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Irrigation water pricing: policy implications based on international comparison

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ABSTRACT. This paper is concerned with the regulation of irrigation water via pricing. The main concepts underlying efficient water use are first discussed and then applied in actual practice to demonstrate empirically how readily available data can be used to implement pricing schemes that achieve efficient allocation of water. The policy discussion includes also equity considerations. The empirical findings, however, reveal that water prices have a small effect on income distribution within the farming sector, thereby supporting the view that water pricing should be designed primarily to increase the efficiency of water use, leaving income distribution considerations to other policy tools.

1. Introduction

Population growth compounded with rising standards of living have led to a rapid increase in the demand for water. Indeed, by 2025 more than 3 billion people will be living in 'water-stressed' countries and by 2050 nearly 1 billion people living in the Middle East and North Africa will have

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less than 650 m^3 of water per person annually – a sever water shortage by any standard (Gleick, 1992, 1997; Postel, 1999). Because water allocation systems require large initial investments in infrastructure, exhibit increasing returns to scale and involve spatial and temporal externalities, some form of regulation is called for. Consequently, a plethora of mechanisms to allocate water have emerged, some more efficient and some easier to implement than others (Tsur and Dinar, 1997; Dinar, 1998). Many involve water pricing mechanisms of one sort or another.

Methods for pricing irrigation water range from per area, through output and input pricing to various volumetric schemes (see Johansson *et al.*, 2002; Tsur and Dinar, 1997, and references they cite). This multiplicity reflects variability in conditions and multiple criteria that underlie water allocation. The main criterion underlying the pricing of any scarce resource is efficiency. However, water pricing is often perceived as a policy intervention that negatively affects poor farmers and small holders. Therefore, the efficiency criteria alone may not always be appropriate. In developing countries, where subsistence farmers rely on irrigation water for basic needs, irrigation water pricing is a sensitive policy intervention. In this work we study efficient pricing of irrigation water and investigate the extent to which the different pricing schemes affect income distribution within the irrigation sector. Our empirical findings corroborate Tsur and Dinar's (1997) claim that water prices have small effects on income distribution within the farming sector. We thus focus on efficiency and demonstrate how available data can be used to arrive at a pricing scheme that achieves efficient allocation of water.

The next section briefly summarizes the theory of efficient water pricing. Section 3 discusses implementation. Section 4 presents three case studies of water pricing in South Africa, Turkey, and Morocco. For each case we discuss actual pricing policies in light of the efficiency concepts. Equity considerations are discussed in Morocco only, where the detailed data permit such analysis. Section 5 concludes.

2. Efficient pricing of irrigation water

2.1. Demand

Consider first the case of a single farmer that produces a single crop (y) with a single input, water (q), according to an increasing and strictly concave production function $y = f(q)$. When the prices of water and output are w (\$/m^3, say) and p (\$/kg, say), respectively, the farmer's operating profit is $\pi = pf(q) - wq$ and the profit maximizing level of water input satisfies $\partial\pi/\partial q = 0$, or $f'(q) \equiv \partial f(q)/\partial q = w/p$; hence the quantity of water demanded at price w is given by $q(w) = f'^{-1}(w/p)$.

When $m > 1$ crops are grown, the profit becomes $\pi = \sum_{j=1}^{m}[p_j f_j(q_j) - wq_j]$, where f_j is the water production function of crop j, q_j is water input for crop j, and p_j is the price of crop j, $j = 1, 2, \ldots, m$. The necessary conditions for profit maximization are $\partial\pi/\partial q_j = f_j'(q_j(w)) - w/p_j = 0$, which give rise to the individual crops derived demand for water functions

$q_j(w) = f_j'^{-1}(w/p_j)$, $j = 1, 2, \ldots, m$. Total demand for water is thus

$$q(w) \equiv \sum_{j=1}^{m} q_j(w) = \sum_{j=1}^{m} f_j'^{-1}(w/p_j)$$

Extension to the general 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, $q_i(w) = \sum_{j=1}^{m} f_{ij}'^{-1}(w/p_j)$ is farmer i's water demand and the demand of all farmers is

$$q(w) = \sum_{i=1}^{n} q_i(w) = \sum_{i=1}^{n}\sum_{j=1}^{m} f_{ij}'^{-1}(w/p_j).$$

To incorporated additional inputs, let $F(q, z)$ stand for the agricultural production function with z representing the vector of inputs other than water (fertilizer, pesticide, labor, machinery). Let $z(q)$ be the outcome of

$$\text{Max}_Z\{pF(q, z) - rz\},$$

where r is the price vector of z and the prices p, w, and r are taken as given, hence suppressed as arguments. The above analysis holds with $f(q) \equiv F(q, z(q))$.

An alternative approach

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 constraints by Δ units? 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, thus, are willing to pay at most $p[f(x+\Delta) - f(x)]$ for the additional Δ m^3 of water, i.e., they are willing to pay 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 called the *shadow price* of water. As we saw above, $pf'(x)$ is the inverse of the derived demand for water.

Formally, we seek the water input that solves the constrained optimization problem: Max_q $pf(q)$ subject to $q \le x$. Defining the Lagrangian function $L = pf(q) - \lambda(q - x)$, with λ being the Lagrange multiplier on the water constraint $q \le x$, the first-order (Kuhn–Tucker) conditions for the optimum include:

(i) $\partial L/\partial q = 0 \Rightarrow pf'(q) = \lambda$,
(ii) $\partial L/\partial \lambda \ge 0 \Rightarrow q \le x$,
(iii) $\lambda(q - x) = 0$ (complimentary slackness).

Now, $f'(x) > 0$ implies $pf'(q) > 0$ for all $q \le x$ (f is strictly concave), hence $\lambda > 0$ (condition (i)), implying (condition (iii)) that water is used up to the constraint, i.e., $q = x$ and $\lambda = pf'(x)$. It follows that the multiplier λ of the water constraint $q \le x$ (i.e., the shadow price of water) equals the inverse demand. By changing the constraint x and calculating the associated shadow price λ, we obtain $\lambda(x) = pf'(x) =$ the inverse derived demand function.

