1. Executive Summary

The notion of economic efficiency is concerned with the totality of wealth that can be generated by a given resource base. Equity concepts, on the other hand, deal with how the total wealth is to be distributed among the society's members. The former receives much more attention, as concept of Pareto Efficiency (i.e., an allocation from which it is impossible to depart without making one or more individuals worse off) captures center stage in Neo-Classical Economics. One reason, perhaps, is that distributional aspects entail interpersonal comparisons which are inherently subjective (i.e., involve value judgment which varies from person to person depending on cultural, traditional and other personal variations).

In this work we investigate efficiency and equity performance of various irrigation water pricing methods. We begin, in the next section, with a summary of water pricing practices as applied in a number of countries. Section 3 defines efficiency concepts in the context of water pricing and evaluates the performance of the different pricing methods in this regard. Section 4 discusses descriptive and normative income inequality measures. Effects on income inequality of the different pricing methods are identified in Section 5. Section 6 concludes with a numerical example.

In general, efficiency of water use is attainable whenever the pricing method affects the demand for irrigation water. The volumetric, output, input tiered and two-part tariff schemes all satisfy this condition and can achieve efficiency, though the type of efficiency (short or long run, first or second best) vary from one method to the other. These methods also differ in how they are implemented and the amount and type of information needed in their implementation. Pricing schemes that do not influence water input directly, such as per unit area fee, lead to inefficient allocation. Such methods, however, are in general easier to implement and administer and they require a modest amount of information.

Concerning equity performance, our (unfortunate) conclusion is that the extent to which water pricing methods can affect income redistribution is rather limited. Farm income disparities are due mainly to such factors as farm size and location, and soil quality, but not to water (or other input) prices. We find that when farmers are per-hectare identical in production (i.e., vary only with farm size), face the same prices, and no quantity quotas are applied, the income distribution profile under most water pricing methods is proportional to the initial farm size distribution profile. Since measures of income inequality (with the exception of the variance) are not sensitive to proportional shifts in income, inequality is due solely to the farm size inequality and is independent of the pricing method or water rates used.

Pricing schemes that do not involve quantity quotas cannot be used in policies aimed at affecting income inequality. This includes the volumetric, output, input, tiered, and per-hectare pricing methods, among others. To affect income inequality, a water pricing method should include certain forms of water quantity restrictions.

These results lend some support to the view that income redistribution policies should not be carried out via water prices (see, e.g., Seagraves and Easter, 1983); not because it involves wrong doing but because water prices serve as a poor means to reduce income inequality. However, pricing schemes that involve water quota rules can reduce income inequality. We demonstrate this with a two rate tiered pricing scheme combined with equal quotas of the cheaper water.

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2. Practices of Irrigation Water Pricing

2.1. Costs of delivery and methods of charge

Costs of irrigation water supply consist of variable costs of processing and delivering the water to end users and of fixed cost of capital operation and maintenance (O&M). Variable costs depend on the amount of water delivered, while fixed costs do not. In most countries, fixed costs are heavily subsidized (UN, 1980).

The method by which irrigation water is delivered affects the variable cost, as well as the irrigation technology applied and the feasible pricing schemes. Water may flow continuously or in certain time periods (in which case it may or may not be delivered upon demand); the conveyance system may consist of open channels or closed pipes. Often, the irrigation water in a region is delivered by more than one method, depending on tradition, physical conditions, and water facilities and institutions (UN, 1980).

Existing water pricing methods include (Rhodes and Sampath, 1988; Sampath, 1992):

Volumetric: Water is charged based on direct measurement of volume of water consumed. Variation 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 for even if not consumed.

Output: Irrigation water is charged on per output basis (irrigators pay a certain water fee for each unit of output they produce).

Input: Water is charged by taxing inputs (irrigators pay a water fee for each unit of a certain input used).

Per unit 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, the 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 acre charges also for the unirrigated acres.

Tiered Pricing: 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: 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: In some developed economies, markets for water or water rights have been formed and determine water prices.

