Economic Aspects of Irrigation Water Pricing

Yacov Tsur

Abstract: Worldwide, irrigation water consumes the bulk of renewable fresh water resources. As water demand increases with rising living standards and population growth, and as prospects for water diversion (extraction) are limited in some regions and nonexistent in others, the course of water policy left open is to increase efficiency of water use. This requires taking account of the full cost of water and the way to achieve this goal inevitably leads to some form of water pricing. Yet, water policy makers and economists are far from agreeing on what constitutes the "right" price of water in any given circumstance and how this price is to be charged. This paper aims to clarify and reconcile some of the conflicting views by discussing the economic aspects underlying irrigation water pricing and their implementation in practice.

Résumé : À l'échelle mondiale, l'eau d'irrigation consomme la majorité des ressources d'eau douce renouvelables. Au fur et à mesure que la demande en eau s'accroît proportionnellement à l'augmentation du niveau de vie et la croissance de la population, et étant donné que les perspectives de détournement des cours d'eau (extraction) sont limitées dans certaines régions et inexistantes dans d'autres, il ne reste plus qu'à intégrer à la politique de l'eau des mécanismes en vue de rendre l'utilisation de l'eau plus efficace. Nous devons alors prendre en considération le coût total de l'eau et, pour atteindre un tel objectif, il faut inévitablement en arriver à une forme quelconque de tarification de l'eau. Pourtant, les décideurs et les économistes sont loin de s'entendre sur ce qui constituerait le « juste prix » de l'eau, dans tout contexte donné, et sur la façon de prélever ce prix. La présente communication cherche à tirer au clair et à réconcilier certains des points de vue divergents en abordant les aspects économiques qui sous-tendent la tarification de l'eau d'irrigation et sa mise en œuvre dans la pratique.

Introduction

Population growth and rising living standards have led to a rapid increase in the demand for water. As the annually renewable fresh water available in any particular location is on average constant and water conveyance is an expensive operation, water has become scarce in many parts of the world. Adding the prevalence of deteriorating water quality and the increased awareness for water-related environmental and social problems explains why water resource management has become a critical policy issue in many parts of the world.

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Submitted July 2004; accepted December 2004. Written comments on this paper will be accepted until September 2005.

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Worldwide, irrigation water consumes the bulk of the available renewable fresh water resources (over 70 percent). Irrigated agriculture is practiced on about 18 percent of total cultivable land (267 million hectares of irrigated land in 1997, of which 75 percent are in developing countries) but produces 40 percent of agricultural output (Gleick, 2000; World Bank, 2001). Irrigated area is expected to expand at an annual rate of about one percent during the next three to four decades (Gleick, 2000; FAO, 2000). The irrigation sector, which already consumes a large share of global water, will thus continue to increase its demand for water in the foreseeable future.

Meeting the water demand of a growing population at the existing level of per capita water use requires increasing water withdrawal. Yet the cost of water supply rises each time a new dam is built and concerns over adverse environmental and social effects of large water projects are mounting. These considerations limit prospects to increase water diversion and extraction. The course of action left open, then, is to do more with the available water (i.e., to increase the efficiency of water use). Achieving this goal requires taking account of the full cost of water, which beyond the engineering cost of water extraction (diversion) and conveyance includes also the alternative cost associated with the different uses of water at present and in the future. One way to achieve this goal entails water pricing.

The wide variety of irrigation water pricing observed worldwide (see the survey by Johansson *et al.*, 2002) reflects variability in physical conditions (climate, soil properties and water scarcity), in culture and institutional setting, and in the criteria that underlie water allocation. For example, economic efficiency (loosely defined as the allocation that generates the largest economic surplus that can be obtained from the available quantity of the resource) is a common criterion used in the allocation of scarce resources. However, the efficiency criterion deals with the aggregate size of the economic surplus but pays no attention to how the surplus is distributed among water users. Since water resources are often perceived as an essential, common resource whose use should benefit the public at large, efficiency criteria alone may not always be sufficient to guide water pricing policies.

Water prices serve as signals of the value of the scarce resource and induce users of various sectors to utilize water accordingly. Yet, it is not always clear what is the "right" price and how pricing is to be implemented. For example, should water prices account for the fixed cost of water supply (the cost-recovery issue)? Should income distribution criteria be considered? How do existing water institutions affect the choice of pricing method and water rates? What are the implications of asymmetry of information between water pricing agencies and water users? How should water of different quality be priced? How should the well-being of future generations be reflected in current water prices? These are some of the questions that will concern us in this paper.

We examine these issues within a conceptual framework, which consists of a set of rules and principles that give rise to basic guidelines for pricing irrigation water. Here we summarize and extend previous work on this topic, in which real-world cases from developing countries are studied (Tsur *et al.*, 2004a; 2004b). Our focus is on demand management of water resources (i.e., how to make the best out of a given (prespecified) water quantity). How to allocate the available water resources between different sectors (irrigation, households, industry, environment) is an important problem that will not concern us here (there is a large literature on this topic; Dinar (2000)). Moreover, we consider irrigation water pricing; the pricing of domestic and industrial water, which is similar in some respects but also has noticeable differences, is beyond the present scope.