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This approach is useful because it easily extends to situations involving additional inputs and constraints. Suppose that, in addition to water, crop production involves k inputs $z=(z_1, z_2, \ldots, z_k)$ that can be purchased at an unlimited quantity at the going market prices $r=(r_1, r_2, \ldots, r_k)$ and l primary inputs (e.g., land) $s=(s_1, s_2, \ldots, s_l)$ that are available free of charge at the limited quantities $b=(b_1, b_2, \ldots, b_l)$. The input/output decision problem is

$$\pi(x, b, p, r) = Max_{\{q,z,s\}}\{pF(q, z, s) - (r_1 z_1 + r_2 z_2 + \ldots + r_k z_k)\}$$
$$\text{s.t. } q \leq x \text{ and } s \leq b$$

(and possibly other, e.g., non-negativity, constraints). To solve this problem one forms the Lagrangian

$$L = pF(q, z, s) - (r_1 z_1 + r_2 z_2 + \ldots + r_k z_k) - \lambda(q - x)$$
$$- [\mu_1(s_1 - b_1) + \mu_2(s_2 - b_2) - \ldots - \mu_l(s_l - b_l)]$$

The multiplier λ on the water constraint ($q \leq x$) is the shadow price of water, which when calculated for all feasible water levels x, constitutes the inverse derived demand for water.

For non-linear production functions $F(q, z, s)$, the above constrained optimization constitutes a non-linear programming (NLP) problem. A special case arises when the function F admits the Leontief (fix coefficient) form

$$F(v_1, v_2, \ldots, v_m) = min\{v_1/a_1, v_2/a_2, \ldots, v_m/a_m)$$

for some constants $a_1, a_2, \ldots, a_m$. In this case the constrained optimization reduces to a Linear Programming (LP) problem, for which efficient algorithms exist.

As an example, consider the case of m crops and four inputs: land, water, labor, and fertilizer. An hectare of crop j requires at least a_{1j} m^3 of water, a_{2j} days of labor and a_{3j} kg of fertilizer, and yields y_j kg of output, $j=1, 2, \ldots, m$. The parameters y_j, a_{1j}, a_{2j}, and a_{3j}, $j=1, 2, \ldots, m$, specify the Leontief production technology. Crop j output in this case is

$$L_j y_j = L_j Min\left\{\frac{q_j}{a_{1j}}, \frac{z_{1j}}{a_{2j}}, \frac{z_{2j}}{a_{3j}}\right\}, j=1, 2, \ldots, m$$

where q_j, z_{1j}, and z_{2j} are respectively per-hectare water, labor, and fertilizer inputs for crop j, and L_j is land allocated to crop j. When no input is wasted $q_j/a_{1j} = z_{1j}/a_{2j} = z_{2j}/a_{3j}$, and the above implies

$$q_j = a_{1j} y_j,\ z_{1j} = a_{2j} y_j, \quad \text{and} \quad z_{2j} = a_{3j} y_j$$

Let r_1 and r_2 be the labor and fertilizer prices, respectively. Excluding water and land costs, the per hectare return for crop j is

$$\pi_j = p_j y_j - r_1 z_{1j} - r_2 z_{2j} = y_j(p_j - r_{1j} a_{2j} - r_{2j} a_{3j}),\ j = 1, 2, \ldots, m.$$

Letting L and x denote land and water constraints, respectively, the profit maximization problem entails finding the land allocation L_j, $j=1, \ldots, m$, that maximizes

$$\pi = L_1\pi_1 + L_2\pi_2 + + L_m\pi_m$$

subject to

$$L_1 a_{11} + L_2 a_{12} + \ldots + L_m a_{1m} \le x \text{ (water constraint)}$$

$$L_1 + L_2 + \ldots + L_m \le L \text{ (land constraint)}$$

$$L_j \ge 0,\ j = 1, 2, \ldots, m \text{ (non-negativity constraints)}$$

This is a typical LP problem (the objective and constraint are linear in the decision variables L_j).

The output of an LP run includes the optimal allocation L_j, $j = 1, 2, \ldots, m$, and a dual multiplier for each constraint. The dual of the water constraint, λ, is the shadow price of water. By running the LP problem with different levels of the water constraint x and recording the shadow price λ (the multiplier of the constraint $q \le x$) that corresponds to each level of x, one obtains a correspondence between x and the shadow price of water λ, which constitutes the (inverse) derived demand for water. We will use this procedure below.

2.2. Supply

The cost of water supply consists of variable cost (*VC*) and fixed cost (*FC*)

$$TC(q^s) = VC(q^s) + FC$$

VC consists of costs directly related to water supply q^s, such as pumping, conveyance, temporary labor, and some operating and maintenance (O&M). *FC* are costs incurred whether or not water is supplied, such as depreciation and interest payments on facility, permanent labor and administration, and some O&M. Typically *VC* is increasing with the quantity of water supply at a non-decreasing rate (i.e., $VC(q^s)$ is increasing and convex).

The marginal and average costs of water supply are, respectively

$$MC(q^s) = \partial VC(q^s)/\partial q^s \text{ and } AC(q^s) = TC(q^s)/q^s$$

Because of the fixed cost component, *AC* typically has a U-shape. *MC* is typically non-decreasing and crosses *AC* from below at the point where *AC* is minimal.

The profit earned by a water supplier that charges the water price w is $\pi^s(q^s) = wq^s - TC(q^s)$ and the supply quantity that maximizes profit satisfies $\partial\pi^s(q^s)/\partial q^s = 0$ or $MC(q^s) = w$. The water supplier will thus supply the quantity

$$q^s(w) = MC^{-1}(w)$$

and will enjoy the operating profit $wq^s(w) - VC(q^s(w))$ and the total profit $\pi^s(w) = wq^s(w) - TC(q^s(w))$. When w lies below the *AC* curve, the operating profit is insufficient to cover the fixed cost *FC* and total profit is negative. In the short run, the fixed cost is a sunk cost (i.e., it must be paid whether or not water is supplied), it pays to continue operation as long as the water proceeds exceed the variable cost (operating profit is positive). In the long run, however, suppliers will have to be compensated to continue operation.

A special case of interest occurs when marginal cost of supply is constant and water supply is restricted not to exceed a capacity limit x, e.g., an irrigation project with a fixed unit cost of supply and limited quantity of water. In this situation, AC is always above MC, so marginal cost pricing always involves a loss to supplier. If demand crosses the capacity limit above the MC level, pricing at the level $AC(x)$ and restricting demand not to exceed x will leave the supplier to break even.