Bos and Walters (1990) investigated farmers representing 12.2 million hectares (1 hectare = 10 dunams $\cong$ 2.5 acres) of irrigated farms world wide and found that in more than 60% of the cases, water charges are levied on per unit area basis. In less than 15% of the irrigation projects, water is charged based on a combination of per unit area and volumetric. In about 25% of the cases studied, the charging method is volumetric.

2.2. Pricing practices in developing countries

The information in this section has been collected based on many sources. Some of the information may be out dated both in terms of price levels, and in terms of water charge system.

Armenia: The Armenian irrigation system was designed to serve big collective farms. It is based mainly on supply of surface water, and is amended in some places by tube wells that are operated by individual farmers. Presently, energy cost for pumping irrigation water is fully subsidized. The pricing system intends to recover O&M costs by per area charges. However in 1992, the collection rate of the water charges was only 27% (World Bank, 1994a).

China: Most Chinese irrigation facilities are publicly owned. Large and medium irrigation projects are managed by government water organizations. Small projects are generally owned by local, collective farmers' organizations. Methods used to charge for irrigation consist of a combination of the per unit area, output and a fixed capital and O&M fee. The rates vary across projects. The irrigation water charge per hectare in rice dominant Dujiangyan from 1940 through mid 1980s was 57-75 kg/hectare of husked rice plus 1/2 day of labor provided annually for repairs and maintenance. In the cotton dominant irrigation area of Jin-wei in the Shaanxi province, since 1956 farmers are charged 10.5 yuan per hectare for their entire irrigable land plus 7.5 yuan for each hectare actually irrigated (2.67 yuan = $US1 in 1971). Chinese irrigation water charges, in general, fall short of capital depreciation and O&M expenses (Guohua, 1987).

Egypt: Farmers are not required to pay for irrigation water. They are responsible, however, for the maintenance of the irrigation canals (*mesqas)* and ditches that are attached to their fields (Arar, 1987).

India: Irrigation pricing practices vary throughout the country, depending on geographical locations, the command area of the project (region, state, country), the system of irrigation (storage, diversion, pumped), crops, seasons, the nature of agreement (long lease, short lease), and the procedure used to extract penalties for unauthorized use (Gole, Amble, Chopra, 1977). Some examples of pricing practices are (United Nations, 1980): (a) Per unit area charges that vary from crop to crop and/or across seasons. (b) Per unit area charges that vary according to the method of irrigation (flood, ridges and furrows). (c) Per unit area charges agreed upon for one or more years (to be paid whether or not water is used). (d) Volumetric rate per estimated volume of water consumed, applied generally in areas with pumped irrigation and tubewells (estimates are based on crop water requirements). (e) Penalty rates per acre charged for use of water in an unauthorized manner or for wasting water. (f) Percolation rates charged for each cultivated acre within 200 yards of a canal which receives percolation or leakage water from the canal. (g) A flat charge per unit area covering all areas serviced by the project, whether or not actually irrigated during a given season or year. (h) A betterment levy, applied per unit area served by the project. Water charges to farmers in Tamil Nadu in 1993 were 200-210 Rs/ha (In 1993, 31.5 RS = $US1). This rate is considered to be amongst the highest water charges in India (World Bank, 1994c).

Indonesia: Farmers are not charged for the water they use, but they are responsible to maintain and operate the tertiary-level facilities (the part of the water conveyance facilities that run through their fields). These activities are administered by Water Users Organizations or by village governing bodies (Sampath, 1992).

Iraq: Per unit area charges are applied. In 1983, rates were 1 Iraqi Dinar per dunam (1ID = $US2.7; 1 dunam = 0.1 hectare) of reclaimed land which is irrigated by irrigation network owned by the government and 1/2 Dinar/dunam of reclaimed land or orchard that is irrigated by non-government means (Arar, 1987).

