Achieving Water Use Efficiency in Irrigation Districts

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Abstract: Irrigation districts are challenging places to achieve efficient water use when the ultimate water users do not individually own the units of water they use. The consequence is that irrigators have difficulty seeing value in water unless they are applying it to their crops. This disconnect is a barrier to the establishment of appropriate signals, thereby leading to deficient conservation and lowered profit in most settings. Two policy avenues for improving these circumstances are examined. Primary attention is devoted to devising principles whereby a district's redesigned water rates could foster greater profitability within the district. Such a pricing policy also identifies needed features of a second policy, a marketing strategy in which district-owned water rights are reassigned with a portion retained by the district. Implicit to both policies is careful regard for marginal conveyance losses associated with surface water delivery via canals.

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Introduction

Rising water scarcity in the western United States has spotlighted irrigation districts (IDs) as prospective agents in the continual reallocation of agricultural water to urban use. The advent of western IDs, primarily during the early 1900s, could not have foreseen the eventual need for water reallocation. So it is not surprising that the institutional frameworks upon which hundreds of IDs were built would become ill tuned to contemporary social problems. Western irrigation arose during a period of low western population, and it benefited from a political climate that was not averse to subsidizing irrigation or radically altering the environment in the process. The present-day consequences are that IDs control, by any possible measure one might employ, an enviable portion of western waters (Leshy 1983; Michelsen et al. 1999), and reallocation is commended by the greater growth in nonagricultural water demands vis-à-vis irrigation demand.

The lynchpin of water marketing is that uneven growth in sectoral water demands can find win-win resolution through voluntary bargains prefaced by well-settled property rights. Institutional reforms have worked to clarify property rights in western water, and growing experience with these transactions has created a solid platform for the conduct of water marketing throughout much of the West. Yet IDs are reluctant participants. In areas where IDs as well as individuals hold title to water rights employed in irrigation, such as in Texas's lower Rio Grande valley, early water market activity is dominated by the exchange of privately held water rights while IDs tend to sit on the sidelines (Griffin 1998).

This does not infer that IDs have never engaged in water sales to external parties—only that their participation is well exceeded by their proportion of water rights holdings. The prime reason for this phenomenon is that IDs disconnect water ownership from water use. Except in mutual IDs, members/clients of an ID use water while the district or a higher authority (e.g., the U.S. Bureau of Reclamation) owns the water rights. Individual clients might be willing sellers in a water market, but they do not hold the necessary entitlements.

According to Smith (1989), this is a "compensation problem" in need of a mechanism that would allow IDs to pursue trades with outside parties and then compensate members for their water sacrifices. Smith recommends the business practice of negotiated corporate tender offers to address this need. A basic requirement of this scheme is to prorate ID water rights among district members. Proration is a challenge for IDs, in part because a portion of water use (some conveyance losses) is communally caused. Efficient water marketing of communally determined water use will not be achieved by assigning this water to individuals. A goal of the research reported here is to examine this issue.

The disconnect issue is also associated with other challenges pertaining to ID water use. Lack of title by ID clients encourages members to treat ID waters as common property, with negative implications for water use efficiency. Similarly, should an ID possess storage facilities or storage entitlements capable of addressing interseasonal climate cycles, nonoptimal interseasonal water use can be induced by the common property character of this storage. For example, what motivation does a member have to forego water use during wetter years (so as to build up stored water) if the member cannot claim the fruits of this sacrifice during dry years?

The objectives of this paper are to review the general problems associated with achieving efficient water use within ID institutions and to identify and examine alternative policies for their efficiency-enhancing potential. We begin by considering the institutional setting faced by IDs and outlining appropriate economic goals. Later sections provide a heuristic discussion of simplified ID circumstances in order to frame important elements of a formal theoretical model. The resultant model helps establish two policy mechanisms for bettering water allocation within IDs and discloses details useful for other policies.

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Institutional Structure of IDs

IDs are collectives that were formed to develop and manage water resources for irrigation purposes. Governmentally, they are licensed as political subdivisions by state governments, and they function as a sort of local government (De Young 1983). Members generally elect a board of directors using a member- or land-area-weighted voting scheme, and the board hires a general manager to conduct the daily operations of the district. Depending on size and complexity, the typical ID may have dozens of or few employees.

Because of their status as local governments, IDs are tax exempt and can issue bonds to generate funds for infrastructural installations and maintenance. Both of these powers have the ability to lower water costs for members, and the power to borrow was a crucial rationale for the original creation of many IDs. Because of the sizable amount of capital required to create the original infrastructure or to reliably guarantee the repayment obligations established by the U.S. Bureau of Reclamation, IDs became a favored mechanism for developing irrigation works.

Depending on their enabling rules, IDs may recover some portion of their costs through property taxation, but user fees are generally favored. Many IDs with the power to implement a property tax do not do so, presumably to avoid having to pacify an extensive set of landowners who do not receive ID water. In some districts, however, board members are elected by the general community, thereby exacerbating the disconnect between decision makers and water users.

Due to the nonprofit status of special districts, IDs focus on rate structures that are revenue neutral; that is, they establish rates just sufficient to recover district-incurred costs. When coupled with the disconnect between water ownership and water use, the revenue neutrality goals of IDs form a major obstacle to achieving economic efficiency in water allocation, as they do in most urban utilities (Griffin 2001, 2006). Detailed treatment of this matter is an important aspect of later discussion.

The less common, mutual institutional form of ID, in which members hold correlative shares of a district's water supply, fares better in achieving efficiency (Smith 1989), but the transfer of such shares to outside urban interests must still accommodate third-party effects involving seepage, runoff, and ID conveyance losses (Miller 1987). Moreover, it may still be advantageous to mutual members to have the ID conduct negotiations with outside water buyers in order to eliminate price-dropping competition among members. Although it may be argued that such collusion impairs prospective market efficiency by creating market power, it may also be an efficiency-serving offset to the monosony power often held by urban utilities.