2.3. Efficient pricing

The total surplus generated by the irrigation water is the sum of farmers and suppliers surpluses. We seek the water price that maximizes total surplus. Given a price w, farmers demand the quantity $q(w)$, satisfying (see above)

$$f'(q(w)) = w/p \text{ or } q(w) = f'^{-1}(w/p)$$

and enjoy the surplus $\pi(w) = pq(w) - wq(w)$. The supplier's operating profit (as a function of water price w) is given by

$$\pi^s(w) \equiv \pi^s(q(w)) = wq(w) - VC(q(w))$$

and the short-run welfare (free of the fixed cost) is

$$\begin{aligned} V(w) \equiv V(q(w)) &= \underbrace{pf(q(w)) - wq(w)}_{\text{farmers surplus}} + \underbrace{wq(w) - VC(q(w))}_{\text{supplier surplus}} \\ &= pf(q(w)) - VC(q(w)). \end{aligned}$$

The water price that maximizes total surplus satisfies $\partial V/\partial w = 0$ or

$$pf'(q(w)) = MC(q(w))$$

But $pf'(q(w)) = w$, hence the efficient water price is defined by

$$w^* = MC(q(w^*))$$

which is the *marginal cost pricing* rule.

Typically, the inverse derived demand $pf'(q)$ slopes downward, the marginal cost curve $MC(q)$ is non-decreasing, and the two curves have a single intersection that determines the marginal cost price w^* – this is the standard supply-equals-demand rule. The operating profits of the water users (the farmers) and the water suppliers are, respectively, the areas with horizontal and vertical lines of figure 1. The short-run (not including fixed costs) welfare is the sum of the two areas.

If the intersection point falls at the decreasing part of AC, where MC is smaller than AC, as is the case under AC_2 in figure 1, 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 (see discussion above). In the long run, the water supplier will need to be subsidized to stay in business. A question then arises regarding whether the water price should be set so as to balance the budget of the water supplier, including the fixed cost. This leads to the consideration of *average cost pricing*, where

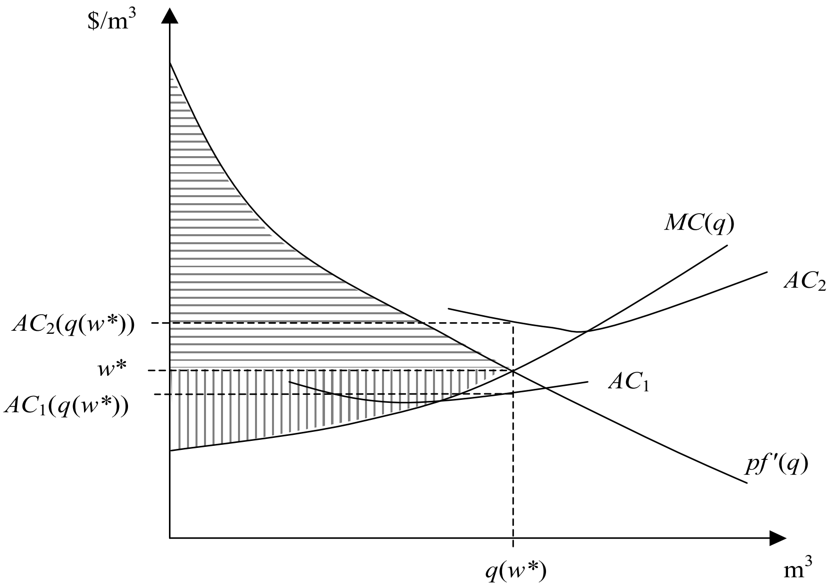

Figure 1. *The marginal cost price w^* is the price at which the inverse demand function ($pf'(q)$) intersects the marginal cost curve. The farmers' operating profit (return to water) is the area with horizontal lines. The water supplier's operating profit is the area with vertical lines. The sum of these two areas is the welfare*

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 2, with the average cost price represented by $w^{\#}$.

Can average cost pricing be justified based on economic efficiency (where the goal is to maximize the joint surplus of farmers and water suppliers)? The answer is a plain, no. To see this, observe figure 2. Moving from marginal cost pricing to average cost pricing involves a shift from the quantity–price configuration $\{q(w^*), w^*\}$ to $\{q(w^{\#}), w^{\#}\}$. Under marginal cost pricing, the joint surplus is the area between the demand and marginal cost curves – the entire marked area in figure 2 – whereas under average cost pricing, it is the non-dotted area (the area with diagonal, vertical, and horizontal lines). Thus the move from marginal cost to average cost pricing involves a loss of welfare given by the dotted area (figure 2). The loss to farmers is the upper triangle dotted area plus the horizontal lines area. Suppliers loose the lower dotted triangle and win the horizontally lined rectangular. A move from marginal cost to average cost pricing, thus, makes water suppliers better off (their gain exceeds their loss) and farmers much worse off. Moreover, the loss exceeds the gain and the result is a net decrease in welfare.

As noted above, however, when the MC curve lies below the AC curve, water proceeds under marginal cost pricing are insufficient to cover the cost of water supply, implying that some form of (supply) subsidy is required. A subsidy usually comes from public sources, and hence tends to distort

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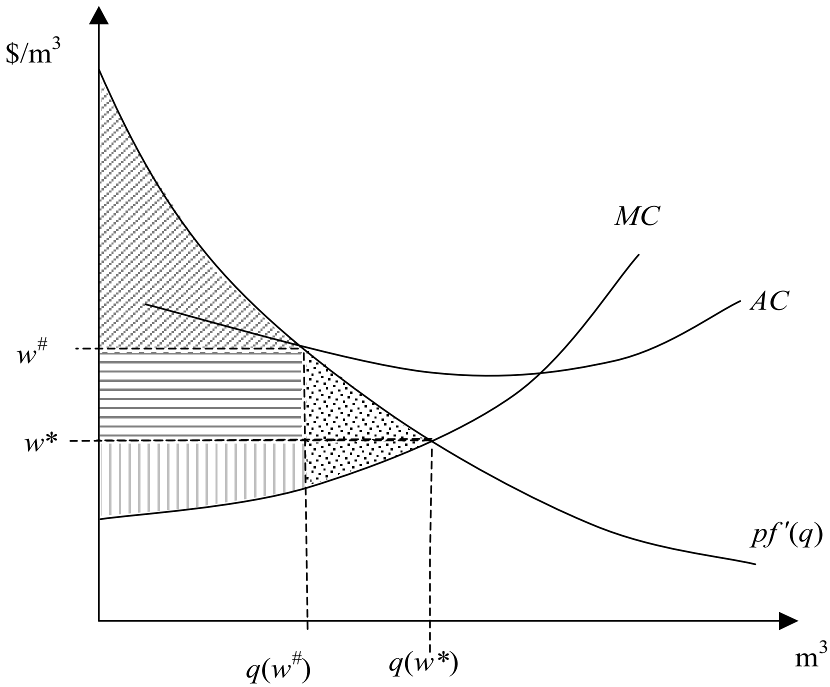

Figure 2. *{q(w*), w*} and {q(w#), w#} are the allocations under MC and AC pricing, respectively. The joint surplus under MC pricing is the entire marked area, whereas under AC pricing it is the area with vertical, horizontal, and diagonal lines. The welfare loss due to AC pricing is the dotted area*

efficiency as well (e.g., if collected through taxes). Thus, marginal cost pricing preserves efficiency in the irrigation sector but by drawing on public funds may contribute to inefficiency in other sectors. The relative damage of these two types of distortions must be evaluated in each case separately.