Efficient Pricing

The Derived Demand for Irrigation Water

We begin with the simple case of a farmer who grows m crops with a single input − water. Let $y_j = f_j(q_j)$ represent crop j yield-water response function, where y_j is yield, q_j is water input and $f_j(q)$ is an increasing and strictly concave production function, j=1,2,…,m. With p_j denoting price for crop j, j=1,2,…,m, and w water price, the profit $\pi = \sum_{j=1}^{m} [p_j f_j(q_j) - wq_j]$ and the

necessary conditions for profit maximization are $\partial\pi/\partial q_j = 0$ for all j, or $f_j'(q_j(w)) = w/p \Rightarrow q_j(w) = f_j'^{-1}(w/p)$, j = 1,2,…,m, where $q_j(w)$ is crop j water input at water price w. The farmer's water demand is thus

$$q(w) = \sum_{j=1}^{m} q_j(w) = \sum_{j=1}^{m} f'^{-1}_j (w/p) \qquad (1)$$

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Extension to the case of n farmers and m crops is straightforward. Let $f_{ij}(q)$ denote the water production function of crop j by farmer i. Then,

$$q_i(w) = \sum_{j=1}^{m} f'^{-1}_{ij}(w/p)$$

is farmer i's water demand and the demand of all farmers is

$$q(w) = \sum_{i=1}^{n} q_i(w) = \sum_{i=1}^{n}\sum_{j=1}^{m} f'^{-1}_{ij}(w/p) \qquad (2)$$

Another approach to obtain the derived demand for irrigation water is as follows. Suppose that water is provided free of charge but is constrained at the level x. How much are farmers willing to pay to relax the water constraint by Δ units, (i.e., to $x+\Delta$)? If water is used up to the constraint x, the revenue is $pf(x)$ and the additional quantity Δ generates the added revenue $p[f(x+\Delta)-f(x)]$. Farmers will thus be willing to pay at most $p[f(x+\Delta)-f(x)]$ for the additional Δ m^3 of water, i.e., the price $\frac{p[f(x+\Delta)-f(x)]}{\Delta}$. For small enough Δ this price equals $pf'(x)$. Thus, $pf'(x)$ is the maximal price the farmer is willing to pay to relax the water constraint by one (marginal) unit. It is also called the *shadow price* of the water constraint or simply the shadow price of water. Notice that this shadow price varies with the level of the constraint and will be positive only when the constraint is binding. Notice also that $pf'(x)$ was shown above to equal the inverse derived demand for water.

This approach is useful because it easily extends to situations involving additional inputs and constraints. Consider the case where crop j production requires inputs q_j, z_j and b_j, j=1,2,…,m, where q_j is water input, $z_j = (z_{j1},z_{j2},\ldots,z_{jK})$ represents K purchased inputs (e.g., fertilizer, pesticide, machine days) that can be purchased at an unlimited quantity at the market prices $r = (r_1,r_2,\ldots,r_K)$, and $b_j = (b_{j1},b_{j2},\ldots,b_{jL})$ represents L primary inputs (e.g., land, family labour) available at limited quantities $B = (B_1,B_2,\ldots,B_L)$. Let the production function for crop j be denoted by $f_j(q_j,z_j,b_j)$. The input decisions of profit-maximizing, price-taking farmers are the input allocations $(q_1,q_2,\ldots,q_m)$, $(z_1,z_2,\ldots,z_m)$ and $(b_1,b_2,\ldots,b_m)$ that solve

$$\pi(x,B,p,r) = Max \sum_{j=1}^{m}\left\{p_j f_j(q_j,z_j,b_j) - \sum_{k=1}^{K} r_k z_{jk}\right\}$$

subject to

$$\sum_{j=1}^{m} q_j \le x \qquad (3)$$

$$\sum_{j=1}^{m} b_{jl} \le B_l,\ l = 1,2,\ldots,L$$

and possibly other feasibility constraints (e.g., non-negativity of some variables). In solving this problem one forms the Lagrangean

$$\Im = \sum_{j=1}^{m}\left\{p_j f_j(q_j,z_j,b_j) - \sum_{k=1}^{K} r_k z_{jk}\right\} + \lambda\left\{x - \sum_{j=1}^{m} q_j\right\}$$
$$+ \sum_{l=1}^{L}\mu_l\left\{B_l - \sum_{j=1}^{m} b_{jl}\right\} + \text{(other constraints times their}$$

multipliers). The multiplier of the water constraint, λ, evaluated at the optimum, represents the shadow price of water, which when calculated for all feasible water levels x, constitutes the inverse derived demand for water.

For nonlinear production functions the above constrained optimization problem constitutes a non-linear programming (NLP) problem. When the production functions f_j admit a Leontief (fix coefficient) form, the constrained optimization reduces to a Linear Programming (LP) problem. In either case the output of the optimization exercise includes the dual multiplier for each constraint. The dual multiplier of the water constraint, λ, is the shadow price of water. By solving the input allocation problem for different levels of the water constraint x and recording the shadow price λ that corresponds to each x level, one obtains a correspondence between x and the shadow price of water λ, which constitutes the (inverse) derived demand for water.

Seasonality

Suppose that both water constraints and crop yield depend on irrigation input at S sub-periods during a year, s =1,2,…,S (e.g., S = 4 for seasonal constraints and S = 12 for monthly constraints). Then q_{js}, j=1,2,…,m, represent crop j water input during sub-period s and x_s is the water availability constraint for sub-period s, s=1,2,…,S. The input allocation problem becomes:

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$$\pi(x_1,x_2,\ldots,x_S,B,p,r) = Max \sum_{j=1}^{m}\left\{p_j f_j(q_{j1},q_{j2},\ldots q_{jS},z_j,b_j) - \sum_{k=1}^{K} r_k z_{jk}\right\}$$

subject to

$$\sum_{j=1}^{m} q_{js} \le x_s,\ s = 1,2,\ldots,S \text{ (sub-period water constraints)} \quad (4)$$

$$\sum_{j=1}^{m} b_{jl} \le B_l,\ l = 1,2,\ldots,L$$

and possibly other feasibility constraints. The shadow price (Lagrange multiplier) λ_s of season s water constraint, evaluated at the optimal allocation, constitutes the value of marginal productivity of irrigation water at sub-period s. By changing the constraint level x_s and calculating the corresponding shadow price λ_s we obtain a correspondence between x_s and λ_s, which constitutes sub-period s derived demand for irrigation water.

Water Quality

The discussion so far assumes that water is a homogenous input of uniform quality. Irrigation water is often derived from different sources, but as long as water productivity is the same across sources, water from different sources are considered the same input and the multiple sources affect the cost of supply (see below). If, however, water derived from different sources is of different quality — measured by electric conductivity (EC), parts per million (PPM), or biological oxygen demand (BOD) — and water quality affects yield production, then water of different quality should be considered as different inputs. A different derived demand is then applied to each type of water.

