental sustainability.

In order to improve irrigation performance and promote sustainable use of agricultural water, an analytical framework for allocating water and levying water charges is needed (Repetto). Although water financing systems vary widely, traditional concepts of irrigation management imply that farmers be charged uniform prices for equal amounts of water delivered (Bishop and Long, Yoo and Busch, Burness and Quirk). Similarly, evaluations of irrigation systems implicitly assume that equal water allocation is desirable and that head versus tail disparities in water allocation are prima facie evidence of inefficiency and inequity. As shown below, however, irrigation policies that prescribe equal allocations of water to farmers may be inefficient because conveyance costs of water increase with distance from the source.

In this paper, conditions for efficient spatial allocation of irrigation water are specified that take into account conveyance losses caused by seepage, percolation and evaporation. In the following section, a theoretical model is outlined that derives rules for optimal allocation of water supplied to farmers at various distances from a water source. Optimal water prices are developed at each location, and their implications for rents and equity are examined. The subsequent section illustrates the analytical results for an empirically derived water demand function.

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Efficiency Rules: A Framework

Abstracting from the costs of information and enforcement, efficient spatial allocation requires equal marginal value products of water measured at a common source point (O’Mara). The purpose of this section is to derive the equal (gross) marginal product rule and demonstrate its implications for (net) marginal value products and water allocations at the farm level and for determination of optimal system size.

Consider a simplified one-period (one season) model of an irrigation system with water supplied from a point source to a canal. Seasonal variabilities in water supply and storage are not considered. Farmers draw water at various points along the canal located at a variable distance \( y \) from the source, \( y = 0 \) representing the water source, and \( y \) increasing away from it. Let \( Q(y) \) be the gross volume of source water sent to a farmer located at \( y \), and \( q(y) \) be the net water received after conveyance losses. \(^2\) Then the relationship between source water \( Q(y) \) and received water \( q(y) \) is given by

\[
q(y) = Q(y)h(y)
\]

(1)

and

\[
 q(y), Q(y) \geq 0;
\]

\[
 0 \leq h(y) \leq 1; h(0) = 1;
\]

\[
 h'(y) < 0; h''(y) \leq 0,
\]

where \( h(y) \) denotes conveyance efficiency as a function of distance of farmer from source. Conveyance efficiency decreases with distance at an increasing rate. The major sources of conveyance loss are seepage and percolation. Evaporation losses are considered unavoidable and are ignored because, even if the water is stored and conveyed, it will evaporate, although at a different rate. Investments in canal lining and maintenance reduce \( h(y) \).

In this model, we abstract from differential conveyance investments over space and from the choice of conveyance technology. \(^3\) Conveyance losses from the farmgate to the root zone of the crop can be regarded as given such that the yield–water relationship is well defined in terms of water delivered at the farmgate. The model also abstracts from the externality effects of conveyance losses on downstream water quality or on irrigation return flows.

We assume a one-input, one-output production function for received water that holds for each farmer in the system. \(^4\) Output per unit area is then given by a production function \( f(q) \), which has the usual properties that apply to stage II of the neoclassical production function: \( f'(\cdot)>0; f'(\cdot)>0; f''(\cdot)<0 \). The value of marginal product function for received water on land of a uniform quality can be written as

\[
\text{VMP}_r = Pf'(q),
\]

(2)

where \( P \) is the competitive crop price. From (2), \( \partial \text{VMP}_r/\partial q<0 \), a result that follows from the concavity of the production function.

The value of marginal product for received water at the source (\( \text{VMP}_s \) ) can be defined (by assuming the necessary continuity and differentiability properties and using the chain rule) as

\[
\text{VMP}_s(y) = Pf'(Q)h(y) = \text{VMP}_r h(y)
\]

from (1) and (2), and

\[
\partial \text{VMP}_s/\partial y = Pf'(q)h'(y) < 0,
\]

using (1). Condition (3) gives the relationship between the two functions \( \text{VMP}_s \) and \( \text{VMP}_r \), one as a function of water measured at the farm and another as a function of water measured at the source. From (4), the value of marginal product of each unit of source water decreases with distance of the farm from source. Intuitively, as \( y \) increases, more source water must be sent to produce one unit of received water on the farm, leading to a lower marginal value product at the source.