We summarize the above:

- *Marginal cost pricing* achieves efficient water allocation in the irrigation sector in that it maximizes the joint surplus of water users (farmers) and water suppliers. If, however, it involves supply subsidy (when the *MC* curve lies below the *AC* curve), it can cause inefficiency in other sectors of the economy through its reliance on public money to subsidize water supply.
- *Average cost pricing* guarantees a balanced budget of the water supply agency, thus relaxes the need to use public funds, but entails an efficiency loss in the irrigation sector (it decreases the joint welfare of farmers and water suppliers). Moreover, the farmers carry most of the burden of the welfare loss.

Block-rate pricing

The marginal cost pricing considered so far consists of a single rate – the marginal cost price w^*. There are variants of marginal cost pricing that

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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 marginal cost 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 marginal cost price. Block-rate pricing can be used to transfer wealth between water suppliers and farmers, while retaining efficiency (i.e., a maximal joint surplus of farmers and water suppliers).

Two points are worth noting in the context of block-rate pricing. First, block-rate pricing may require special handling for each farmer or group of farmers separately. For example, when farmers pay a lower rate for some of their water intake, the quantity of water charged at the lower rate should vary with farm size in order to ensure that the last water unit is charged at the marginal cost of supply (e.g., by applying the lower rate at a fraction of total water intake). Second, block-rate pricing involves wealth transfer, and hence may have long-run consequences by affecting the distribution of farm size as well as exit from and entry into the irrigation sector. For example, a two-rate pricing policy with the lower rate applied to a fraction of total water input benefits large farms more than small farms and may induce large farms to expand by overtaking smaller farms.

3. Empirical considerations

The first step is to obtain the derived demand for irrigation water, which can be done by econometric or programming methods. In the econometric approach, data on water use (and possibly other inputs) and prices are used to estimate the water demand as a function of other inputs and of prices, along the line of the dual approach to production theory (see Fuss and McFadden, 1978). Alternatively, if input–output data are available, the production technology (the water response function) can be estimated, and the derived demand for irrigation water is then obtained via the programming approach.

In the programming approach, the production technology is assumed known and the optimal crop production program is calculated under various resource constraints and the prevailing input–output prices. The shadow price of the water constraint constitutes the marginal value of irrigation water. By calculating the shadow price of water, at each level of water constraint, we obtain the derived demand for water (as explained in section 2).

Here we follow the programming approach and assume a fixed coefficients (Leontief) production technology. The derived demand for water is thus obtained by applying Linear Programming (LP) repetitively with different levels of water constraints (see section 2). The LP output under the actual water constraint may give rise to crop allocation that is far from the actual allocation. There are number of reasons for such a divergence, including misspecification of the production technology, data

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limitation (various constraints that are known to producers but not to the researcher), and farmers' decisions that are based in part on considerations other than (short-run) profit maximization. The Positive Mathematical Programming (PMP) method, suggested by Howitt (1995) can be used to circumvent this limitation of the LP method. We use PMP in the analyses of South Africa and Turkey, where data are aggregate (hence unlikely to account for various farm-level constraints) and LP for the Moroccan region, where detailed data are available.

4. Case studies

We apply the procedure discussed above to study water pricing in regions of South Africa, Turkey, and Morocco. Since these regions vary in almost any respect, they span a wide spectrum of agro-socio-climatic conditions. Comparing these case studies will therefore provide a good basis for policy discussion.

4.1. The Loskop Irrigation Scheme in South Africa

The Loskop Irrigation Scheme receives its water from the Loskop Dam, a 348 million m^3 capacity reservoir operating since 1945. The main left bank canal is 96 km long with a capacity of 10.2 m^3 $second^{-1}$ at the headworks and serves 14,305 ha. The right bank canal is 51 km long with a capacity of 1.7 m^3 $second^{-1}$ at the headwork and serves 1,984 ha.

At present there are about 16,117 scheduled hectares of irrigatable land, but it is estimated that over 33,000 hectares are actually irrigated. The fact that a greater area is irrigated with the same annual allocation is attributable to improved irrigation techniques and more scientific farming practices. The entire scheme covers approximately 43,000 hectares, including grazing and fallow land (Further details on Loskop and on SA water economy can be found in Schur, 2000).

Water Demand

Table 1 gives a breakdown of the major crops cultivated on the Scheme, their water requirements and the 1999 crop prices.

Winter wheat covers the largest area and is popular because it is grown in winter, while all the other crops are primarily summer crops. This improves farming enterprises' cash flow and allows farmers to use land that would otherwise lie fallow. The most water-intensive crop is maize, which requires 6,500 m^3 ha^{-1} and has a relatively low return, at only R900 per ton.

Inputs requirements and prices are given in table 2. Because these crop budgets have been compiled from different sources, not every budget is identical in format. The water cost item, for example, for maize, wheat, groundnuts, and cotton includes electricity and maintenance of the irrigation equipment. For tobacco and citrus these costs feature separately and the cost of the water itself only is shown.

The total cost of irrigation water supply, including electricity and maintenance, is R21.6 m^{-3}, of which the unit cost of the water supply is R0.07 m^{-3} (it does not vary with the quantity of water supply).

Table 1. *Area allocation in 1999, yield, irrigation requirements and crop prices in the Loskop Irrigation Scheme*

Crop	*Area* (L_j*, ha*)	*Yield* (y_j*, kg ha*$^{-1}$)	*Water requirement* (x_j*, m*^{3} *ha*$^{-1}$)	*Crop price* (p_j*, R per ton*)
Tobacco	4,400	2,200	5,500	11,500[1]
Cotton	6,000	3,000	4,500	2,650
Wheat (winter)	9,000	5,500	5,500	1,150
Soya beans	3,000	3,000	4,000	1,300
Ground nuts	3,000	3,500	3,800	1,800
Peas	2,000	4,500	4,000	1,335
Maize	5,000	8,000	6,500	900
Citrus (perennial)	4,000	45,000	10,000	1,500
Table grapes (perennial)	250	13,500	7,700	8,800

Note: [1] Price refers to dried tobacco.
Source: Loskop Irrigation Board.