Efficiency Issues

Dynamic economic efficiency—maximizing the net present value (NPV) of water use—is an excellent objective because it is able to address interseasonal as well as intersectoral water allocation. Dynamic efficiency endogenizes the intraseasonal criterion of net benefits maximization, and it also acknowledges nonwater values (such as conservation costs) appropriately. Thus net benefits maximization during a given period is necessary though not sufficient for dynamic efficiency. Physical or water-centric measures of efficiency such as irrigation application efficiency or delivery efficiency are not suitable candidates because they neglect the value of resources that substitute for water in production/consumption activities, and they neglect the value of the goods or satisfaction produced using water (Griffin 2006).

Engineers and other noneconomists usually lack knowledge of or enthusiasm for economic efficiency objectives because they are satisfied with "a system that works." Ultimately, however, it is the summed rewards enabled by all of mankind's natural and human resources that allow for improvements in human welfare. Net benefits and net present values translate into gains usable by people to improve their conditions. This is certainly true for IDs, which exist mainly to enable profitable irrigation. Thus unrealized gains for IDs translate directly into reduced welfare for their service areas. If total profits enabled by an ID are limited due to deficient ID policy, then farmers lose, the agricultural competitiveness of the region is diminished vis-à-vis other production regions, and regional economic activity and employment are likely to be reduced.

What prescriptions does this efficiency goal suggest? The allocative issues here are numerous, for there are many ways in which an ID can impact internal and external water use. Some of the more noteworthy questions are assembled in Fig. 1.

Efficient management can be well examined as the correct selection of water rates within the district. From an optimization perspective, best rates are duals to best quantities, so knowing one reveals the other. The applicable prices include both water prices (per unit volume) and nonwater prices (such as irrigated area charges). When water use can be metered and pricing is the only efficiency-advancing, revenue-neutral policy, rates must include these two parts (to be shown later). In this case, the correct water price spurs efficient water use and the nonwater price balances the ID's budget. Even if institutional rigidities prevent the establishment of efficient rates, knowledge of efficient rates is an important datum for analyzing district decisions. Because departures from efficient rates detract from member profits, benchmarking actual rates against efficient rates is a useful exercise.

Theoretical Depiction

Within a given ID the main intraseasonal, allocative matter is to determine how much water to distribute to each client. The physical attributes of the ID, such as the state of its facilities, are intraseasonally fixed in that major canal maintenance activities will normally await the offseason. Similarly, the ID has water rights and long-term contractual obligations pertaining to its water supply, and these obligations constitute constraints for the current season. Whether or not the district can volumetrically price its deliveries to members is also determinant, depending on whether a metering system is already in place. Given the source(s) of their water supply (reservoirs, snowpack, aquifers, upstream rainfall), IDs may "know" this season's available quantity of water with varying degrees of confidence as the irrigation season commences.

If the ID is metering its water deliveries to individual members, then efficiency prescribes marginal-cost (MC) pricing (Young 1986; Brill et al. 1997), though such advice has received little attention from IDs due to the disconnect. Economic theory further indicates that short-run marginal cost is to be used (Kahn 1988; Turvey 1976). If MC pricing is in force, then all the major consumption, conservation, and cropping decisions made by rational irrigators will represent efficient decisions. Thus the efficiency goal reduces to the determination of optimal prices. While economic theory is clear about the need for MC pricing, specification of MCs varies with circumstances, and the economic lit-

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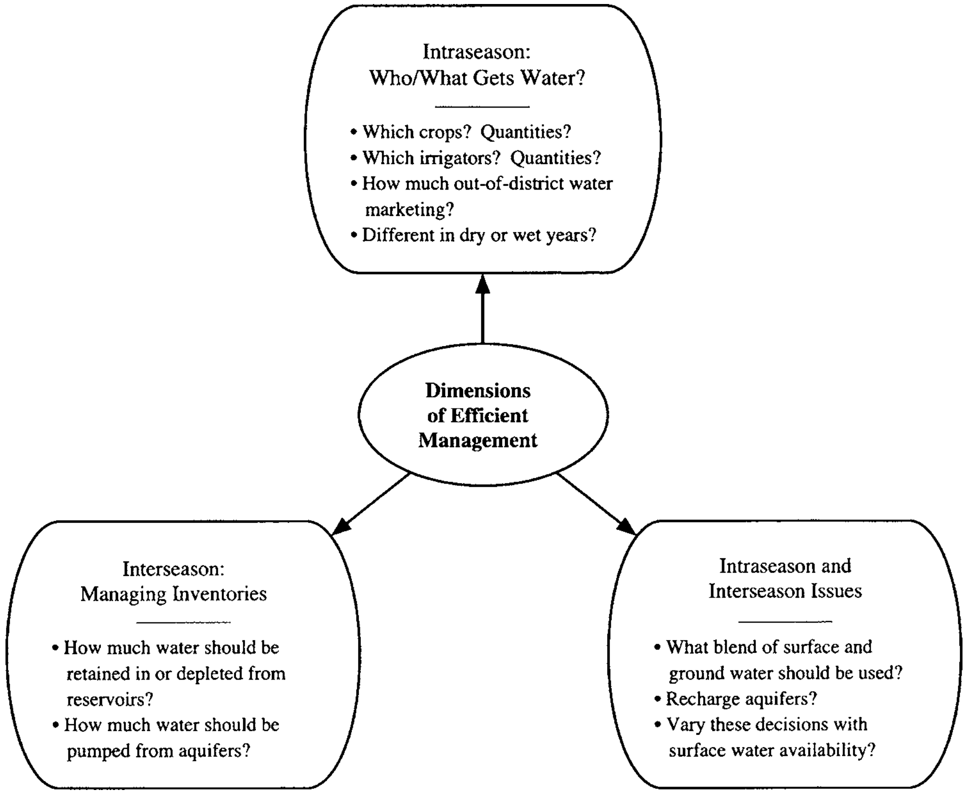

Fig. 1. Allocation issues for irrigation districts

erature has steadily entertained more realistic (and more complex) visions of these circumstances (Herrington 1987; Griffin 2001; Tsur et al. 2004). To build intuition concerning optimal ID rates, consider two distinctive settings: a metered ID having no canals (Pond ID), and a metered ID with a single nonforking canal (Canal ID).