Jordan: The country faces a severe water scarcity. Irrigation is the major user. Crop water requirements vary substantially between regions due to soil and climatic conditions. Upland irrigation is based mainly on ground water extraction. Private wells are not monitored. The cost of pumped water in 1993 is estimated at 50 fills/m^3. In the Jordan Valley, water is provided through pipes to more than three quarters of the irrigated land. A volumetric pricing is used. Water is greatly under priced. In the East Ghore canal (Jordan Valley Irrigation Project) farmers were charged 3 fils/m^3 (1000 fils = 1 Jordanian Dinar = $US2.85 in 1986) for the first 1.5 meter of irrigation depth and 6 fils/m^3 for any additional amount. O&M costs alone are estimated at 20 to 30 fils/m^3 (Arar, 1987). In 1993, all irrigation water in the Jordan Valley were priced at 6 fils per m^3 (in 1993 1 Jordanian Dinar = $US1.5) irrespective of volume used (Hayward and Kumar, 1994).

Mexico: Volumetric, per unit area, and crop and tiered methods are used. The Volumetric method is used in 55 percent of the irrigated land. For each farmer, water rates vary with the total amount used as well as with the crop grown. In the other 45 percent of the area, the pricing method consists of a per unit area rate that varies with the season, the crop, the size of well from which water is pumped and the land tenancy structure (United Nations, 1980).

Moldova: Irrigation in Moldova is supplemental in some years, and used for drought mitigation in other years. Irrigated area is about 220,000 ha Currently, water charges are not paid by the agricultural sector and the irrigation water delivery cost is fully paid by the government (Herman, 1995).

Morocco: Agriculture uses 92 percent of water resources in Morocco. Most water originates in rainfall and snow melt that is harvested by big dams and delivered by a long canal system. Some areas have ground water supply to amend surface water. Volumetric pricing is mostly used, either measuring volume directly, or via conversion of flow time. Water rates do not cover the cost of water. Rates differ based on the region. They range according to Arar (1987) between Dh 0.22/m^3 and Dh 0.27/m^3 (1 Dh = $US0.113 in 1986). Recent information (World Bank, 1994d) suggests that rates range between Dh 0.12/m^3, for gravity irrigation and Dh 0.33/m^3, for Sprinkler irrigation (1 Dh = $US0.111 in 1993).

Nigeria: Per area pricing is used. River Basin authorities are empowered to charge (in consultation with the government) a fee for irrigation water. Each River Basin Authority decides on the appropriate rate. In general the charges range between N15 - N100 per hectare of irrigated land (N1 = $1). No charge is imposed on ground water (Akinola, 1987).

Pakistan: Water charges are on per unit area basis and vary across provinces, crops and seasons. Though water rates vary considerably among crops, this variation is unrelated to consumptive crop water requirements or income generated by the different crops. Water charges depend also on whether the flow of water in the canal is continuous or not. In the publicly funded project of SCARP (Salinity Control and Reclamation project) water rates are higher than in privately funded areas. In the present system, an irrigation *patwari* (an assessor) assesses the water rates on the basis of crop conditions. The assessor is a poorly paid official who enjoys a considerable power within his area of jurisdiction, typically encompassing 4 or 5 villages. The incentive for bribes is apparent (Chaudhry, 1987). In 1981, the per acre water charges were Rs21.6/acre for wheat, Rs32/acre for rice, Rs33.6/acre for cotton and Rs61.6/acre for sugar cane (11.52 Rupee = $US1 in 1981, and 28.11 Rupee = $US1 in 1993).

Peru: Per unit area method is used which consists of national tariffs and local fees. The national tariffs, which vary across crops, cover the costs of administration and O&M provided by the Ministry of Agriculture through its irrigation districts. Local fees are levied by the local user associations to pay for their investments, canal cleaning and flood protection activities. When water is plentiful it is supplied with no limitation. When water is scarce and highly variable, it is distributed in the canals on a rotational basis (United Nations, 1980). The existing legislation prescribes two types of water tariffs (for agricultural and non-agricultural uses), but neither reflects the true cost of producing the water. In agriculture, the tariff includes three components: (1) a water user association component to meet O&M expenses, (2) A water levy component, and (3) an amortization component to recover cost of public investment, mainly storage (World Bank, 1995)

Philippines: A uniform rate of P12/hectare/year was collected from all water users until 1964 (1 P = $US0.05 in 1980). The National Irrigation Administration increased the charges and adopted a dual pricing scheme in 1966 at a rate P25/hectare in the wet season and P35/hectare in the dry season. Non-rice and corn lands paid P20/hectare. In 1975, the pricing method was changed to output/area basis with the rates of 100 kg/hectare in wet seasons and 150kg/hectare in dry seasons. A higher rate of 175 kg/hectare was collected in irrigation projects located in Central and Northern Luzon and Mindoro to offset regional disparities in irrigation service. Additional water rights fees per volume of water were introduced in 1976 by the National Water Resources Council (an autonomous agency in charge of the management of all water resources in the country). These rates change progressively with the amount of water used (Cruz et al., 1987).