Average farm size is 35 hectares. With a few exceptions, each farm is entitled for 197,890 m^3 (sufficient to irrigate 25.7 hectares at 7,700 m^3 per hectare). The Scheme draws approximately 124 million m^3 of water from the Loskop Dam each year to serve 626 farmers.

Table 1 contains L_j (area allocated in 1999 for each crop), y_j (yield per hectare in 1999), x_j (water requirement per hectare) and p_j (crop prices in 1999), while table 2 contains per hectare production costs c_j (on the bottom line). These data are sufficient to apply the PMP method and obtain a representative farm derived demand for water function, as depicted in figure 3.

Water Supply

The Loskop dam is owned and managed by the Department of Water Affairs and Forestry (DWAF). At present, farmers are not required to pay the capital costs of the scheme. This however is set to change, with the new water pricing strategy, where full costs will be recovered from water users. The annual water quota available to farmers is 124 million m^3 per year. This figure is fixed except in drought years when the DWAF restricts water release into the irrigation canal.

The variable costs of water supply in Loskop amount to R 1.5 million. Assuming that the variable cost is proportional to the quantity of water supplied (i.e., $VC(q) = aq$), the marginal cost is slightly above 1.2 c/m^3. The fixed cost amount to over R9.5 million.

The actual irrigation water tariffs charged vary by crops. Soya beans, wheat, maize, ground nuts, and cotton growers are charged R0.216/m^3. Tobacco, citrus, table grapes, and peas growers are charged approximately R0.07/m^3. Farmers are also required to pay a per hectare tariff of about R24 per ha.

Surplus

When the water price is R0.07 m^{-3}, irrigators' surplus, calculated as the area between the derived demand for water and the 0.07 (horizontal) price line,

Table 2. *Cost of inputs (R ha*$^{-1}$)

Crop	*Tobacco*	*Cotton*	*Wheat (winter)*	*Soya beans*	*Ground nuts*	*Peas*	*Maize*	*Citrus*	*Table grapes*
Land Preparation						451			
Seed		167	480	1,032	600	1,021	100		
Fertilizers	1,950	542	642			784	870	555	4,000
Weed control		430	62	175	240		312	1,608	
Pesticides	3,040	754	85		462		250	1,208	15,000
Seedlings	850								
Curing	900								
Chemicals						1,005			
Irrigation equipment						408			
Machinery		150	150	150	150		150	185	1,500
Hire services		200	310	168	90		440		
Packaging					205			7,928	18,000
Electricity	1,192					598			
Fuel	1,450	369	340	350	369		369		1,000
Maintenance	1,400	353	340	300	350	650	353		
Insurance	2,400	780	280	380			198		
Miscellaneous	500	48	48	40	48	350	48		
Labor	7,830	1,445	355	350	900	360	430	990	25,000
Water cost	375	972	1,188	864	868	242	1,404	737	540
TOTAL	21,887	6,210	4,280	3,809	4,282	5,868	4,924	13,211	65,040
TOTAL (excluding water cost)	21,512	5,238	3,092	2,945	3,414	5,626	3,520	12,474	64,500

Sources: OTK, MKTV, Department of Agriculture COMBUD, Hereford Irrigation Scheme, I & J Groblersdal.

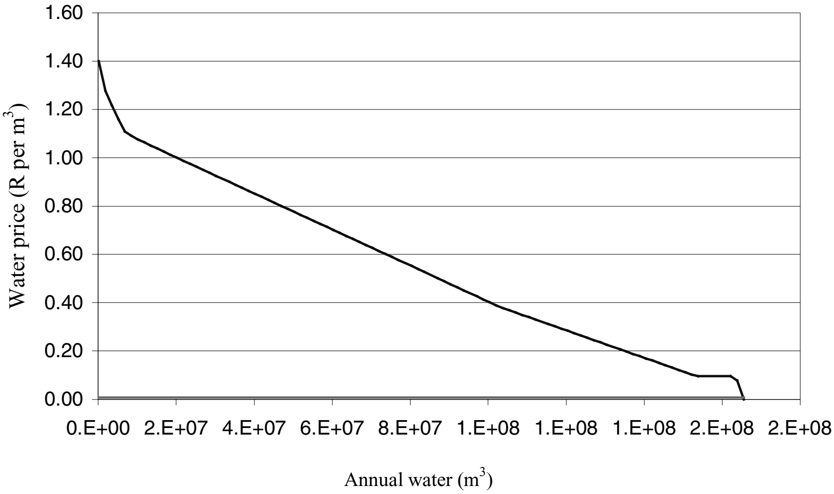

Figure 3. *The derived demand for irrigation water in the Loskop Irrigation Scheme*

equals R90.5 million. Under constant marginal cost of supply, the water supplier surplus (operating profit) is zero. Compared with the fixed cost of R34.6 million (projected for the year 2000/01) this gives the total surplus of R55.9 million.

Policy comments

(i) It is typical in large-scale irrigation projects that the (annually imputed) fixed cost of water supply is significantly larger than the variable cost (in Loskop, it is more than six fold larger). As discussed in section 2, including the fixed cost in the volumetric price of water leads to average cost pricing and reduces efficiency (i.e., it decreases the joint surplus of farmers and water suppliers). Moreover, the burden of the welfare loss falls mainly on the farmers.

(ii) Another feature typical in large-scale irrigation projects is the constant marginal cost of supply. In such a case, marginal cost pricing implies that the water supplier has no positive surplus that can be used to cover the fixed cost (as explained in section 2, the water proceeds, under marginal cost pricing with a horizontal marginal cost curve, cover only the variable costs). If the supplier is required to operate with a balanced budget, it is recommended that the money to cover the fixed costs will be raised by non-volumetric methods, without affecting farmers' input–output decisions. This can be done, for instance, by a per-area fee.

(iii) There does not seem to be any justification for the volumetric price disparity between crops. Such a disparity practically amounts to subsidizing some crops or taxing others and distorts the input–output decisions of farmers. Farmers will use water up to the level where its value of marginal productivity just equals the price of water. If water price varies from crop to crop, farmers will tend to grow crops with lower water prices and this distorts economic efficiency.

Farmers will select crops based on the return they get from each crop and other constraints, such as crop rotation, labor, or machine availability. But, if efficiency is sought, irrigation water derived from the same source with the same supply cost should have the same price. This rule does not apply for non-volumetric pricing methods, such as per-area pricing. In such cases, it is possible to increase efficiency by changing the water fee across crops, as illustrated in Tsur and Dinar (1997).