Pond Irrigation District

Imagine first the simple case of an ID pumping water from a river to a pond where all ID members are peripheral to the pond. The pond's purpose is to buffer withdrawals and maintain sufficient hydraulic head to allow each member to take water via gravity flow by opening a gate/valve. "Pond irrigation district" can be used to illustrate some basic tenets of MC pricing applicable to metered circumstances.

Pond ID has three categories of costs to consider: (1) the value of river water before it is pumped to the pond, (2) the cost of lifting river water to the pond, and (3) overhead costs. The latter tend to include the wages of the manager and employees, office and vehicle costs, maintenance costs for the pond and the conveyance to it, and all other costs not captured by (1) or (2). To determine the MC of water, one need only ask which costs change if a member alters his/her water consumption by a cubic meter. Overhead costs will not change and are thus irrelevant to the MC of water this season. Overhead costs are unallocatable in the sense that they cannot be unambiguously assigned to individual members.

The MC price of water should only include the marginal value of river water, the marginal costs of lifting water to the pond, and marginal conveyance losses. With respect to the last item, while some of the water pumped to the pond will be lost in conveyance, either at the pond or in the canal leading to it, the water elevation in the pond is used to serve water to all members. Delivering another cubic meter will require a longer operating time for the pumping plant, but added conveyance losses will be imperceptible since there is almost no increase in wetted canal/pond area or water surface. What conveyance losses do occur are nonmarginal common costs, such as administration costs, and they are not efficiently recovered through a water charge upon members. Only marginal conveyance losses can be included in MC. Similarly, at the conclusion of the irrigation season, some water may remain in the pond or in the conveyance between the river and the pond. This "dead" water is also a common cost, not to enter into the calculation of water's MC.

Based on these observations for the simple conditions faced by Pond ID, the district must employ a rate structure with at least two facets. The first is an MC price upon metered water that should be the same for all members. Profit-maximizing farmers will respond by consuming water up to an amount yielding equal private marginal benefits, thus achieving maximal net benefits for the aggregated community of irrigators.

A second part of the rate structure will ordinarily be necessary to balance Pond ID's budget. Normally, district revenues stemming from its MC water price will be insufficient to cover administration and common water costs, so another rate instrument must make up the difference. If these costs are directly incorporated in water price, the price would exceed MCs and motivate inefficiently low water use by members. Options for the second instrument include membership dues, area fees, and assessments on crop sales. Economic thinking favors second instrument options that are "lump sum," that is, unrelated to water use, so that water use efficiency is not disturbed by the second instrument. Membership dues fare especially well here. While taxes levied on nonusers or government subsidies are potential instruments as

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well, such cost exporting is more likely to promote socially unproductive entry/exit decisions by district members. It is inefficient to encourage the entry of irrigators who require subsidies to be profitable.

Canal Irrigation District

Moving beyond the simplistic conditions of Pond ID, consider the more realistic scenario of Canal ID, which also employs meters. Here, water is pumped from a river into a single canal, gravity flow propels water down the canal, and members' properties are located along the canal. Some members may be located close to the river, near the head of the canal, while others near the tail of the canal may be far from the river. The same cost categories apply as with Pond ID. Again, the MC of water includes the value of river water and the pumping costs of lifting the clients' water into the canal. The complication entering for Canal ID is that the water costs associated with conveyance and evaporation losses are not as nonmarginal or common as they were for Pond ID.

The final canal segment, that portion of the canal between the tailmost district member and the member before, serves only the tailmost member. Therefore all water losses and maintenance costs for this segment are the consequence of the tail member's irrigation. These costs are not commonly caused by any other member. Likewise, the canal segment separating the second tailmost irrigator and the third tailmost irrigator exists only to serve the final two irrigators. Therefore this segment's costs and conveyance losses are common costs for the final two irrigators, and so on. Only system administration costs and the costs of the headmost segment of the canal are common costs for all district members.

The other interesting nuance of Canal ID is the largely nonmarginal nature of conveyance losses, as was the case for Pond ID. On any particular canal segment, conveyance losses are functionally dependent on the water surface area exposed to the air (evaporation) and on the wetted area of the canal (seepage/leaks). Canal geometry and slope, combined with the inevitable low spots of a heterogeneous canal, infer that there can be substantial economies of scale in canal water delivery. Moreover, canal outlets to fields employ gates that cannot access water in the lower portion of the canal. To be useful to the irrigator, there must be adequate hydraulic head at the farm gate, so that the water will flow with sufficient force to operate the receiving lateral canal and in a timely manner. These observations affect the marginal conveyance losses associated with water deliveries.

For a full-time canal that is constantly routing water during the season, an added delivery of one cubic meter will require more than one cubic meter at the canal head, but how much more? The additional flow of water will add slightly to the water height in the canal, thus increasing wetted area and seepage, but the added water also adds hydraulic head, thus increasing canal water velocity and moderating the associated increase in wetted area. Similarly, the opposing sides of a filled canal may approach parallelism, implying that the water-air interface area (and the resulting evaporative losses) are not proportionally increased by a cubic meter increase in deliveries. Therefore, the marginal conveyance losses due to seepage and evaporation tend to be well exceeded by the canal's average variable conveyance losses. One upshot is that MC pricing of water inclusive of marginal conveyance losses still cannot reimburse the district for the total value of water spent as conveyance losses, again suggesting simultaneous use of a second rate instrument.