Zimbabwe: Water charges are mostly on a per unit area basis, and vary with crop according to crop return. A revised payment scheme, instituted in 1986, consists of a uniform rate designed to secure water supply and crop gross margins. A latest proposal is to base water charges on average net profitability of the two major crops in the country (Mudimu, 1987).

2.3. Pricing practices in developed countries

Australia: The price of public irrigation water has generally been set to cover, on an average cost basis, only part of annual servicing (maintenance and operation) costs and has often excluded completely the cost of capital. Two water market experiments in transferring irrigation rights were undertaken on a trial basis. In New South Wales, the annual water entitlements were recently made transferable for a one year trial. In South Australia, water rights have been transferable (saleable) in private irrigation areas (OECD, 1987).

California (**USA):** Multi-rate Volumetric pricing of publicly supplied water is common (depending on the irrigation district) . Prices range between $2/Acre- Foot (AF) to more than $200/AF (1 AF = 1256 m^3). On average, farmers paid about $5/AF for federal Central Valley Project water during 1988, compared with $48/AF average capital depreciation cost and $325/AF average marginal cost of delivery (Rao, 1988). Cummings and Nercissiantz (1992) estimated average water price at $19.32/AF, which they claimed covers a mere 39 per cent of the estimated scarcity value (the *in situ* value of groundwater). The recent prolonged drought in California has led to the development of innovative water banks and water markets through which water prices are determined (see Easter and Tsur, 1992).

Canada: Per area pricing is common. In Alberta, farmers pay a one-time charge of up to $50/acre to cover capital costs, and an annual charge of $1.50 to $10.00 per acre to cover some operating expenses. These amount to about 14 percent of the cost of capital and other operating expenses (OECD, 1987).

England and Wales: Multi-rate volumetric pricing is common. Water authorities vary greatly in the sophistication of their charging systems. For example, in 1984/5, the Wessex Water Authority had 9 rates of charge and the Yorkshire Water Authority 45 rates (OECD, 1987).

France: Irrigation water is commonly priced by a two-part tariff method, which consists of a combination of a volumetric and a flat rate. In 1970, the *societe du Canal de Provence et* *d'Amenagement de la Region Provencal*, which supplies 60,000 hectares of farmland and nearly 120 communes, introduced a pricing scheme in which rates vary between peak demand and off-peak periods. The peak period rate is set to cover Long-run capital and operating costs. The off- peak rate is set to cover only the operating costs of water delivery. About 50 percent of total supply costs (variable and fixed) are subsidized by the state (OECD, 1987).

Greece: Per area charges are common. The proceeds usually cover only the administrative costs of the irrigation network. The irrigation projects are categorized as basic, local and private importance and the project areas are also classified as areas of national, public or private interest. The parts of the capital (development) costs of an irrigation project paid by farmers are 30%, 50%, and 40% for project classified as national, public and private interest, respectively (Gole et al., 1977).

Israel: A multi-rate volumetric method coupled with quantity regulation is used to price publicly supplied water. Farmers entitlements for water quantities at the different rates vary from year to year based on precipitation. Water rates are the same for all, which means that farmers in the rainy north pay above supply cost while farmer in the dry south pay below it. Water rates cover only a small part of capital depreciation (Tahal, 1993).

The pricing methods discussed above and their characteristics are summarized in Table 1 below.