\( \text{VMP}_s \) curves can now be derived as a function of source water for farmers at different locations along the canal. Define \( q^n \) and \( Q^n(y) \) as the amounts of water at which \( \text{VMP}_r = 0 \) and \( \text{VMP}_s(y) = 0 \), respectively. Note that from (2), \( q^n \) is not a function of \( y \). For the farmer at the source \( (y = 0) \), \( q^n = Q^n(0) \), and when \( y > 0 \), \( q^n = Q^n(y)h(y) \), from which we get \( Q^n(0) < Q^n(y) \). In other words, the amount of source water at which \( \text{VMP}_r \) becomes zero increases with distance.

---

\(^2\) The theoretical construct used in this paper parallels that presented in Caswell and Zilberman, although the nature of the problem is different.

\(^3\) For a model that allows for endogenous choice of conveyance technology and investment in on-farm water conservation, see Chakravorty, Hochman, and Zilberman.

\(^4\) The monocropping assumption is retained for model simplicity but can be relaxed easily by specifying a unique production function for each farmer. Differences in farmers’ preferences, skills, and financial endowments can also be accommodated by indexing on the production function.
The above results can be used to draw $VMP_i(y)$ curves at different distances from the source as shown in figure 1. For the farmer located at the source, $VMP_i(0) = VMP_s$ and $q^n = Q^n$. Curves $VMP_i(y_1)$ and $VMP_i(y_2)$ at increasing distances from the source flatten out toward the x-axis, as shown.

The rule for optimal spatial allocation of water is now derived by maximizing consumers’ plus producers’ surplus, subject to a capacity constraint as follows:

$$\text{(5) Maximize} \quad \sum_{i=1}^{n} \int_0^{Q^e} VMP_i(\beta) \, d\beta - \int_{0}^{Z} C'(\theta) \, d\theta,$$

subject to

$$Z = \sum_{i=1}^{n} Q'_i,$$

where $i$ represents the $i$th farmer and $i = 1, 2, \ldots, n$; $Z$ is the total stock of water at source; $C'(Z)$ is the total long-run marginal cost of water; and $\beta$ and $\theta$ are variables of integration. In this discrete optimization problem, each farmer $i$ is associated with a distance $y$. In a continuous model, the same result could be obtained by summing the area under the $VMP_i$ function for each $y$.

The first term in (5) represents the aggregate willingness-to-pay schedule. It is obtained by the horizontal summation of the $VMP_i$ curves for each of the $n$ farmers in the system. However, all the $n$ farmers need not be within the efficient boundary of the system because the allocation rule derived from the above optimization exercise gives an efficient boundary beyond which farmers will not receive any water allocation. Choosing a value of $n$ large enough will ensure the optimal solution (the allocation to some farmers may be zero).

$C'(Z)$ is the sum of the marginal costs of supply and distribution. The marginal cost of water supply includes the per-period equivalent of capital construction costs and costs of operation and maintenance of the head works. The marginal cost of distribution includes construction, operation, and maintenance of the canal as well as pumping and metering costs. The marginal cost of supply (distribution) usually decreases (increases) with capacity (Koenig). The resulting total marginal cost function could be rising or falling with $Z$. We have assumed that the topographical constraints on system expansion are not binding such that economies of scale in the total marginal cost schedule have been fully exploited, giving us a rising marginal cost curve. In an ex ante setting, the long-run marginal cost of water will be determined endogenously by choosing an optimal water stock, $\tilde{Z}$. However, if the model is applied to an existing project with a fixed capacity, $C'(Z)$ will be a short-run marginal cost function.

Homogeneity in demand is assumed for the purposes of allocation of capital costs among consumers. The marginal cost-based pricing rules, however, generally will not be optimal if users are heterogenous or if there are decreasing costs or jointness of supply. In those situations, other pricing rules, such as those based on incremental pricing, might be more relevant (Loehman and Whinston).