In the case of a part-time canal, which is periodically filled to serve its clients and then idled until the next cycle, a marginal increase in water delivery may cause the same slight increase in conveyance losses as a full-time canal. Or the additional delivery might be accomplished with a slight increase in the operational cycle of the canal. In the latter case, not even a small increase in wetted area or water surface area would be caused, but the added operating time to deliver another cubic meter could slightly add to conveyance losses along the utilized length of the canal. Because the saturated soils along the canal serve to seal the canal by way of soil particle expansion, and because these soils are already waterlogged, it is again true that marginal conveyance losses should be well exceeded by average conveyance losses. Thus average variable conveyance losses are again an overestimate of marginal conveyance losses.

In light of these considerations, a great deal of Canal ID's conveyance losses are likely to be common costs and are largely independent of water consumption decisions at the margin. As a consequence, much (most?) conveyance loss constitutes a type of fixed cost for each canal segment and would not enter the MC of metered water. It is appropriate, however, to collect these fixed costs from those benefiting from each canal segment, so as to foster efficient entry/exit decisions. As with all common costs, they cannot be unambiguously partitioned across benefiting members, with the exception of the final segment, which serves only the tailmost member. It appears equally practical and efficient to employ any one of many rate instruments for assigning these fixed water costs: dividing them equally or unequally across each segment's beneficiaries while collecting them through membership fees, area charges, or charges based on ability-to-pay measures (such as crop sales).

Thus Canal ID also needs a multipart system of rates if it is to foster efficiency in resource use and preserve its financial integrity. Its metered water charges should certainly incorporate the value of river water, marginal lift costs, and marginal conveyance losses. All other costs are to be collected through a nonwater rate instrument. Unlike Pond ID, however, canal delivery means that Canal ID serves many separate "commons," each associated with different community costs. If districtwide profitability is the goal, the tailmost district member should be responsible for all costs associated with the tailmost canal segment, including its conveyance losses. These costs are not appropriately collected with a per-unit charge on delivered water. The tailmost two members should jointly bear the costs of the second-tailmost segment, and the efficiency criterion does not specify a single division of these costs. Equal or nonequal division might be equally efficient.

Overall, then, economic prescriptions favor increases in both parts of a rate schedule as we proceed downcanal. Water price increases toward the tail due to increasing marginal conveyance costs (Chakravorty and Roumasset 1991). The nonwater price may increase because tailward members are parties in more common costs (more canal segments). When contrasted to present-day practices, it is common for rates to be higher for members receiving relifted water, thereby responding to the extraordinary costs of added pumping plants and energy costs caused by tailward members. To date, however, efficient pricing reflecting differential conveyance losses and canal maintenance costs has not been established. As water scarcity increases, this policy failure will increase in importance.

Pricing Model for Canal ID

To achieve a more formal foundation for investigation, the modeling framework established by Chakravorty, Hochman, and

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Zilberman (CHZ, 1995) can be adapted to examine the efficiency requirements of Canal ID. Their model emphasizes optimal control methods where irrigators are located continuously along a canal. Among other things, the CHZ model investigates optimal canal maintenance and optimal on-farm water conservation investments, which are secondary concerns here. The CHZ model also assumes that all conveyance losses are a fixed proportion of flows, which is a rejected presumption in the arguments above due to dead losses and nonlinearities. The model that follows uses the CHZ notation in a discrete environment where unnecessary features are omitted and some greater generality is achieved otherwise.

Suppose that Canal ID serves J members who are located at particular nodes along the canal ordered from x_1 to x_J; thus x_J is the location of the tailmost member. The district pumps z_0 units of water into the canal at node x_0, and this pumpage is constrained by the ID's water entitlement, $\bar{z}$. Along the jth canal segment, $[x_{j-1}, x_j)$, there are two types of conveyance losses: fixed losses unique to the canal segment and variable losses dependent upon the flow at the beginning of the segment. The fixed losses are denoted by n_j.

For hydrologic reasons developed in the appendix, variable conveyance losses are a multiple of the square root of flow. Denote these variable losses by $2a_j z_{j-1}^{1/2}$, where the a_js are known constants. At x_j the jth irrigator takes q_j units of water per hectare to serve α_j ha, leaving z_j units of water in the canal. Combining these elements, the quantity of water flowing in consecutive segments is linked as follows:

$$z_j = z_{j-1} - n_j - 2a_j z_{j-1}^{1/2} - q_j\alpha_j \quad \text{for } j = 1,2,\ldots,J \tag{1}$$

A production function f maps each irrigator's per hectare water deliveries into units of output per hectare. The value of this output net of nonwater farming costs is $\$p$ per unit. Thus, $pf(q_j)\alpha_j$ denotes the profit accruing to irrigator j except for fees to be paid to the ID. No significant loss of generality occurs due to the use of a single production function for all irrigators and a single output price.

Costs experienced by Canal ID are given by $g(z_0)+\Sigma_{j=1}^{J} M_j + G$ to capture three expenditure categories: (1) pumping costs, (2) canal maintenance costs, and (3) system costs independent of both z_0 and the costs of operating every canal segment.

Maximizing net benefits (total profits) across the district yields the following optimization problem expressed in Lagrangian form:

$$L = \sum_{j=1}^{J} pf(q_j)\alpha_j - g(z_0) - \sum_{j=1}^{J} M_j - G + \lambda_0(\bar{z} - z_0) + \sum_{j=1}^{J} \lambda_j(z_{j-1} - z_j - n_j - 2a_j z_{j-1}^{1/2} - q_j\alpha_j) \tag{2}$$

where the $J+1$-introduced λ terms are the Lagrange multipliers. Presuming an interior solution, the following first-order conditions are obtained for the decision variables q_j, z_0, and z_j.

$$pf'(q_j) = \lambda_j \text{ for all } j = 1,2,\ldots,J \tag{3}$$

$$\left.\begin{aligned} \lambda_1 &= \frac{g'(z_0)+\lambda_0}{1 - a_1 z_0^{-1/2}} \\ \lambda_{j+1} &= \frac{\lambda_j}{1 - a_{j+1} z_j^{-1/2}} \quad \text{for all } j = 1,2,\ldots,J-1 \end{aligned}\right\} \tag{4}$$