Suppose there are H sources of water of different quality with capacity constraints x_h, $h = 1,2,\ldots,H$. Let $f_j(q_{j1},q_{j2},\ldots,q_{jH},z_j,b_j)$ be crop j production function of the H water inputs $(q_{j1},q_{j2},\ldots,q_{jH})$, the K purchased inputs z_j, and the L primary inputs b_j. Following the above analysis, the derived demands for the H water inputs (types) stem from the input allocation problem:

$$Max_{\{q_j,z_j,b_j\}} \sum_{j=1}^{m}\left\{p_j f_j(q_{j1}, q_{j2},\ldots q_{jH},z_j,b_j) - \sum_{k=1}^{K} r_k z_{jk}\right\}$$

subject to

$$\sum_{j=1}^{m} q_{jh} \le x_h,\ h = 1,2,\ldots,H, \quad (5)$$

$$\sum_{j=1}^{m} b_{jl} \le B_l,\ l = 1,2,\ldots,L$$

and possibly other feasibility constraints. The shadow price (Lagrange multiplier) λ_h of quality h water constraint, evaluated at the optimal allocation, constitutes the value of marginal productivity of water quality h, h=1,2,…,H. By changing the constraint level x_h and calculating the corresponding shadow price λ_h we obtain a correspondence between x_h and λ_h, which constitutes the derived demand for irrigation water of quality h.

Notice that this derived demand function corresponds to a particular configuration of the other water quality constraints $x_{-h} = (x_1,x_2,..,x_{h-1},x_{h+1},..,x_H)$. The derived demand for water of quality h is thus defined relative to a particular set of capacity constraints x_{-h} of the H–1 other water sources, output price p, purchased input prices r and primary input constraints B.

Water Demand by Quality and by Season

If the constraints on the supply of each water quality change by season the water constraints of the input allocation problem become

$$\sum_{j=1}^{m} q_{jhs} \le x_{hs},\ h = 1,2,\ldots,H,\ s = 1,2,\ldots,S,$$

where q_{jhs} is crop j water input of quality h at sub-period s. The derived demand for water of quality h at sub-period s is then obtained by the shadow price on the constraint $\sum_{j=1}^{m} q_{jhs} \le x_{hs}$.

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Positive Approach

The positive approach to obtaining the derived demand for irrigation water is based on fitting a quantity-price relationship to observed data on irrigation water prices and quantities. Figure 1 displays price-quantity data on irrigation water in Israel during the period 1968–2001. Regression methods can then be used to estimate the empirical derived demand for irrigation water.

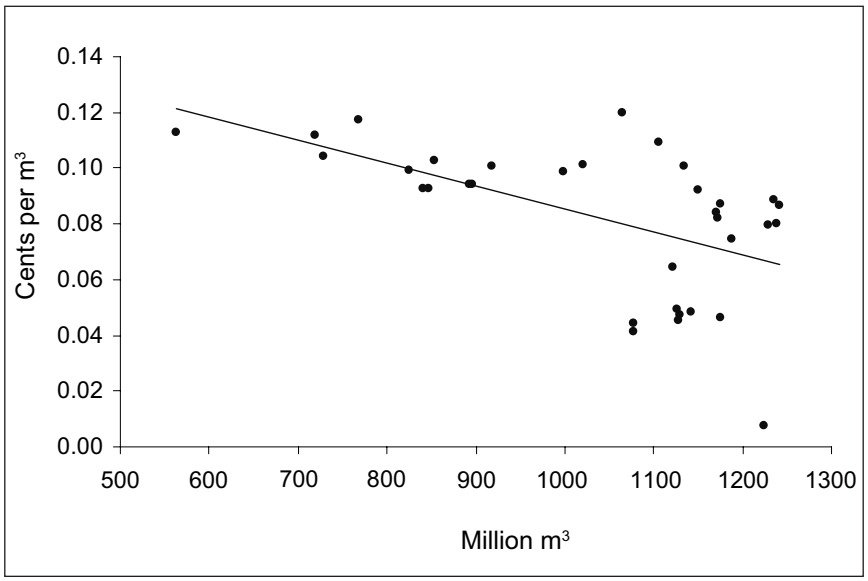

Figure 1. Water prices and quantity data for Israel's agriculture during 1968-2001. (Source: Kislev, 2001.)

There are a few problems with this approach. First, price-quantity data may not be available (recall that a small fraction of irrigated area is metered). When price-quantity data are available, the variation of the water price is typically small, which leads to low accuracy of estimates. Finally, if water quotas are used, the irrigation system may not be in equilibrium, as was the case in Israel until about the mid-1980s.

Surplus

The derived demand for water can be used to calculate farmers' surplus. To see this, recall that the shadow price of water at constraint level x represents farmers' willingness to pay for relaxing the water constraint by one marginal unit. Suppose the water constraint is relaxed from zero to 1 (m^3, say). The water shadow price at $x = 0$, i.e., $\lambda(0)$, measures the farmers' willingness to pay for that change. If farmers actually pay $w < \lambda(0)$ for the first 1 m^3 of irrigation water, their net gain from the first m^3 is $\lambda(0)-w$. The same argument can be used to show that changing the water constraint from x=1 to x=2 generates the (approximate) farmers' surplus of $\lambda(1)-w$, and so on until the constraint level at which $\lambda(x) = w$, which, as we saw above, equals $q(w)$ (i.e., $\lambda(q(w))=w$). Summing over all water constraints from x=0 up to $x=q(w)$ gives the farmers' surplus as the area between the inverse derived demand for water and the water price (see Figure 2).

More formally, it can be shown, using the first order conditions of the input allocation problem above, that $\lambda(x) = \partial\pi/\partial x$, which, together with $\pi(0) = 0$, implies $\int_0^x \lambda(q)dq = \pi$

= farmer profit not including the cost of water and other primary inputs. But the integral represents the area below the inverse derived demand function $\lambda(q)$ to the left of $q=x$. By subtracting the cost of water, wx, we see that the farmers' surplus after paying for the water is the area between the derived demand for water and the water price line w; this is the return to the fixed (primary) inputs, such as land and family labour.