Table 1: Summary of Irrigation Pricing Practices in Selected Countries

Country	Basis of Water Charging			Cost Recovey		Remarks
	Volume	Area	Others	O & M	Capital	
I. DEVELOPING COUNTRIES						
China		Yes	vary with crop.	partly	No	Paid in output/hectare + labor contribution.
Egypt				No	No	No charges; responsible for O&M of tertiary facilities.
India	Yes	Yes (Ground Water)	vary with crop and season.	partly	partly	wide divergence in methods of charging across the country.
Indonesia				No	No	No charges; responsible for O&M of tertiary channels.
Iraq		Yes				Government owned systems charge twice the rate of non-governmental systems.
Jordan	Yes			partly	No	Water supplied on demand.
Mexico	Yes	Yes	Combination of volumetric and area; vary with season & crop.	partly	No	Many different sophisticated pricing methods practiced across the country.
Morocco	Yes			mostly	partly	
Nigeria		Yes		partly	No	
Pakistan		Yes	vary with crop, perennial flow, government or private project.	partly		

Table 1: Summary of Irrigation Pricing Practices in Selected Countries (Cont'd)

Country	Basis of Water Charging			Cost Recovey		Remarks
	Volume	Area	Others	O & M	Capital	
Peru		Yes		partly	partly	Water is charged only in scarcity regions.
Phillipines		Yes	vary with season & crop.	partly	N. A.	Additional Water rights fee charged.
Zimbabwe		Yes		partly	No	New uniform charges based on crop profitability levied.
II. DEVELOPED COUNTRIES						
Canada		Yes		partly	partly	
England & Wales	Yes		A variety of pricing systems.	partly	partly	
France	Yes	Yes	A combination of volumetric and area based.	partly	partly	Peak and off-peak rates are used.
California, U.S.A.	Yes		vary with topography, ownership, extent of subsidy.	partly	partly	Water entitlement vary with preci-pitation; water markets begin to emerge.
Israel	Yes		Tier pricing; penalty for excess use.	partly	partly	Ninenty percent of irrigation uses sprinkler and drip; water entitle-ments vary with precipitation.

3. Efficiency Performance of Pricing Methods

3.1. Efficiency concepts

An efficient allocation of water resources (or any other resource) is an allocation that maximizes the total net benefit that can be generated by the available quantity of the resource. If the net benefit to be maximized involves only variable costs and abstracts from (imputed) annual capital and other fixed costs, the efficiency is that of a short run. In the absence of taxes or other distortionary constraints, an efficient allocation is first-best (or Pareto efficient). In the presence of distortionary constraints, an allocation that maximizes the total net benefit under the constraints is called second-best efficient (see Baumol and Bradford, 1970). Such is the situation, for example, when taxes exist that distort input output decisions. In this section we discuss the performance of the above listed pricing schemes vis-a-vis efficiency criteria.

3.2. General setup

Let there be n farmers, indexed i=1,2,...,n, that extract/divert water from the irrigation project (or any source of water). Let L_i denote land endowment (farm size) of farmer i measured, say, in hectare (ha). Let q and x denote respectively per hectare water and other (possibly more than one) inputs of production. Let $g_i(x,q)$ represent farmer i's per hectare production function, indicating the maximum output that can be produced for any feasible choice of inputs x and q.

Let p represent output price and r be the price of x. Water charges can be applied directly, i.e., per unit of water used (volumetric), or indirectly on a per output, input or hectare basis. Accordingly, let z^w, z^g, z^x and z^a represent the water fees charged per volumetric unit of water, unit of output, unit of input and on a per hectare basis, respectively. Let $z = (z^w,z^g,z^x)$.

The operating profits are

$$y_i = (p-z^g)g_i(x,q) - z^wq - (r+z^x)x - z^a, \; i=1,2,...,n. \tag{3.1}$$

Profit seeking farmers choose q and x to maximize y_i, the necessary conditions for which are

$$(p-z^g)g_{ix}(x_i^*(z),q_i^*(z)) - (r+z^x) = 0 \qquad (3.2a)$$

and

$$(p-z^g)g_{iq}(x_i^*(z),q_i^*(z)) - z^w = 0 \qquad (3.2b)$$

where $g_{ix} \equiv \partial g_i/\partial x$, $g_{iq} \equiv \partial g_i/\partial q$, $p-z^g>0$, and p,r are suppressed as arguments of x^* and q^* for convenience. The solutions $q_i^*(z)$ and $x_i^*(z)$ of (3.2), when feasible, are the input demand functions, which when substituted back in (3.1) give the per- hectare indirect profit functions

$$y_i(z,z^a) = (p-z^g)g_i(x_i^*(z),q_i^*(z)) - z^w q_i^*(z) - (r+z^x)x_i^*(z) - z^a \qquad (3.3)$$