Eq. (3) implies that each irrigator should face a metered water price given by the shadow price λ at the irrigator's location. To see this more firmly, consider the individual irrigator j's profit maximization problem when faced with a per-unit price of water given by c_j and the district's nonwater levy upon j, d_j

$$\underset{q_j}{\text{Max}}\ \pi_j = \underset{q_j}{\text{Max}}[pf(q_j)\alpha_j - c_j q_j \alpha_j - d_j]$$

The irrigator's first-order condition is $pf'(q_j)=c_j$, which, together with Eq. (3), implies that c_j should be set to λ_j

$$c_j^* = \lambda_j \tag{5}$$

thus proving the efficiency of MC pricing and indicating that the Lagrange multipliers disclose these marginal costs.

The first equation in Eq. (4) specifies the water price for the headmost irrigator. The two components in the numerator are the district's marginal cost of placing water in the canal, $g'(z_0)$, and the marginal value of the ID's water entitlement constraint, λ_0. If the ID's water entitlement exceeds the system's pumping, then $\lambda_0=0$ in this model, which currently omits excess water demand from other districts or sectors. The denominator of this equation increases the value of water to account for marginal conveyance losses along the first canal segment. Note that no water price adjustments are caused by the fixed conveyance losses, n_1, of canal segment 1.

The last equation in Eq. (4) indicates the increase in water price for irrigators at each successive node downcanal. Note that optimal water prices are equal along the canal's length only if $a_j=0$ for all j (i.e., if there are no variable conveyance losses). The denominator of the fraction in Eq. (4) lies on the (0,1) interval under the very reasonable assumptions that there are some variable conveyance losses, but these losses do not consume the entire flow. Rearranging Eq. (4) and differentiating with respect to z_j, it can be shown that

$$\frac{d\left(\frac{\lambda_{j+1}}{\lambda_j}\right)}{dz_j} < 0$$

That is, decreasing canal flow gives rise to a larger proportional separation between λ_j and λ_{j+1}. In general, then, optimal water prices may rise more rapidly as we get closer to the canal tail. These results differ from the CHZ model results, which exclude fixed canal losses and assume linearity in variable conveyance losses.

Two realistic elements of the model make it unlikely that pricing water according to Eq. (4) will compensate Canal ID for its costs. First, G, the portion of costs unrelated to water pumpage and canal usage, does not enter efficient water rates. These costs tend to be unallocatable in the traditional sense and may be recovered using alternative mechanisms (James and Lee 1971, pp. 527–538). In general, the available options cannot be ranked on the basis of economic efficiency except to observe that the unallocatable costs should not be recouped using metered water fees. Adding to the water prices indicated by Eq. (4) would encourage inefficient underuse of water.

The second element causing difficult cost recovery is summed fixed conveyance losses, $\Sigma_{j=1}^{J} n_j$, as well as summed canal maintenance costs, $\Sigma_{j=1}^{J} M_j$. As noted earlier, fixed conveyance losses are partially allocatable in that n_J is completely attributable to member J; n_{J-1} is jointly attributable to members $J-1$ and J, and so on. Because these costs are partially allocatable, there are incomplete efficiency arguments for assigning these costs. Member

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J receives benefits in the amount of $pf(q_j)\alpha_j$ and causes system costs valued at $\lambda_J(n_J+q_J\alpha_J)+M_J$. If the member's benefits do not exceed these costs, then J should exit the district.

To encourage good entry/exit decisions, J could bear the costs given by $\lambda_J n_J+M_J$ in addition to J's metered water bill, but $\lambda_J n_J+M_J$ should not be included in water price. By extension, members $J-1$ and J could jointly pay $\lambda_{J-1}n_{J-1}+M_{J-1}$. If their collective benefits are insufficient to cover these costs, then district service to both members should be terminated. Collecting this efficiency information yields the following set of pricing rules for the nonwater components (d_js) of rates.

$$\left.\begin{array}{c} d_J \geqslant \lambda_J n_J + M_J \\ d_{J-1} + d_J \geqslant \lambda_J n_J + M_J + \lambda_{J-1} n_{J-1} + M_{J-1} \\ \vdots \\ \sum_{j=1}^{J} d_j \geqslant \sum_{j=1}^{J} \lambda_j n_j + \sum_{j=1}^{J} M_j \end{array}\right\} \quad (6)$$

Operationalizing the requirements of Eq. (6) is difficult because of the variety of cost shares that conceivably might be applied and because the district lacks information about the specific profitability of each irrigator. If, after paying his/her metered water bill, any member can make an additional positive contribution toward defraying the costs of any fixed conveyance losses and overhead costs that are unallocatable, then a specific cost-sharing arrangement might mistakenly cause the irrigator's exit, thereby harming efficiency. For example, the district could adopt an allocation rule specifying that all irrigators benefiting from a canal segment should share equally the fixed conveyance losses and maintenance costs of the segment. This would imply that member J pay, in addition to a bill for metered water deliveries, $\lambda_J n_J+M_J+(\lambda_{J-1}n_{J-1}+M_{J-1})/2+(\lambda_{J-2}n_{J-2}+M_{J-2})/3+\ldots+(\lambda_1 n_1+M_1)/J$.

Such a rule might inefficiently induce member J's exit as a district client even if J's net revenues are more than sufficient to pay J's allocatable costs of $\lambda_J(n_J+q_J\alpha_J)+M_J$. In the latter case, continued service to J is economically efficient as long as it is efficient to serve $J-1$, so a cost allocation rule is needed that will extract some financial contribution from J without urging J's exit from the district. Hence, acceptable nonwater components of rates are likely to exist, yet they are underdetermined by the economic efficiency goal. Note that efficient nonwater rates tend to increase downcanal, but this tendency is not conclusive.