This derivation applies to more complex pricing rules, such as a two rate pricing, under which the farmer pays w_1 ($w_1 < w$) for the first a units of water and w for any water input above a when $pf'(a) > w$ (see Figure 2).

Water Supply

The cost of water supply consists of variable cost (*VC*) and fixed cost (*FC*). *VC* consists of costs directly related to water supply q^s, such as pumping, conveyance, temporary labour and some operating and maintenance (O&M). *FC* consists of costs incurred whether or not water is supplied, such as depreciation

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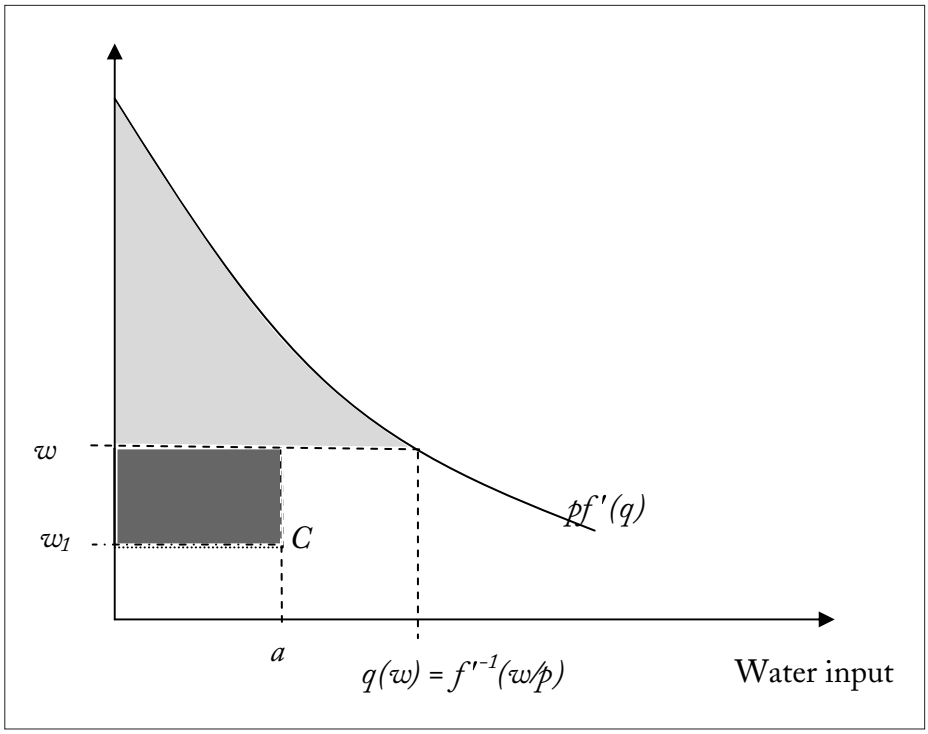

Figure 2. Under a flat-rate water price *w*, farmer's return equals the area between the derived demand curve *pf´*(*q*) and the price line *w* (lighter gray area). Under a two-rate (block rate) pricing with prices w_1 or *w* for water use below or above *a*, respectively, the added profit is the darker gray area.

and interest payments on the facility, cost of permanent labour and some O&M. Typically, *VC* is increasing in the quantity of water supply at a non-decreasing rate ($VC(q)$ is increasing and convex).

The marginal and average costs of water supply are, respectively, $MC(q) = \partial VC(q)/\partial q$ and $AC(q) = TC(q)/q$. Typical *MC* and *AC* curves are shown in Figure 3a. Because of the fixed cost component, *AC* typically has a U-shape (it decreases up to the point *b*, where a ray from the origin is tangent to *TC*, and increases thereafter). *MC* is typically non-decreasing and crosses *AC* from below at the point where *AC* is minimal.

When the price of water is *w*, the profit of the water supplier is $wq - TC(q)$ and the supply level that maximizes profit satisfies $\partial[wq - TC(q)]/\partial q = 0$ or $MC(q) = w$. The water supplier will thus supply the quantity $q(w) = MC^{-1}(w)$ and enjoy the operating profit $wq(w) - VC(q(w))$ and the total profit $wq(w) - TC(q(w))$. In Figure 3a, the water supplier's operating profit is the area between the price line *w* and the *MC* curve. The total profit is the area between the price line and the *AC* curve to the left of $q(w)$. Notice that if *w* lies below the *AC* curve, the operating profit does not cover the fixed cost *FC* and the water supplier operates at a loss. In the short run, while the fixed cost is taken as a sunk cost and must be paid whether or not water is supplied, it pays to continue operation as long as the operating profit is positive. In the long run, however, suppliers will have to be compensated to continue operation. Such compensation may come from the water users (farmers) or from the public at large.

A special case occurs when the marginal cost of supply is constant and water supply is restricted to not exceed a capacity limit *x*. This situation is typical for large irrigation projects where the cost of water conveyance is relatively low once the infrastructure has been constructed, yet water supply is limited due to water availability or conveyance capacity. In this situation, *AC* is always above *MC* and any water price at the level of *MC* involves a loss to the supplier (Figure 3b). If demand crosses the capacity limit above the *MC* level (as is the case under D_2 in Figure 3b), pricing at the level $AC(x)$ and restricting demand to not exceed *x* will allow the supplier to break even.