4.2. The Harran Plains Irrigation Scheme in Turkey

The Harran Plains Irrigation Scheme extends south of the city of Sanliurfa (the city of prophets) in southeast Turkey not far from the Syrian border. Covering 142,000 ha, it lies at the heart of the Fertile Crescent – where the first cereal varieties were domesticated some 10,000 years ago. The district receives its water from the Ataturk dam and from underlying aquifers in the lower plains. The water from the Ataturk dam is conveyed via the Sanliurfa Tunnels (two tunnels, each 26.4 km long by 7.6 m diameter, capable of carrying up to 328 m^3 $second^{-1}$ that can irrigate an area of more than 400,000 ha). The Ataturk dam on the Euphrates is the largest of the 22 dams owned by the GAP (the Southeastern Anatolia Project) and is among the ten largest worldwide (completed in 1992, it took ten years to build, with a reservoir capacity of 48.7 km^3, an installed hydroelectric power of 2400 MW, and a production rate capacity of 8.1 billion KWh yr^{-1}).

The GAP was started in 1970 as a water, power, and socio-economic development project on the lower Euphrates and Tigris Rivers. Upon completion it will contain 22 dams, 19 hydropower plants, and 13 irrigation projects (at the end of 2000 all the dams were completed, about three quarters of the planned hydroelectric power plants were in operation, but only 11 per cent of the irrigation projects had been completed). It covers an area of 75,000 km^2 and directly affects the life of more than 6 million people. Upon completion the GAP is planned to irrigate 1.7 million ha (at 2000 it irrigated about 215,000 ha), will have an installed power capacity of 7400 MW and will have a power production capability of 27 billion KWh yr^{-1}. The total direct cost of the GAP is expected at $32 billion – $14 billion of which have already been spent (this cost figure does not include the indirect cost associated with the thousands of people that had to be displaced, as well as the lost benefit that could be obtained from tourism to the many recreational and archeological sites that now lie under water). Further details on the water economy in Turkey can be found in Cakmak (2000).

Water demand

The main crops grown in the Harran Plains are cotton, wheat, corn, and pepper. Applying the PMP procedure (data used by the procedure are available upon requst) yields the derived demand for water given in figure 4.

The very high levels of the marginal value of water at low water constraints are due to the high profitability of pepper. As the water constraint is relaxed, farmers shift to other crops (wheat and then corn and cotton) and the marginal value (the shadow price) of water drops steeply.

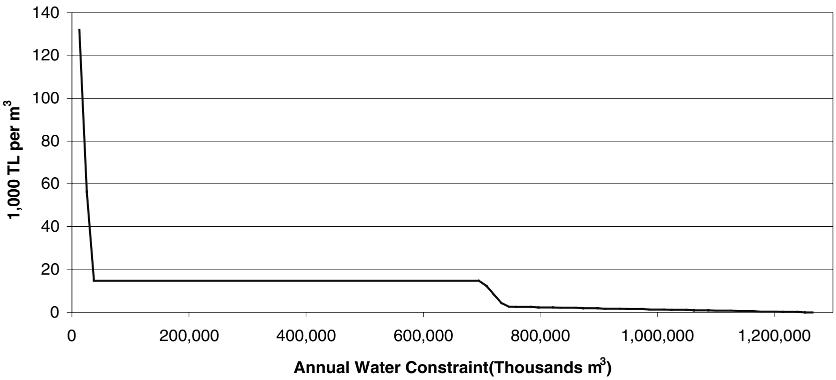

Figure 4. *The derived demand for irrigation water in the Harran Plains*

In the PMP procedure, pepper is restricted not to exceed the acutal land allocation of 1876 ha.

Irrigation water is charged on a per hectare basis, with a different rate for pepper and for other crops (16 million or 12 million TL per hectare of pepper or other crops, respectively, in 2000). The area below the derived demand for water is calculated at 13.34 billion TL. The total water charges (according to the above rates and actual land allocation) are 1.65 billion TL. The difference of 11.69 billion TL constitutes the net value of water to irrigators.

Policy comments

The Harran Plains Irrigation District is another example of a (very) large-scale irrigation projet with a high fixed investment component (the Sanliurfa Tunnels and convayence facility) and relatively small variable and marginal cost of supply. The huge Ataturk reservoir implies no water scaricty and the conveyance facilities impose no capacity constrains. Thus there are no scarcity or capacity limit components to water pricing and efficiency requires some form of volumetric pricing based on the marginal cost of supply (flat or block rate pricing), and a non-volumetric part to cover fixed costs. The non-volumetric part is captured by the per area prices. The volumetric part is missing, implying a loss of efficiency, as measured by the joint surplus of farmers and water suppliers (see discussion in section 2). From the farmers' point of view, once paid, the per area charges are sunk costs; they will therefore demand water up to the level where its marginal productivity equals zero – more than the economically efficient quantity. However, volumetric pricing entails additional implementation costs (metering, fee collection, etc.), and whether or not the gain in efficiency outweighs the added implementation costs needs to be investigated.

4.3. The Rmel Drader perimeter in Loukkos, Morocco

The Loukkos basin is located in the northwest part of Morocco, on the Atlantic Ocean coast and between the areas of Tangier and the Gharb. The

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Table 3. *Farm size distribution in Lonukkos*

Farm size	*Number of farms*
Small (about 3.5 ha)	1,950
Medium (about 15 ha)	322
Large (about 150 ha)	103

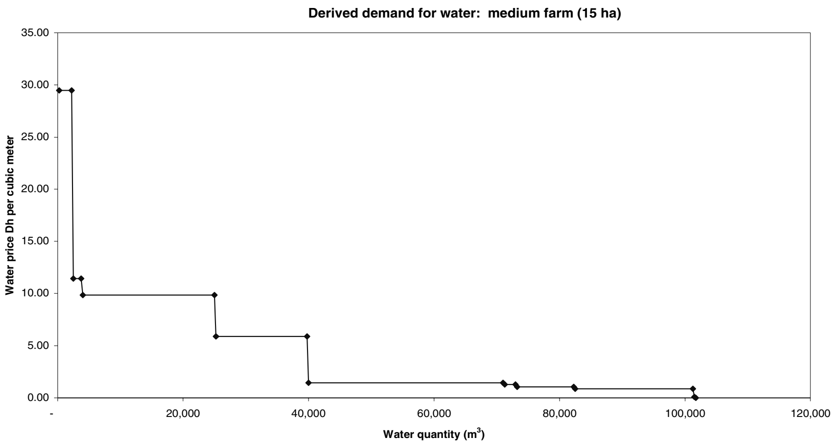

Figure 5. *Water derived demand for medium-size farms (15 ha) in Rmel Drader*

area offers the characteristic features of the coastal river basins (a detailed account of Morocco water economy can be found in BenAbdelrazzik, 2000). The area enjoys a Mediterranean climate, with an alternation of a fresh humid season from November to April, and a hot, dry season from May to October. Average annual rainfall is around 700 mm. The Loukkos water district (ORMVA) covers three major catchment basins, supplying on average 2.5 billion m^3 of surface irrigation water. Additional 75 million m^3 are supplied from groundwater sources each year. Farm size distribution in Loukkos is presented in table 3.