Interseason and Regional Efficiency

In the preceding model, optimal water prices depend on three factors: the marginal cost of pumping water into the canal, the shadow price of water at the canal head, and marginal conveyance losses. In that model, water only has value to the district if it is used in the district this season, thereby neglecting options to transfer low-value water to future irrigation seasons or to other users. If such opportunities are available to the district, then the district can increase the net present value of membership profits by expanding elements observed by the shadow price of water. This conclusion can be demonstrated by a suitable extension in the prior model, but the primary points are easily recognized.

If the ID has higher than normal water supplies in the current season, then the model solution of the previous section may indicate that $\lambda_0=0$ because water is in surplus for the district. However, if the district possesses storage facilities capable of holding some water until the next growing season, then dynamic economic efficiency can be enhanced by revising λ_0 upward. In available storage situations where irrigators are risk neutral, current season λ_0 should be bounded below by water's expected value in future seasons discounted by the discount rate and, if applicable, marginal storage losses. For example, if the expected value of λ_0 is \$20 per million liters for the forthcoming year, the discount rate is 5%, and 25% of additionally stored water will be marginally lost to leakage and evaporation, then current-year λ_0 should be at least \$14.29 ($=0.75\cdot 20/1.05$).

In terms of regional efficiency, the ID pricing plan should acknowledge profitable options to benefit from water market transactions. If the ID operates in a region where excess water demand exists outside the district, then λ_0 should be bounded below by the current marginal value of water to external water users. Thus, if the district can lease river water for a marginal price of \$30 per million liters to external parties, then the current year λ_0 should be at least \$30.

Two Prospective Policies

Eqs. (3) and (4) indicate that efficient water prices to all irrigators are dependent upon λ_0, which is the opportunity cost of raw water prior to being pumped into a district's canals. In accordance with the prior section, λ_0 is bounded below by properly adjusted regional and future water values. Failure to include these opportunity costs in metered water price detracts from the profitability of water use for IDs. Inclusion of λ_0 in water prices motivates efficient cropping decisions, induces economic levels of water conservation, frees optimal amounts of water for external marketing, and lowers the nonwater prices IDs must employ to offset total costs. If λ_0 is large enough, possibly due to heavy external water demand from urban centers, then it is conceivable that the district would incur a profit without using any nonwater charges for its members. In this case, the optimal nonwater part of rates becomes negative. While IDs do not have policies in place for distributing such "dividends" to members, the eventual need for such policies is evident from the growing discrepancies between urban water values and ID water values.

To date, IDs have tended to digest new water revenues from outside sources by undertaking new expenditures and investments. This is an economically wasteful, cannibalizing practice unless the new projects have benefits in excess of costs and are cost effective. One interesting example of increasing relevance pertains to contract situations in which urban authorities finance an ID's conveyance-enhancing project (e.g., canal lining) in return for the conserved/salvaged water. Such alliances often have benefits in excess of costs for both parties, but they are not cost-effective projects unless the marginal value of raw water to irrigators is greater than the effective price of the conserved water. Under normal conditions, it is cheaper for cities and/or more profitable for irrigators to simply transfer water rights without engaging the conservation project. Again, such transfers require that the ID have an internal means of distributing external water right sales revenues so as to compensate and reward the farmers sacrificing this water. That is, the disconnect issue must be corrected.

Application of the pricing rules established by conditions in Eqs. (3) and (4) is one policy mechanism for solving the disconnect problem. Efficient prices will lower the quantity of water demanded by ID members, and the "excess supply" of water held by the district can be marketed. Under this policy the rewards of water conservation are received by ID members in the form of

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lowered nonwater fees. Here, the nonwater rate endogenizes the dividend to be received by members. Brill, Hochman, and Zilberman (1997) refer to this type of policy as "passive trading" since it accomplishes reallocation without necessitating actual trading of water rights by individual ID members. Instead, the appropriate prices encourage reallocation.

A second, "active trading" policy option capable of performing the same function is to deed or "earmark" ID water rights to its members. The first step in this process is to vest each irrigator with his/her normal allotment of water and to allow irrigators to market their water both internally (to other members) and externally. These assignments would ideally include marginal conveyance losses. Therefore, employing prior notation, member j's ordinary use of $q_j\alpha_j$ units of water implies that j should be vested with $q_j\alpha_j\Pi_{i=1}^{j}(1-a_iz_i^{-1/2})^{-1}$ units of water. Member j would then be entitled to consume this water, bank it in the district's storage facilities, or market it.

Any deeded water consumed in district, either by j or a trading partner, would be subject to the pricing rules expressed in Eqs. (3) and (4), except that the λ_0 term is dropped from the first equation of Eq. (4). λ_0 is dropped because the conservation and trading opportunities now experienced by members allow them to experience the opportunity cost of raw water; including λ_0 in the price would constitute double counting, given that the members own this water. To preserve the financial integrity of the district, each member should continue to pay applicable nonwater charges without change (regardless of banking and marketing actions), and the district would retain full ownership of all fixed conveyance losses, $\Sigma_{j=1}^{J}n_j$.

To account for marginal conveyance losses, any trade policy will obviously have to face the different exchange rates embedded in the marginal conveyance loss multiplier

$$R_j = \prod_{i=1}^{j} \frac{1}{1 - a_i z_i^{-1/2}} \tag{7}$$

Depending on the location of one's trading partner, obvious adjustments based on Eq. (7) will be necessary since this relationship presumes only out-of-district trading partners. Better exit decisions and scheduling of canal closures could also be fostered by allocating fixed conveyance losses to each of the J commons they serve (rather than to the ID), if the resulting rights distrbution is sufficiently understood to motivate coalition building among members. For example, if member J is vested with $n_J+q_J\alpha_J\Pi_{i=1}^{J}(1-a_iz_i^{-1/2})^{-1}$, member $J-1$ is vested with $q_{J-1}\alpha_{J-1}\Pi_{i=1}^{J-1}(1-a_iz_i^{-1/2})^{-1}$, and members $J-1$ and J are jointly vested with n_{J-1}; then they might efficiently enter into a permanent arrangement with an outside party whereby both members cease to irrigate and turn all their water entitlements over to the outside party. (The two members or the new owner must continue to pay their share of the ID's administrative costs.)