From (5), the following lagrangian can be maximized:

$$\text{(6) Maximize} \quad L = \sum_{i=1}^{n} \int_0^{Q^e} VMP_i \, d\beta - \int_{0}^{Z} C'(\theta) \, d\theta - \lambda \left( Z - \sum_{i=1}^{n} Q'_i \right)$$

with respect to the decision variables $Q'_i$ and $Z$, where $\lambda$ is the usual Lagrange multiplier. The first-order conditions are as follows:

$$\text{(7a) } VMP'_i = \lambda, \quad \text{and}$$

$$\text{(7b) } C'(Z) = \lambda.$$
giving

$$VMP'_t = C'(Z),$$

where $\lambda$ represents the shadow price of water at
the source. Equations (7) equate the shadow price
$\lambda$ to the value of marginal product at source
for each farmer and to the long-run marginal cost
at optimal system capacity. They give the equi-
librium condition for optimal allocation of water
under spatial efficiency.

Condition (7b) gives $Z^*$, the optimal stock of
water at source.\(^2\) Let us denote the optimal val-
ues of $q$ and $Q$ (those satisfying condition 7) by
$q^*$ and $Q^*$, respectively. Equation (7a) can be
rewritten as $\lambda = Pf'(q*)h(y)$ and totally differen-
tiated to yield

$$dq^*/dy = -f'(q*)h'(y)/f''(q*)h(y) < 0,$$

which implies that farmers further from the source
receive less received (or net) water. Differenti-
ating (2) and using (8) yields

$$dVMP_t(q*)/dy = Pf'(q*)h(y) > 0.$$ The above discussion can be
summarized as follows:

**Proposition 1.** Optimal allocation implies that
the value of marginal product of water at the
source is equal across farmers. The on-farm value
of marginal product of water is unequal across
farmers and rises with distance from the source.
At the optimum the value of marginal product
at source equals the total long-run marginal cost
of water.

\(^2\) $Z^*$ is optimal given an exogenously fixed conveyance system.
If the conveyance was endogenously chosen, the optimal water stock might be different.

Figure 2 shows the determination of the shadow
price, $\lambda$, at the intersection of the aggregate
marginal benefit and marginal cost curves. The
aggregation of marginal benefit curves is in units
of source water. There is a unique transforma-
tion from units of source water to units of water
received for each farmer through condition (1).
Here, $\lambda$ is equated to individual $VMP_t$ curves
to give the optimal source water allocation $Q^*(0)$
at $y = 0$, and $Q^*(y)$ at any downstream location
$y$. Water received by a farmer at the source $q^*(0)$
is the same as water sent, while an amount $q^*(y)$
$= Q^*(y)h(y)$ is received at any downstream
location $y$ after conveyance losses.

**Spatial Allocation of Source Water**

The optimal allocation of source water for each
farmer can now be determined by differentiating
(1) and substituting (8) to get

$$dQ^*/dy = \left[-f'(q*)h'(y)/f''(q*) - q^*h'(y)/h^2(y)\right]h'(y),$$

where $\varepsilon = -f''(q*)q^*/f'(q*)$ is the absolute value
of the elasticity of marginal product of received
water in crop production. Hence, $dQ^*/dy = 0$
if either $q^* = 0$ (which is trivial) or $\varepsilon = 1$. Evaluating $d^2Q^*/dy^2$ at $\varepsilon = 1$ and cancelling terms yields

$$d^2Q^*/dy^2 \bigg|_{\varepsilon=1} = -(de/dy)q^*h'/h^2 < 0$$

because $de/dy = -f''/f'\cdot dq^*/dy = -f''/f'$

Note: $VMP = $ value of marginal product, $q(y) = $ water received and $Q(y) = $ source water related by
the equation $q(y) = Q(y)h(y)$. $MB = $ marginal benefit, $MC = $ marginal cost, $Z = $ total stock of water,
$P_w = $ effective price of water, $\lambda = $ shadow price of water.
f’(-f’h’/f”h) = h’(y)/h(y) < 0. Therefore, the Q*(y) function has a local maximum at ε = 1. These results can be combined as follows:

PROPOSITION 2. Spatial efficiency implies that the allocation of source water increases with distance from source until the absolute value of elasticity of the marginal product for received water equals unity. Optimal water sent decreases with distance beyond that point.  