Within Loukkos we concentrate on a 15,565 ha perimeter called R'mel-Drader, for which detailed production and cost data are available and arranged in a format suitable for LP application. Applying LP repetitively, while varying the water constraint, yields the derived demand for water (as discussed in section 2). This was done separately for each of the three farm types – small, medium, and large (the only difference between the farm types was the land constraint). In the interest of space, only the derived demand for a medium-size farm (15 ha) is presented (figure 5).

As expected, we observe that smaller farms have steeper (i.e., inelastic) derived demand curves. This observation means that smaller farms are more sensitive to changes in water prices, in that their relative change of surplus is larger. The reason for that lies in the land restriction, which reduces the flexibility of smaller farms to change their production plans (e.g., crop areas) in response to changes in water price. The relative effect of

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water prices will therefore be larger on smaller farms. As a result, a change in water price policy may also affect income distribution within the irrigation sector (between groups of different farm size). Below we investigate the magnitude of such an effect and find it to be rather small.

Water pricing

Water authorities control water allocation to farmers and encourage certain cropping patterns, leaving little room for farmers to make their own decisions. These policies stem from the *Code des Investissements Agricoles* (CIA) – a set of rules regarding public irrigation that was adopted in 1969. The CIA is presented as a contract between farmers and the state, defining rights, and duties for large-scale irrigation (LSI) projects. CIA rules pertaining to a public LSI project include:

1. The area of the project is defined and the CIA provisions are to be applied in the delimited area.
2. Land consolidation is conducted by the ORMVA, in order to adapt the size and disposition of farms to rational irrigation. When the plots are small, they are aligned in a rectangle, perpendicular to the tertiary canals, in order to optimize the sequence of irrigation and water application. Land consolidation entails setting aside all the land needed for roads, network, and drainage. In order to avoid land fragmentation, all transactions on farms of less than 5 ha are prohibited.
3. A cropping pattern is defined, usually with about 20 to 25 per cent of irrigated land freely chosen and the other part with a compulsory cropping pattern. The techniques to be used are also defined by the commission that is in charge of the cropping pattern. The rational is to optimize water distribution by having the same water requirements and schedule of distribution all over the perimeter.
4. Finally, CIA defines the level of equipment subsidy, the financial participation of farmers to the equipment of the perimeter, the pricing structure, and the level of cost recovery.

The cropping pattern was largely defined by the 'Self sufficiency objective' of agricultural policy. Sugar and dairy production were prominent in the northern ORMVAs, with an integrated development of agricultural production (irrigated forage, sugar beet, and sugar cane), a state provision of inputs (improved dairy cattle, veterinary services, collect centers, and extension), and public investment in sugar and dairy factories.

Following the CIA, the price of water in each separate perimeter has three components: investment recovery, operating and maintenance, and a minimum consumption charge. The investment recovery component is set to cover 40 per cent of the fixed cost (after deducting the share of other water uses – urban and electricity). Thirty per cent of the recovery charge is proportional to the irrigated area, i.e., a per hectare charge. The remaining 10 per cent is included in the volumetric charge. The first five hectares on farms of less than 20 hectares are exempted from this charge.

Operating and maintenance cost is fully covered by the volumetric charge. The computation of this charge is based on the present value of

Table 4. *Water tariff structure based on the 'Agriculture Investment Code' (Dh m^{-3})*

Actual tariff charged in 1997	*Base tariff*	*Tax on pumping*	*Cost of lifting*	*Total*
0.4	0.308	0.205	0.215	0.729

Table 5. *Surpluses for small, medium, and large farms under different water pricing policies*

Farm size	$P_{MC} = 0.46$ *Dh m^{-3}*	$P = 3$ *Dh m^{-3}*
Small	173,967	126,083
Medium	433,836	286,867
Large	5,784,108	3,819,806

operating, maintenance, and replacement cost, plus 10 per cent of initial investment, and then converted to a per cubic meter of average water flow.

The CIA rule implements water charges progressively in the first five (for annual crops) or ten (for perennial crops) years of irrigation. In addition, discounts of up to 80 per cent are applied to farmers that divert water directly from the river without using public infrastructure, or if the secondary and tertiary canal are not concrete lined, or if the farmer takes responsibility for maintenance of the canal, or if water salinity is to the extent that it reduces yields for the crops foreseen in the mandatory cropping rotation.

A minimum consumption charge applies in LSI to allow for the covering of the fixed part of the maintenance and operating cost. This means that each farmer is charged for at least 3,000 m^3/ha, whether or not he uses that amount.

An energy cost charge is added whenever lifting and pressuring is required. The structure of water tariff in the perimeter implemented in 1997 is as shown in table 4.

The surpluses for small, medium, and large farms under different water pricing policies are obtained by calculating areas between the price curves and the derived demand for water (as explained in section 2). These surpluses are given in table 5 for a flat rate volumetric pricing at the marginal cost of 0.46 Dh/m^3 and a higher cost of 3 Dh/m^3.

Income distribution within the irrigation sector

Given these surplus measures and the farm distribution data, an income inequality index can be calculated, using any one of the indexes discussed in Tsur and Dinar (1995). We use the Gini index

$$G = 1 + \frac{1}{n} - \frac{2}{n^2 \mu} \sum_{i=1}^{n} i \pi_i$$

where π_i represents farm i's profit, n is the number of farms, $\mu = \frac{1}{n} \sum_{i=1}^{n} \pi_i$ is

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the mean farm profit, and farms are ordered so that $\pi_1 \geq \pi_2 \geq \ldots \geq \pi_{\mathrm{n}}$. In our case there are three farm types: small, medium, and large, indexed 3, 2, and 1, respectively, with n_1 (number of large farms) = 103, n_2 (number of medium farms) = 322, n_3 (number of small farms) = 1950 and $n = n_1 + n_2 + n_3 =$ 2,375. Since the π_is are the same within a farm size group, the Gini index specializes to

$$G = 1 + \frac{1}{n} - \frac{2}{n^2 \mu}\left[\pi^1 \sum_{i=1}^{103} i + \pi^2 \sum_{i=104}^{425} i + \pi^3 \sum_{i=426}^{2375} i\right]$$

$$= 1 + \frac{1}{2375} - \frac{2}{2375^2 \mu}[5356\pi^1 + 85,169\pi^2 + 2,730,975\pi^3]$$

where π^j is the profit of farm type j, $j = 1, 2, 3$ and $\mu = \frac{103\pi^1 + 322\pi^2 + 1950\pi^3}{2375}$.