Such contractual opportunities have the potential to encourage efficient exits from irrigation without spatially fracturing the ID's membership. As another opportunity, if the ID retains ownership of all fixed conveyance losses, then it too can be party to multimember water contracts (e.g., joining members $J-1$ and J) with the potential additional benefit of resolving terms for absolving $J-1$'s and J's future nonwater payments to the district. Of course, for headward canal segments, such proposals become less tenable because of the large number of co-owners of n_j.

Both of these policies are capable of solving the disconnect issue because they provide inducements for more profitable behavior by irrigators. Both policies are also "price guided" because they employ price signals to achieve efficiency. In one case the prices are administered by the ID; in the other, the crucial price is market produced.

Conclusions

Achieving efficient water use in the presence of common property institutions such as irrigation districts presents an important challenge. The main problem is not that these districts exist or use water for irrigation, but rather that their operational rules are not designed for the modern era of water scarcity in which IDs should interact with nonmembers as well as members. The disconnect issue means that members lack individual entitlements, thereby implying that they have incomplete incentives for behaving in an efficient manner. Moreover, the disconnect harms overall profitability within districts. New policies and insights are needed to obtain better, more profitable service within IDs. Such policies hold promise for broader society as well, since it is important to use limited water resources in the most socially important ways.

Thoughtful inspection of these issues must combine economic precepts with a hydrologically informed understanding of ID operations. The central model explored here maximizes summed, in-district profits subject to a realistic yet generalized depiction of water transport and loss. A specific functional form for the dependence of conveyance losses on water flows is determined by applying basic hydrology. By directly incorporating the common costs intrinsic to ID overhead costs and conveyance losses, interdependencies among ID members are successfully recognized in the model.

Results identify a pricing scheme capable of advancing the collective interests of ID members. The water price elements of this strategy are well specified and provide insights that have not been achieved previously. The nonwater elements of the rate structure necessary to achieve a balanced budget are underidentified in the sense that many different divisions of common costs are conceivably compatible with efficiency goals. However, there are certain patterns and expectations of the nonwater rate elements if efficiency is to be advanced; a random or equal partitioning of common costs need not improve total profits.

Hence, one policy to achieve efficiency in ID water use is to establish the "correct" rates. Contrasting "real-world" rates to efficient rates identifies multiple recommendations. Primary problems for real-world prices are the omission of shadow prices from water price elements and the presence of level water prices along a canal system's length. Other differences are also apparent.

A second policy option for solving the disconnect is also investigated here. Efficient rates perform well because they signal social values to individual agents. Another policy avenue is to place valued resources in the hands of these agents and allow market-based signaling by allowing internal and external transferability. Due to the complications posed by marginal conveyance losses, prospective exchanges should acknowledge appropriate exchange rates. Yet the entirety of the disconnect cannot be resolved so easily. Nonmarginal conveyance losses and canal maintenance costs are not generally allocatable to a single member, so these shared costs limit the prospective achievements of a fully decentralized market. Options for confronting this matter include different assignments of nonmarginal conveyance losses and maintenance responsibilities to various member groups, including, in the limit, all ID members.

Despite the hurdles faced by these two policies, they represent helpful steps in understanding the efficiency of water use—both

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in and out of irrigation districts. Furthermore, their study contributes additional insights useful for framing other policies, such as regulatory policy.

Appendix: Marginal Conveyance Loss

Water pumped into a canal may be lost to seepage, evaporation, or dead water losses. Dead water losses, especially water remaining in canals at the season's conclusion, are fixed forms of conveyance loss, while seepage and evaporation are variable forms of conveyance losses and are functionally related to canal properties, climate, and canal flows. Dead water losses do not enter the calculation of marginal conveyance loss and therefore do not affect the marginal cost of delivered water, and hence the determination of marginal conveyance loss should focus upon the impact of changed water deliveries on seepage and evaporation.

Determining Functional Form

Consider a homogeneous canal segment that tapers toward its tail because conveyance losses steadily lower canal contents. The segment delivers W cubic meters of water at the constant rate Q (m^3/day) over a given length of time T (days). Definitionally

$$W = Q \cdot T \tag{8}$$

If the average velocity of water in the segment is V (meters/day) and the average cross-sectional area of the segment is A (m^2), then

$$Q = V \cdot A \tag{9}$$

According to Swanee, Mishra, and Chahar (SMC, 2000), trapezoidal canals dominate rectangular and triangular canals with respect to seepage loss minimization. General dimensions for a trapezoidal canal are illustrated in Fig. 2.

For trapezoidal canal segments, $A = \frac{1}{2}y(b+r) = \frac{1}{2}y(b+b+2ym) = by + my^2$.

The results of the SMC study are that seepage-minimizing canal parameters are $b = 1.646y^2$ and $m = 0.598$. Substituting these values yields $A = 1.646y^2 + 0.598y^2 = 2.244y^2$.

Placing this result in Eq. (9) and solving for y, we obtain

$$y = \left(\frac{Q}{2.244V}\right)^{1/2} \tag{10}$$

According to SMC, seepage losses per unit of canal length (m^2/day) are given by

$$q_s = kyF \tag{11}$$

where k is the hydraulic conductivity of the canal's lining (m/day) and F is the seepage function (dimensionless). SMC provides estimates of $F(b/y, m)$ and, because optimal b/y and m have been adopted from SMC here, F can be taken to be a constant. Total seepage losses across a segment of length L (meters) are $W_s = Q_s T = q_s LT$, where Q_s denotes the rate of seepage (m^3/day). Combining Eqs. (10) and (11) and collecting constants into c_s

$$q_s = c_s Q^{1/2} \tag{12}$$

which provides the important result that seepage losses vary with the square root of canal deliveries.