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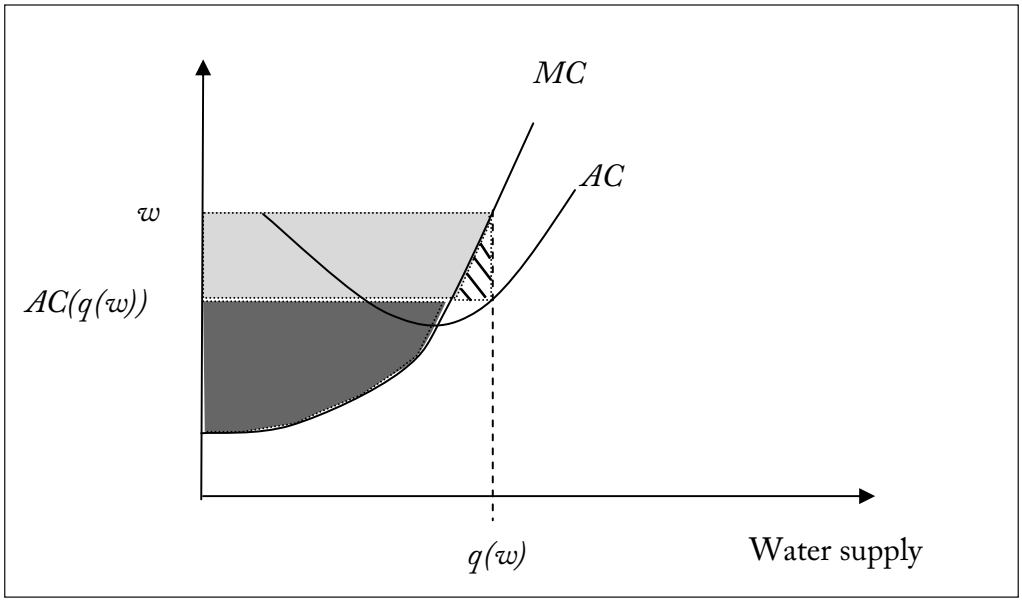

Figure 3a. The corresponding average cost (*AC*) and marginal cost (*MC*) curves. Operating profit for the water supplier equals water proceeds minus variable cost [*wq*(*w*) - *VC*(*q*(*w*))], which is the area between the price line and *MC* (light gray plus dark gray areas). The profit *wq*(*w*) - *TC*(*q*(*w*)) = (*w* - *AC*(*q*(*w*))*q*(*w*), equals the areas between the price (*w*) and *AC* lines to the left of *q* (light gray area plus diagonal lines).

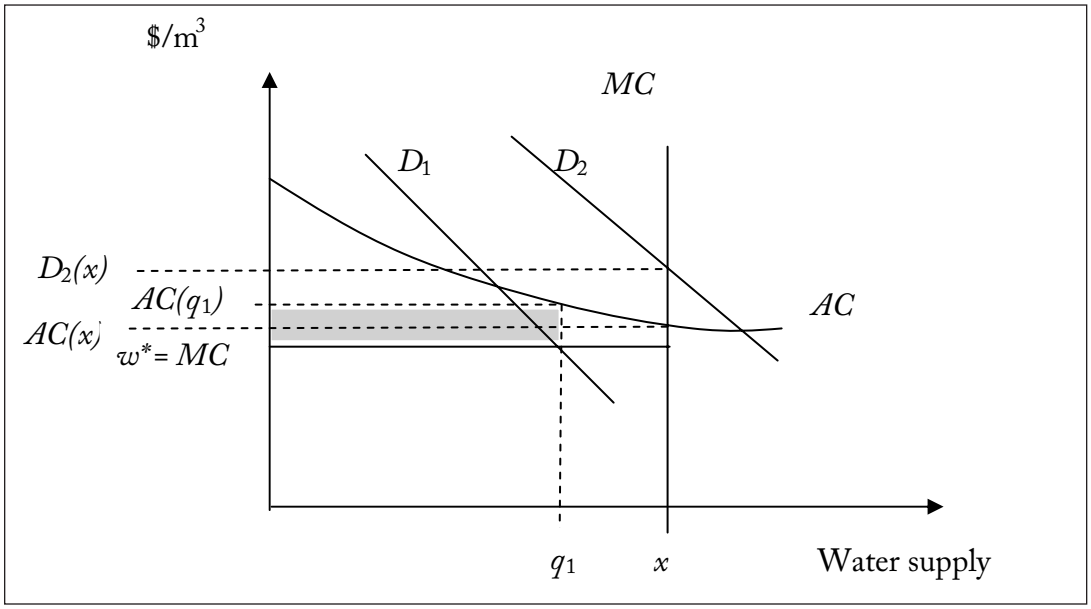

Figure 3b. The case of constant marginal cost of supply with capacity limit *x*. Average cost is always above marginal cost. Under demand D_1, efficiency is achieved with *MC* pricing *w under which the supplier loses the shaded area. Under demand D_2, irrigation water is supplied up to the capacity limit *x*. Any price between *w** and $D_2(x)$ will achieve the same water allocation and will be efficient (will maximize the joint surplus of farmers and water suppliers). A price below $D_2(x)$ requires some quota restrictions (since at that price farmers will demand beyond the constraint level *x*). The price *AC*(*x*) will allow the supplier to break even.**

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Efficient (Welfare Maximizing) Water Pricing

Total welfare generated by irrigation water is the sum of users' (farmers') and suppliers' surpluses. Given a water price w, farmers demand the quantity $q(w)$, satisfying (see above) $f'(q(w)) = w/p$ or $q(w) = q(w) = f'^{-1}(w/p)$, and enjoy the surplus $pq(w) - wq(w)$. The water supplier's operating profit is given by $wq(w) - VC(q(w))$ and total welfare net of fixed cost is

$$V(w) \equiv V(q(w)) = \underbrace{pf(q(w)) - wq(w)}_{\text{farmers' surplus}} + \underbrace{wq(w) - VC(q(w))}_{\text{supplier operating profit}} = pf(q(w)) - VC(q(w)) \tag{6}$$

The welfare maximizing water price satisfies $V'(w)=[pf'(q(w))-MC(q(w))]q'(w)=0$ or $pf'(q(w)) = MC(q(w))$. But $pf'(q(w)) = w$, hence the efficient water price satisfies $w^* = MC(q(w^*))$, which is the marginal cost pricing rule.