Note that the length of the canal L (and hence the irrigated area, because we have assumed constant width) is endogenously determined at the point where farmers do not receive any water allocation, or q*(L) = 0.

Spatial Distribution of Charges and Rents

In this section we derive optimal water prices and spot rents accruing to farmers at each location along the canal. The localized shadow price of received water at a distance y is Pw(y). Efficient allocation requires that the marginal product of received water be equated to its shadow price, or Pw(y) = VMP,(q*) = λ/h(y), using (3) and (7a). At the source, the localized shadow price of water is equal to its system shadow price, since h(0) = 1. In addition, dPw/ dy = -λh’(y)/h^2 > 0, i.e., the localized shadow price of water increases away from the source.

Marginal cost pricing implies that farmers at any location y pay either the system shadow price of water per unit of source water or the localized shadow price per unit of received water. Both satisfy AMQ* = (λ/h(y))q* = Pwq* from (1). Intuitively, both marginal cost pricing solutions are equivalent because the total products from source water and received water are equal [from equation (7)], marginal cost pricing is the same as marginal product pricing. It can be shown, by changing the variable of integration, that the areas under the corresponding value of marginal product curves for source water and received water are equal, or

\[
\int_0^\infty VMP, da = \int_0^\infty VMP, dt,
\]

where α and τ are variables of integration.

At marginal cost prices, spot rents from land R(y) at location y are given by

\[
(10) \quad R(y) = Pf(q^*) - Pwq^*.
\]

Differentiating (10) with respect to y yields

\[
R'(y) = dq^*/dy[Pf'(q^*) - Pw] - q^*dPw/dy < 0
\]

because Pf'(q^*) = Pw; or spot rents decrease away from the source when each farmer is making the optimal decision given his (her) location.

In order to examine the effect of conveyance efficiency on optimal water prices and rents, (10) is differentiated with respect to h(y) to obtain

\[
dR/dh = q^*$\lambda/h^2 > 0,
\]

which indicates that a higher conveyance efficiency increases land rents. Similarly, dPw/ dh = -λ/h^2 < 0 and dPw/ dh^2 = 2λ/h^3 > 0, or increased conveyance efficiency lowers the localized shadow price at an increasing rate. We can thus state the following:

PROPOSITION 3. Under marginal cost pricing, the localized shadow price of water increases with y and decreases with improved conveyance efficiency. Land rents net of water charges decrease with y and increase with improved conveyance efficiency.

These results explain the behavior of farmers in response to any given shadow price of source water λ. All farmers pay the same shadow price per unit of source water. As distance from the source increases, the divergence of VMP, from VMP, increases, so that the effective price per unit of received water becomes increasingly greater than the price per unit of source water.

The marginal cost pricing solution is shown in figure 2. At the source, the localized shadow price Pw(0) = λ, corresponding to the optimal quantity received q*(0), is read off the VMP, curve. For a farmer located at any y, the price for Q*(y) units of source water is λ. The localized shadow price for q*(y) units of received water is given by the VMP, curve, Pw*(y). Under marginal cost pricing, water charges for the downstream farmer could be expressed as λQ*(y) or Pw*(y)q*(y).

Even though marginal cost pricing is efficient, it may still be objectionable on equity grounds, given that rents near the system head are much higher than those at the tail of the system and because farmers in the middle and tail of the system may pay more money for less total water received. Moreover, marginal cost pric-
ing is not necessary on fiscal grounds. Because marginal cost is rising, marginal cost pricing would lead to more than 100% cost recovery. If rationing mechanisms are available to set quantity independently of water charges, then efficient allocation can be achieved without resorting to marginal cost pricing. This facilitates the apparent separability of efficiency and equity and permits a range of possible taxation schemes, including the following:

Rule 1. Proportional benefit taxation. Project beneficiaries could pay in proportion to their individual benefits (Wicksell). This scheme would involve tail farmers receiving less net rents than head farmers, although the benefit distribution would be less skewed than under marginal cost pricing.