Similarly, it can be presumed that evaporative losses per unit of canal length, q_e (m^2/day), are proportional to the surface width

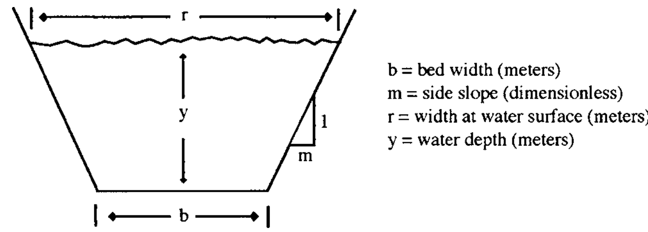

Fig. 2. Canal cross section

of the canal, $q_e = k \cdot r$. Working to replace r with the known constants m and b/y and thereby determine the functional dependence of q_e on total water deliveries

$$q_e = k(b + 2ym) = k\frac{b}{y}\left(y + \frac{y}{b}2ym\right) = k\frac{b}{y}\left(1 + \frac{y}{b}2m\right)y$$

$$= k\frac{b}{y}\left(1 + \frac{y}{b}2m\right)(2.244V)^{-1/2}Q^{1/2} = c_e Q^{1/2} \tag{13}$$

where c_e collects all of the constant terms. Thus evaporation, like seepage, is dependent on the square root of canal water deliveries.

Additional Observations

Using prior notation and definitions and using the subscript *se* to denote summed seepage and evaporation, we first combine Eqs. (12) and (13) as follows: $q_{se} = c_{se}Q^{1/2}$. Then

$$W_{se} = Q_{se}T = q_{se}LT = c_{se}Q^{1/2}LT$$

and thus

$$W_{se} = c_{se}LT^{1/2}W^{1/2} \quad \text{[from Eq. (8)]}$$

$$W_{se} = CW^{1/2} \tag{14}$$

where C collects the constant terms $c_{se}LT^{1/2}$.

Marginal conveyance losses are then

$$\frac{dW_{se}}{dW} = \frac{C}{2W^{1/2}} \tag{15}$$

which obviously rises with C and falls with deliveries, W. Because the latter equation presumes that operating time T is fixed, the change in water deliveries underlying Eq. (15) is accomplished by changing the rate (and height) of canal flow.

The relevance of C to marginal conveyance losses implies that we would like to have a method of calculating it from available data. Setting aside dead water canal losses, conveyance efficiency is given by

$$E = \frac{W}{W + W_{se}} = \frac{W}{W + CW^{1/2}} \tag{16}$$

Having an estimate of E and knowing the amount of canal segment inflow ($W + W_{se}$) allows W to be calculated, which subsequently allows C to be estimated using Eq. (16).

Eq. (16) provides a base method of obtaining C for a canal segment providing segment inflow and E (or outflow) are known. A problem with using Eq. (16) to obtain C across multiple segments or an entire canal system is that there are intermediate water deliveries; all the deliveries do not occur at the terminus. Solving Eq. (16) for C for a single segment results in

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$$C = \left(\frac{1}{E} - 1\right) W^{1/2} \tag{17}$$

To generate some idea of the error Eq. (17) might introduce if it was used for a canal system, assume a canal system without forks making equal deliveries to each of J nodes. Under these conditions, Eq. (16) is altered to

$$E = \frac{W}{W + CW^{1/2}\left(1 + \left(\frac{J-1}{J}\right)^{1/2} + \left(\frac{J-2}{J}\right)^{1/2} + \ldots + \left(\frac{1}{J}\right)^{1/2}\right)}$$

which embeds a generalized Riemann zeta function. Solving for C

$$C = \frac{\left(\frac{1}{E} - 1\right) W^{1/2}}{1 + \left(\frac{J-1}{J}\right)^{1/2} + \left(\frac{J-2}{2}\right)^{1/2} + \ldots + \left(\frac{1}{J}\right)^{1/2}} \tag{18}$$

The denominator of Eq. (18) is larger than unity, indicating that use of Eq. (17) to estimate C would result in an overestimate. Simple linear regression of the denominator of Eq. (18) as a function of J yields a perfect fit as long as $J > 1$. Using the regressed result, we have

$$C = \frac{\left(\frac{1}{E} - 1\right) W^{1/2}}{0.438 + 0.667J} \quad \forall\, J \geqslant 2 \tag{19}$$

More refined examinations of this type, exploring forked canal systems and unequal or efficient diversions, are undoubtedly possible, so many variants of these pursuits and Eq. (18) are conceivable.

If analysts employ a canal system's average conveyance loss to approximate marginal conveyance loss, how much error is introduced? To investigate this question, let us first set aside dead water conveyance losses. Dead water losses contribute to average conveyance losses without influencing marginal conveyance losses. Using Eq. (14) to obtain the ratio of marginal conveyance losses to average ones

$$\frac{\text{marg}_{se}}{\text{ave}_{se}} = \frac{\frac{1}{2}CW^{-1/2}}{\frac{CW^{1/2}}{W + CW^{1/2}}} = \frac{W^{1/2} + C}{2W^{1/2}} = \frac{1}{2}\left(1 + \frac{C}{W^{1/2}}\right) = \frac{1}{2}\left(1 + \frac{W_{se}}{W}\right)$$

Therefore, when the dead water losses are omitted that further increase average conveyance losses relative to marginal conveyance losses

$$\frac{\text{marg}_{se}}{\text{ave}_{se}} = \begin{cases} <1 & \text{when} \quad W_{se} < W \quad (E > 50\,\%) \\ 1 & \text{when} \quad W_{se} = W \quad (E = 50\,\%) \\ >1 & \text{when} \quad W_{se} > W \quad (E < 50\,\%) \end{cases} \tag{20}$$

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