Typically, the inverse derived demand slopes downward, the marginal cost curve *MC* is non-decreasing, and the two curves have a single intersection that determines the marginal cost price w^*. If the intersection point falls at the decreasing part of *AC*, where *MC* is below *AC*, then $w^* < AC(q(w^*))$, implying that the operating profit of the water supplier (water proceeds minus variable costs) is insufficient to cover the fixed cost. Eventually, the water supplier will need to be subsidized to stay in business. This brings up the *cost recovery* issue, regarding whether water price should be set so as to balance the water supply budget, including the fixed cost. Doing so leads to *average cost pricing*, where the price of water is set at the intersection of the demand and average cost curves. Under such pricing, water proceeds must equal total cost (recall that $AC = TC/q$). Such a situation is depicted in Figure 4, with the average cost price represented by $w^{\#}$.

Average-cost pricing is not efficient, in that it does not maximize the joint surplus of farmers and water suppliers, as seen by observing Figure 4. A move from *MC* to *AC* pricing makes water suppliers better off (their profit is negative under *MC* pricing and zero under *AC* pricing) and farmers much worse off. Moreover, the farmers' loss exceeds the suppliers' gain and the result is a net decrease in welfare.

The *MC* pricing rule considered so far consists of a single rate – the *MC* price w^*. There are variants of *MC* pricing that contain multiple rates. As long as the water price does not exceed the derived demand for water and the price paid on the last unit is the *MC* price w^*, the demand for water will be $q(w^*)$. Multiple (or block) rate pricing, thus entails a transfer of wealth between irrigators and water suppliers. It is possible, then, to use block rate pricing to balance the supply budget while retaining the efficient allocation $q(w^*)$. Alternatively, when water suppliers run a positive profit (water proceeds exceed variable and fixed costs), block-rate pricing can be used to transfer wealth from suppliers to farmers by setting the initial prices below the *MC* price.

It should be noted that block rate pricing complicates the pricing procedure and in general increases the cost of implementation. Moreover, the wealth transfers it involves may have long-run consequences by affecting exit from and entry into the irrigation sector.

Pricing Methods

Existing water pricing methods include (Tsur and Dinar, 1997):

Volumetric: Water is charged based on direct measurement of volume of water consumed. Variations of the volumetric approach include: (1) indirect calculation based on measurement of minutes of known flow (as from a reservoir) or minutes of uncertain flow (proportions of a flow of a river); and (2) a charge for a given minimal volume to be paid even if not consumed.

Output/input: Irrigation water is charged on per output basis (irrigators pay a certain water fee for each unit of output they produce) or by taxing other inputs (irrigators pay a water fee for each unit of a certain input used).

Area: Water is charged per irrigated area, depending on the kind and extent of crop irrigated, irrigation method, the season of the year, etc. In many countries, water rates are higher when there are storage works (investment) than for diversions directly from streams. The rates for pumped water are usually higher than for water delivered by gravity. In some cases, farmers are required to pay the per area charges also for the non-irrigated areas.

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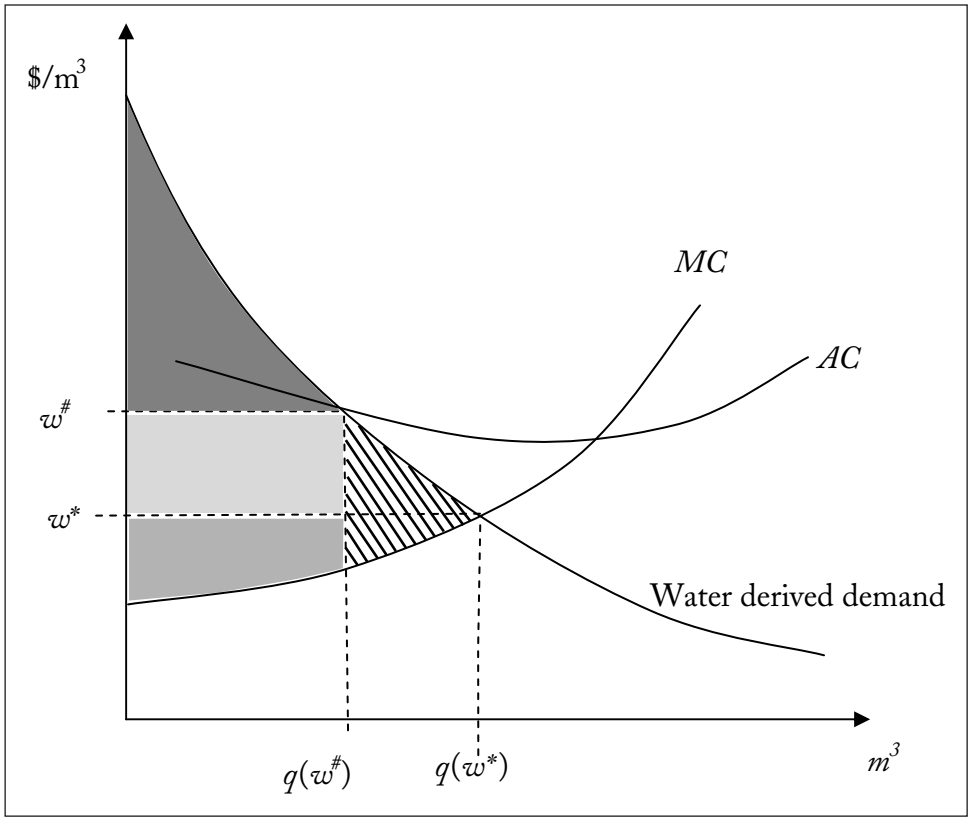

Figure 4. {$q(w^*)$,w^*} and {$q(w^\#)$,$w^\#$} are the allocations under *MC* and *AC* pricing, respectively. The joint surplus under *MC* pricing is the entire marked area, whereas under *AC* pricing it is the area with three shades of gray. The welfare loss due to *AC* pricing is the area with diagonal lines.

Block-rate: This is a multi-rate volumetric method, in which water rates vary as the amount of water consumed exceeds certain threshold values.

Two-part tariff: This involves charging irrigators a constant marginal price per unit of water purchased (volumetric marginal cost pricing) and a fixed annual (or admission) charge for the right to purchase the water. The admission charge is the same for all farmers. This pricing method has been advocated, and practiced, in situations where a public utility produces with marginal cost below average cost and must cover total costs (variable and fixed).