Rule 2. Equal rents. The total cost of the system is to be shared among farmer beneficiaries so as to equalize the net rents for all farmers in the system. However, equalizing rents would induce rent-seeking pressures at the boundaries of irrigation systems for system expansion. This is a serious problem of irrigation design in many parts of the world where the target irrigated area is much larger than what the system capacity can efficiently support (Repetto).

Rule 3. Equal charges. Farmers are charged equal amounts for membership in the system. This may provide a pragmatic compromise where the administrative costs and political feasibility of collecting differential water charges is a concern. Equal charges do not achieve equal rents but at least eliminate the “more money for less water” inequity of marginal cost pricing. These alternative financing schemes are illustrated below.

Low versus High Conveyance Losses: An Application

The above model is illustrated by taking conveyance and production functions that closely represent the physical and engineering characteristics of irrigation systems. Representative patterns for the price, quantity, and rent functions are obtained under spatial efficiency for conditions typical to actual irrigation systems.

We construct a VMP, function from a survey of functional water-use yield relationships (Hillel) and from linear programming studies of cash crops in Pakistan (Carruthers and Clark). Hillel approximates a yield-water use curve with two segments—a flat portion with constant marginal product and a downward-sloping portion with decreasing marginal product at higher quantities of water:

\[
VMP_q = \begin{cases} 
1.75 & \text{for } 0 \leq q \leq 0.3 \\
2.66 - 3.0q & \text{for } 0.3 < q < 0.875,
\end{cases}
\]

where \( VMP_q \) and \( q \) are in U.S. cents and meters of water, respectively. The two-part function is more accurate than the uniformly downward-sloping curve usually assumed because, at low quantities of water, on-farm losses through deep percolation and evaporation are proportionately higher, justifying a relatively high but constant marginal product over some range of water use. The above function can be treated as a special case of the more general concave, downward-sloping functions analyzed in the previous sections.

The loss of water from seepage and evaporation is assumed proportional to the volume of water carried in the canal (e.g., Tolley and Hastings). Thus, (1) becomes

\[
q = Q \cdot e^{-aw},
\]

where \( a \) is the conveyance loss coefficient. Values of \( a \) from 0.015–0.02 are commonly found in developing country irrigation systems, where canals are often unlined or have linings of low quality, maintenance is poor, and evapotranspiration is high because of higher ambient temperatures (Bos and Nugteren, Hillel). In the simulations that follow, alternative values for \( a \) of .01 and .02 have been considered.

We assume a hypothetical long-run marginal cost function

\[
C'(Z) = Z \cdot 10^{-6}/30,
\]

where \( C'(\cdot) \) is in cents and \( Z \) is in cubic meters. Although the marginal cost function for water supply can vary with specific irrigation technologies, projects, and geographical region, a linear form is assumed for simplicity. The total width of the system is 1,000 meters (500 meters on each side of the canal) with a uniform farm size of 5 hectares, which means that canal outlets to successive farms are located every 50 meters.

By taking a starting value of \( Z \), we can com-
pute $C'(Z)$ and $\lambda$ from (13) and (7b). Conditions (7a) and (3) give $VMP_y$ and $VMP$, at $y = 0$. From (11), we obtain $q^*$ and $Q^*$. Because $a$ is known, $h(y)$ is known; and, hence, $P_v(y)$, $q^*(y)$, $Q^*(y)$, and $R(y)$ can be directly obtained. This process is continued for each $y$ until the total stock of water $Z$ is exhausted. By iterating on $Z$, we choose the optimal $Z^*$ that maximizes total net benefits as defined by the objective function in (5). The efficient length of the canal $L$ is thus determined endogenously.

**Simulation Results**

Figure 3 and table 1 show the water allocations and charges under alternative conveyance losses and taxation schemes. The results can be summarized as follows:

- **(a)** If conveyance efficiency is low, the aggregate marginal benefit curve shifts up, leading to increased aggregate water use, a higher shadow price of water at source, and a larger irrigated area (see fig. 3, where the efficient length of the system increases from 37.2 k.ms. to 54.5 k.ms.). In this case, reducing the conveyance loss coefficient by one-half leads to expansion of the command area by almost 50%.