The Gini index was calculated under a flat rate MC pricing at P_{mc} and two block-rate pricing schemes. The numbers show little effect of water pricing on profits and the Gini index G, suggesting that the effect of water prices on income distribution within the irrigation sector is small. This finding supports Tsur and Dinar's (1995) conclusion that water pricing, while very effective in achieving efficient allocation, is ineffective as far as income distribution is concerned.

Policy comments

(i) The water allocation rules, particularly quota allocation by crops, leave little room for farmers to make their own production plan. The main drawback of such a centralized approach is that it cannot account for individual farms' characteristics, such as soil type and farmers' ability, which farmers know quite well but water regulators do not. For this reason it is preferable to avoid inflexible restrictions and let farmers make their own input–output decisions, while pricing water at a level that reflects the cost of water supply and water scarcity. Problems of asymmetric information between irrigators and water policy makers are discussed in Tsur (2000).

(ii) Farmers are required to cover 40 per cent of fixed (investment) costs: 30 per cent on a per area basis and 10 per cent as a volumetric charge. How much of the fixed costs to impose on farmers will affect income distribution between farmers and other groups, but will not affect efficiency so long as it is not imposed volumetrically. Pricing (some of) the fixed cost volumetrically involves efficiency implications: the part (10 per cent) of the fix costs that is charged volumetrically should be abandoned; it should either be levied on the society at large or, if imposed on farmers, on a per area basis (see discussion in section 2).

(iii) Exempting small farms ($\leq$ 20 hectares) from the fixed cost charge is likely motivated by income distribution concerns.

(iv) Covering all O&M costs by the volumetric charge is appropriate when these costs are part of the variable cost of water supply (see discussion in section 2).

5. Concluding comments

As the competition for water increases, the irrigation sector must manage its shrinking water supplies more efficiently. In this paper we investigate the use of water pricing to achieve this goal. First the underlying economic principles are discussed and clarified and the ensuing policy recommendations are pointed out. The theory is then applied to three regions, located in three different countries, which vary in almost any respect, including physical and economical conditions and data availability.

The district analyses demonstrate that similar pricing policies may have very different impacts under different conditions, as reflected in the shape (elasticity) of the derived demand for water curves, e.g., the steeper (inelastic) the demand curve the less responsive farmers are to changes in water prices.

In general, farmers' response to water prices depends on endogenous variables (crop mix) and on a variety of exogenous conditions, including farm size, soil type, water supply reliability, existing water institutions, prices of other inputs and outputs, extension and availability of appropriate technologies, production quotas, and access to market and credit. The analysis considers only the effect of farm size. Effective policy interventions should account for the other conditions as well.

The ability of farmers to respond to changes in water price depends to a large extent on their capacity to adapt, e.g., by changing technology, crop mix, or both. If farmers are restricted to a small set of crops because of agronomic-climatic conditions or lack of know-how due to inappropriate extension services, it will be reflected in the shape of their derived demand. The same applies when farmers are restricted (administratively) in their crop selection or are limited in the quantity to produce because of marketing restrictions.

Farmers' adaptability depends, inter alia, on water institutions, such as the water user organization. For example, in the Loskop irrigation district (South Africa) a wide range of crops can be grown and this enables farmers to respond better to policy interventions. Farmers of the Harran Plains Irrigation Scheme in Turkey, however, are limited in their crop selection and this shows up in their derived demand for irrigation water.

In the case of the Rmel-Drader perimeter of the Loukkos ORMVA in Morocco, the derived demand for irrigation water is affected by the constraint on strawberry production dictated by EU regulations. This constraint implies that only 25 per cent of the water in the perimeter is used for high-value crops (strawberries) and the rest for low-value alternatives, which affects the shape of the water derived demand curve.

References

BenAbdelrazzik, H. (2000), 'Pricing of irrigation water in Morocco', Country Report, Guidelines for Pricing Irrigation Water, World Bank, Washington, DC.

Cakmak, E.H. (2000), 'Pricing of irrigation water in Turkey', Country Report, Guidelines for Pricing Irrigation Water, World Bank, Washington, DC.

Dinar, A. (1998), 'Water policy reforms: informational needs and implementation obstacles', *Water Policy* **1**: 367–382.

Fuss, M. and D. McFadden (eds) (1978), *Production Economics: A Dual Approach to Theory and Applications*, Amsterdam: North-Holland.

Gleick, P.H. (1997), 'Water and conflict in the twenty-first century: the Middle East and California', in D. Parker and Y. Tsur (eds), *Decentralization and Coordination of Water Resource Management*, Boston: Kluwer Academic Publishers, pp. 411–428.

Gleick, P.H. (1992), 'Effects of climate change on shared fresh water resources', in I.M. Mintzer (ed.), *Confronting Climate Change: Risks, Implications and Responses*, Cambridge: Cambridge University Press, pp. 127–140.

Howitt, R. (1995), 'Positive mathematical programming', *American Journal of Agricultural Economics* **77**: 329–342.

Johansson, R.C., Y. Tsur, T.L. Roe, R.M. Doukkali, and A. Dinar (2002), 'Pricing and allocation of irrigation water: a review of theory and practice', *Water Policy Bulletin* **4**: 173–199.

Postel, S. (1999), *Pillars of Sand: Can the Irrigation Miracle Last?* New York: W.W. Norton & Co.

Schur, M. (2000), 'Pricing of irrigation water in South Africa', Country Report, Guidelines for Pricing Irrigation Water, World Bank, Washington, DC.

Tsur, Y. (2000), 'Water regulation via pricing: the role of implementation costs and asymmetric information', in A. Dinar (ed.), *The Political Economy of Water Pricing Reforms*, New York: Oxford University Press (Published for the World Bank), pp. 105–120.

Tsur, Y. and A. Dinar (1997), 'On the relative efficiency of alternative methods for pricing irrigation water and their implementation', *World Bank Economic Review* **11**: 243–262.

Tsur, Y. and A. Dinar (1995), 'Efficiency and equity considerations in pricing and allocating irrigation water', Policy Research Paper 1460, World Bank, Washington, DC.