Betterment levy: Water fees are charged per unit area, based on the increase in land value accruing from the provision of irrigation.

Water markets: Such markets exist in different forms throughout the world. They may be formal or informal, organized or spontaneous. Their participants may trade water rights (e.g., the right to purchase some quantities of water at a particular price during specific periods of time), or they may trade water at the spot price or for future delivery. In some countries, markets for water or water rights have been formed and determine water prices (usually measured on a volumetric or water flow basis). They range from sanctioned markets for water rights, such as in Chile (Hearne and Easter, 1998) to spontaneous spot markets such as in Brazil (Kemper and Olson, 2000).

Implementation

One may wonder why there are so many pricing methods if efficiency can be achieved by a variant of *MC* pricing. The reason lies in implementation costs. Implementing *MC* pricing is a costly operation, requiring metering, monitoring, fee collection and various administrative activities. For this reason, *MC*

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pricing is not ubiquitous. Bos and Wolters (1990) investigated farmers representing 12.2 million hectares of irrigated farms worldwide and found that area pricing is used on more than 60% of the cases, while volumetric pricing is used in about 25% of the cases studied. Tsur and Dinar (1997) found that in some cases area pricing outperforms volumetric pricing when implementation costs are included.

Implementation of water pricing requires appropriate institutions and entails costly activities (e.g., administration and information collection). Volumetric pricing requires information on the volume of water used by each user (i.e., it requires facilities to meter water). Once water meters are installed, implementation is fairly straightforward, involving routine maintenance and periodic meter readings. In the absence of water markets, some kind of central water authority or water user organizations are required to set water price, monitor water use and collect water fees. The implementation cost associated with volumetric pricing is relatively high.

Output pricing requires information on the output level of each water user. It does away with the need to measure individual water inputs, but requires measurement of output. If the water-yield response function $y=f(q)$ is known, it is straightforward to deduce water input q from observations on output y (by inverting f) and then price water volumetrically. However, water-yield response functions typically involve parameters that are known to the irrigators but not to the water regulator due, for example, to specific soil properties or irrigation efficiency (a situation known as asymmetric information). In such cases it is impossible to directly deduce water input from output observations. Smith and Tsur (1997) developed a pricing mechanism based on output when the yield-water response functions involve private information. The outcome of this procedure consists of water fee schedules $t^i(y^i)$, based solely on the observed output of farmer i, $i=1,2,\ldots,n$, that induce farmers to irrigate at the socially optimal level. In the absence of implementation costs, the optimal output fee schedules achieve the best outcome.

Area pricing is easy to implement and administer and does not require water conveyance facilities to be metered. It requires land-by-crop data (if the per hectare water fees vary across crops) or total irrigated area (if a unified fee is used). Simplicity and low agency costs explain the popularity of this method.

Tiered (block rate) pricing and two part tariff elaborate on the volumetric method and hence will be somewhat more involved. Once water meters are installed, the extensions to multiple rates (tiered pricing) are straightforward; the two part tariff requires, in addition to the volumetric rate, a fixed admission fee per farmer.

Which Method to Implement?

The preferred pricing method is the one that yields the highest benefit, including transaction costs. In the absence of implementation costs, the volumetric (or one of its related methods — the tiered or two-part tariff) method is efficient. With implementation costs, other methods may perform better. As the implementation costs associated with each pricing method vary widely from region to region, due to variations in climate, demography, social structure, water rights, water facilities, history and general economic conditions, the net benefit associated with each method will vary from region to region.

Tsur and Dinar (1997) compared the performance of volumetric pricing with that of per area pricing when implementation costs (of volumetric pricing) are proportional to water proceeds. They found that the latter outperforms the former when implementation costs exceed 7.5% of water proceeds. While confined to the particular case considered by Tsur and Dinar (1997), this finding illustrates the possible effect of implementation costs on the performance of volumetric pricing.

Regarding water markets, it is expected that well-defined tradable rights would formalize and secure the existing water rights held by users, economize the transaction costs, and increase efficiency of water use by inducing users to internalize the full opportunity cost of water, determined by the market, as opposed to a price imposed administratively. Water projects, however, often involve a small number of participants, entail uncertainty (e.g., in rainfall and streamflows) and exhibit increasing returns to scale (e.g., large-scale water projects), and each of these factors leads to market failure. Thus the scope for using water markets is rather limited.

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Prices versus Quantities

As prices and quotas are fundamental means of regulation, their use in any given circumstance has attracted much research (Weitzman (1974) is an important contribution). In principle, any water allocation can be attained by an appropriate set of quotas or a combination of quotas and prices (the block-rate pricing scheme discussed above involves such a combination). The difference in the performance of price-based and quota-based allocation schemes depends mainly on two factors: implementation costs and the information available to the water users, water suppliers and water regulator (Tsur, 2000). In a world of complete information and no implementation costs, the two types of allocation schemes are equivalent. But in the real world, transaction costs and incomplete information abound.

Take, for example, the case of unmetered irrigation water, which prevails in about 75% of the irrigated area worldwide (Bos and Wolters, 1990). Unmetered water implies that water intakes are the irrigators' private information, which they may not disclose to the water supplier or regulator. This situation rules out the possibility of using volumetric pricing and explains the popularity of area pricing. Yet water meters can be installed and maintained at a cost. The question then is whether the welfare gain due to the increased efficiency resulting from the shift from per area pricing to volumetric pricing is sufficient to cover the cost of water metering. The answer depends on the circumstances at hand. It may also be possible to deduce water input indirectly via a proxy, such as output or a certain input (see discussion above of Smith and Tsur's (1997) mechanism).

Cost Recovery

Efficiency dictates that volumetric pricing of irrigation water should be based on the marginal cost of supply. Fixed costs, including part of O&M, capital depreciation and replacement, and administration, should not affect volumetric rates. To cover the fixed cost, a two-part tariff can be used, whereby independently of the per volume charges, a fixed fee (a hookup or per area fee) is levied on water users.