So far, we have considered the case of a single crop. Often farmers can switch between a few crops, each with its specific production function and water requirement. In such cases, let the subscript j=0,1,2,...,m indicate the corresponding function for crop j, with j=0 signifying unirrigated farming. Accordingly, $g_{ij}(x,q)$ is farmer's i per-hectare production function for crop j, x_{ij}^* and q_{ij}^* are the per-hectare inputs demanded by farmer i for crop j, $(z_j,z_j^a) \equiv (z_j^w,z_j^g,z_j^x,z_j^a)$ represent water fees for crop j, and y_{ij} are the per- hectare profits.

In addition to input/output choices for each crop, farmers must also decide on the mix of crops to grow. Avoiding such considerations as crop rotation, constrained regulations on x and q, or yield and price uncertainties, at any given water prices configuration $(z,z^a) \equiv \{z_j^w,z_j^g,z_j^x,z_j^a, j=0,1,2,...,m\}$, each farmer will grow only one crop: the crop that yields the highest per-hectare profit. Farmer i's crop decision, thus, can be represented by the indicator function

$$I_{ij}(z,z^a) = \begin{cases} 1 \text{ if } y_{ij}(z,z^a) > y_{ik}(z,z^a) \text{ for all } k \neq j \\ 0 \text{ otherwise} \end{cases}$$ **Error! Switch argument not specified.**

(ties are determined arbitrarily). That is, $I_{ij}=1$ if farmer i chooses crop j and $I_{ij}=0$ otherwise. Farmer i's per-hectare input demands, output and profit are:

Water: $q_i^*(z,z^a) = \sum_{j=0}^{m}$ **Error! Switch argument not specified.**$I_{ij}(z,z^a)q_{ij}^*(z,z^a)$

Other inputs: $x_i^*(z,z^a) = \sum_{j=0}^{m}$ **Error! Switch argument not specified.**$I_{ij}(z,z^a)x_{ij}^*(z,z^a)$

Output: $g_i(x_i^*(z,z^a),q_i^*(z,z^a)) = \sum_{j=0}^{m}$ **Error! Switch argument not specified.**$I_{ij}(z,z^a)g_{ij}(x_{ij}^*(z,z^a),q_{ij}^*(z,z^a))$

and

Profit: $y_i(z,z^a) = \sum_{j=0}^{m}$ **Error! Switch argument not specified.**$I_{ij}(z,z^a)y_{ij}(z,z^a)$.

The aggregate water demand of all farmers is

$Q(z,z^a) = \sum_{i=1}^{n}$ **Error! Switch argument not specified.**$L_i q_i^*(z,z^a)$. (3.4)

A change in $z = \{z_j^w, z_j^g, z_j^x, j=1, 2,..., m\}$ affects water demand in two ways. First, it changes the per-hectare water demand functions--the $q_{ij}^*(z,z^a)$'s. Second, it affects the crop choice--the $I_{ij}(z,z^a)$'s. For example, raising water price z_j^w for all crops j will decrease $q_{ij}^*(z,z^a)$ for all crops, and may lead to some farmers switching from water intensive crops to water saving crops.

A change in the per-hectare water fees, z_j^a, j=0,1,2,...,m, has no effect on the per-hectare water demands of each crop, but it can affect the crop choice. For example, raising z_1^a relative to z_2^a may lead to some farmers switching from crop 1 to 2. An extreme case occurs when large z_j^a, j=1,2,...,m, relative to z_0^a causes some farmers to switch to dryland farming or to retire farmland from production altogether.