- **(b)** Under both high and low conveyance loss regimes, source water allocations increase away from the head and are maximized at about 25 kilometers from the source (see fig. 3). Farmers

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![Graph showing spatial variation of source water and received water for Pakistan](image)

**Figure 3.** Spatial variation of source water and received water for Pakistan

**Table 1.** Effect of Alternative Taxation Schemes on Water Charges and Rents for Pakistan (with high conveyance loss)

<table>
<thead>
<tr>
<th>Water Charges per Farm ($)</th>
<th>Rents per Farm ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Head</td>
</tr>
<tr>
<td>Marginal cost pricing</td>
<td>250.1</td>
</tr>
<tr>
<td>Proportional benefit taxation</td>
<td>247.0</td>
</tr>
<tr>
<td>Equal charges</td>
<td>207.8</td>
</tr>
<tr>
<td>Equal rents</td>
<td>282.2</td>
</tr>
</tbody>
</table>

$^a$ Qmax denotes the location where source water allocations are maximized.

$^b$ L denotes the system boundary.
beyond that point get decreasing amounts of source water. 9

(c) Received water decreases steadily with distance from source (fig. 3). With an increase in conveyance efficiency, the curve for received water flattens, reducing spatial differences in water received. Under high conveyance losses, efficient allocations at the head are approximately double that at the tail.

(d) If farm size is uniform, total water charges under marginal cost pricing are maximized at the point of maximum source water and do not vary substantially over space (table 1). 10 Thus, schemes that charge spatially uniform taxes but ration efficient water allocations (q*) might be an attractive policy option.

(e) When compared to the other taxation schemes discussed, marginal cost pricing is most inequitable, while proportional benefit taxation permits all farmers to collect a higher degree of rents than if there was no taxation (table 1). The scheme that equalizes net rents across locations benefits farmers located at the tail of the system the most while equalizing water charges provides administrative simplicity. 11

Concluding Remarks

In the presence of conveyance losses, efficient spatial allocation of irrigation water implies that the quantity of water applied should fall with distance from the water source. In terms of water produced at the source (before subtracting conveyance losses), the optimal quantity of water allocated to further reaches of the system increases and then decreases with distance from the source.

Under marginal cost pricing, the effective price of water on the farm increases and quasi-rents decrease away from the source. If nonprice instruments for enforcing water allocations are available, then a variety of benefit taxation schemes can be adopted to make the spatial distribution of rents more uniform, the choice of which depends upon the welfare objectives of the irrigation agency. Water charges that equalize net benefits are vertically equitable but could lead to political pressures for expansion of irrigated area beyond its efficient size. Water charges proportional to net benefits allow higher rents towards the tail of the system, relative to marginal cost pricing, and also preserve horizontal equity and mitigate against rent seeking. Equalizing water charges provides a pragmatic compromise by limiting rents from expansion of the project area, avoiding the additional administrative problems of differential pricing and responding to unfairness associated with paying higher water charges for less total water received.

The model also provides an operational basis for estimating irrigation benefits under alternative allocation rules as the aggregate area under the individual demand curves. Existing methods of estimating irrigation project benefits have largely been based on ad hoc estimates of expected increases in revenues or profits, not on theoretical foundations that take into account the specific characteristics of irrigation systems. The model can also be used to address the concerns of irrigation planners regarding the distribution of benefits and costs in various combinations of allocation rules and financing arrangements.

The benefits of efficient spatial management as described here should be weighed against the higher administrative costs that may be incurred. The model can also be expanded by allowing for the endogenous choice of conveyance and on-farm irrigation technology, and private groundwater extraction. Methods for classifying land quality can also be incorporated (e.g., Caswell and Zilberman). Empirical work is needed to determine the shape of the marginal product schedule under varying environmental conditions. In empirical applications, the framework suggested above can also be extended to estimate the expected benefits of irrigation in different (stochastic) rainfall environments.

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References


Bos, M. G., and J. Nugteren. Irrigation Efficiency in Small-