As far as efficiency is concerned, it is immaterial who pays for the fixed cost of water supply as long as this payment is decoupled from farmers input/output decisions. The fixed cost payment, however, does affect income and can be based on income distribution considerations.

Equity

While efficiency is concerned with aggregate wealth, equity deals with how this total wealth is to be distributed among society's members. Equity measures differ depending on the particular object according to which equity is measured (opportunities, needs, income, utility) and usually require interpersonal comparisons that are inherently subjective (involve value judgments that may vary from person to person). For these reasons, equity concerns have been overshadowed by efficiency criteria. Yet it appears reasonable to require that policies aimed at allocating publicly owned, essential natural resources not eschew equity considerations altogether and the question is how to incorporate such considerations within water allocation policies.

Tsur and Dinar (1995; 1997) investigated the equity performance of various methods of irrigation water pricing and concluded that the extent to which water pricing can affect income redistribution within the irrigation sector is rather limited. Their results support the view that income redistribution policies should not be carried out via water prices — not because it involves wrongdoing but because water prices are ineffective in dealing with income inequality within the farming sector.

But if water pricing is to be used for that purpose, it should be confined to the fixed cost of water supply; how to charge for the fixed cost of water supply (when suppliers' operating profit falls short of the fixed cost) can be determined based on income distribution criteria.

Economy-wide Considerations

The derived demand for water underlies almost any aspect of water pricing. Yet this relation depends heavily on the rest of the economy through output and purchased input prices $(p_1,p_2,\ldots,p_m)$ and $(r_1,r_2,\ldots,r_K)$. Since these prices are often distorted due to government intervention, a change in government policy that is seemingly unrelated to irrigated agriculture may

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affect the derived demand for irrigation water and the ensuing water pricing. It is for this reason that water pricing must be considered in the context of the broader economy. A detailed account of micro-macro links in the context of irrigation water pricing can be found in Tsur *et al.* (2004b).

Intertemporal Considerations

Intertemporal considerations become relevant when actions taken today have consequences in the future. This is the case when the quantity or quality of water stocks change over time due to exploitation. To understand intertemporal effects one must first distinguish between water flows and water stocks. Water flows are measured in volume per unit time (e.g., litre per second, m^3 per day, million m^3 per year), whereas stocks are measured in volume units (million m^3). Water stocks appear in the form of lakes, reservoirs or aquifers. The change in a water stock during a time period (a year, say) equals recharge minus withdrawal during that time period. If this change is negative (withdrawal exceeds recharge), then the water stock shrinks over time and if the situation persists the stock will eventually be depleted. The immediate impact is often more expensive extraction. In the long run, withdrawal will be restricted to not exceed recharge (if depletion occurs) or may even cease completely if depletion ruins the water stock (e.g., due to seawater intrusion). Future consequences of current actions must thus be taken into account.

This can be done by imposing a *user cost* on water withdrawals aside from the engineering cost of extraction and conveyance. To have the right to withdraw water over and above recharge, users must pay a price in addition to the engineering cost of supply, and the price of water should include this user cost. Although it appears under different names (abstraction, royalty, scarcity), this intertemporal cost of water has a precise meaning and must be calculated within an intertemporal optimization framework. The literature on this issue is large (e.g., Burt (1964b); Tsur and Graham-Tomasi (1991); Tsur and Zemel (1995; 2004)) and we shall not discuss details here.

Two points ought to be mentioned. First, when many users extract water from an aquifer or a reservoir and the extraction cost depends on the water stock, the users inflict spatial externalities on each other — a situation that calls for some form of (administrative) coordination and regulation. Second, although the user cost of the water stock varies with time and its determination requires solving the complete dynamics of the intertemporal allocation problem, there is a possible simplification based on the property that in most cases the optimal stock process (eventually) enters a steady state (in which extraction just equals recharge and the stock remains constant). Tsur and Zemel (2001) offered a simple way to solve for the optimal steady state and the corresponding user cost (or shadow price) without the need to solve the entire dynamic problem. The optimal (time-varying) user cost can be approximated by its asymptotic (constant) steady-state value, in which case the situation is similar to the static problem with an added water cost (the user cost).

Conclusions

Our point of departure is that the scope for supply management of water resources — whereby a new dam or diversion project is built in response to a water shortage — is already limited and will become more so in the future. The ultimate (and practically unlimited) source of water supply is seawater, but even optimistic cost projections render desalinated water too expensive for most irrigation purposes (the current minimal desalination cost lies between 50 and 60 cents per cubic metre). As a result, water policies will become ever more dependent on demand management, of which pricing is a central means.

This paper discusses economic aspects of irrigation water pricing and summarizes the ensuing policy recommendations. The discussion is far from exhaustive, in that it does not provide a policy prescription for any possible circumstance; rather it includes those that are pressing and prevalent. Moreover, irrigation water pricing as such is but one aspect, albeit an important one, of water allocation policies. Other considerations, such as the role and potential of water markets (Olmstead *et al.,* 1997; Easter *et al.,* 1998; Horbulyk and Lo, 1998), adoption and use of water-saving irrigation technologies (Caswell and Zilberman, 1985; Shah *et al.,* 1995), conjunctive management of ground and surface water (Burt, 1964a; Tsur, 1990; Tsur and Graham-Tomasi, 1991; Provencher and Burt, 1994; Knapp and Olson, 1995; Tsur, 1997), water institutions

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and regulation (Ostrom, 1990; Boggess *et al.,* 1993; Easter and Tsur, 1995; Maria-Saleth and Dinar, 2000; 2004; Dinar and Mody, 2004; Dinar and Maria-Saleth, 2005), the political economy of water reforms (Dinar, 2000), uncertainty in water supply and demand (Tsur, 1990; Tsur and Graham-Tomasi, 1991; Tsur and Zemel, 1995; 2004), environmental and agricultural externalities (Zilberman and Marra, 1993), as well as intersectoral (urban and industrial) water allocation (Renzetti, 2002) are all relevant issues to be considered by comprehensive water policies.

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