On the water supply side, let $C(Q)$ represent the cost of supplying Q m^3 of irrigation water at a given time period (a year, say), so that $C'(Q) \equiv \partial C/\partial Q$ is the MC of water supply. The short run water supply may be constrained (due to water scarcity or a capacity limit on the conveyance system or both), so that $Q \leq \overline{Q}$

The overall benefit (B) associated with supplying Q m^3 of water at a fee structure $(z^w,z^g,z^x,z^a) \equiv (z,z^a)$ is

$B(z,z^a) = \sum_{i=1}^{n}$ **Error! Switch argument not specified.**$L_i y_i(z,z^a) - C(Q(z)) + \sum_{i=1}^{n}$ **Error! Switch argument not specified.**$L_i[z^g g_i(x_i^*(z),q_i^*(z))+z^w q_i^*(z)+z^x x_i^*(z)+z^a)]$

or, using (3.3),

$B(z) = \sum_{i=1}^{n}$ **Error! Switch argument not specified.**$L_i[pg_i(x_i^*(z),q_i^*(z)) - rx_i^*(z)] - C(Q(z)).$ (3.5)

For clarity of exposition we maintain the single crop case, unless otherwise indicated.

3.3. Volumetric pricing

In this method $z^g=z^x=z^a=0$ and water is priced directly via z^w. A volumetric pricing policy in which the price of water is set at the marginal cost (MC) of water supply (i.e., the cost of processing and delivering the last water unit) is called *marginal cost pricing*. Such a policy achieves first best efficiency.

To see this note that the necessary condition for maximizing the benefit (3.5) with respect to z^w is

$\sum_{i=1}^{n}$ **Error! Switch argument not specified.**$L_i[pg_{iq}(x_i^*(z^w),q_i^*(z^w)) - C'(Q(z^w))]\ q_i^{*'}$ **Error! Switch argument** provided $Q(z^w)$ does not exceed the capacity limit $\overline{Q}$. But, from (3.2), $pg_{iq}(x_i^*(z^w),q_i^*(z^w)) = z^w$ for all i, hence (3.5) implies $z^w = C'(Q(z^w))$, which is the marginal cost pricing rule. The marginal cost pricing policy, thus, leads to an efficient allocation (the sufficient condition is satisfied when the g_i's are concave in x,q and C is convex).

A departure from marginal cost pricing may be required if the objective (3.4) is to be maximized subject to additional constraints. Such constraints may, for example, require that the proceeds from selling the water should cover also capital depreciation and other fixed costs. Volumetric pricing in this situation can achieve second best efficiency.

3.4. Output and input pricing

The output method corresponds to the case where z^w, z^x and z^a vanish and only z^g is used. The output fee that maximizes the benefit (3.5), if it exists, must satisfy the first order condition

$$\sum_{i=1}^{n} \textbf{Error! Switch argument not specified.} L_i[(pg_{ix}(x_i^*,q_i^*)-r)x_i^{*\prime} - C'(Q)q_i^{*\prime}] = 0$$

which, using (3.2), can be written as

$$\sum_{i=1}^{n} \textbf{Error! Switch argument not specified.} L_i[z^g g_{ix}(x_i^*,q_i^*)x_i^{*\prime} - C'(Q)q_i^{*\prime}] = 0 \qquad (3.7)$$

where $x_i^{*\prime} \equiv \partial x_i^*/\partial z^g$, $q_i^{*\prime} \equiv \partial q_i^*/\partial z^g$.

In general there may not exist a fee $z^g \in [0,p)$ that satisfies (3.7). However, when farmers are per-hectare identical, i.e., $g_i(x,q) = g(x,q)$ for all i=1,2,...,n, a feasible z^g that satisfies (3.7) may exit. This is the case, for example, when g(x,q) is increasing and strictly concave in q and x, and $g_{qx} \equiv \partial^2 g(x,q)/\partial q\partial x > 0$. To see this note that when per-hectare input demands are identical across farmers, (3.7) can be written as

$$z^g g_x(x^*,q^*)x^{*\prime} - C'(Q)q^{*\prime} = 0. \qquad (3.8)$$

Now, both $q^{*\prime} \equiv \partial q^*/\partial z^g$ and $x^{*\prime} \equiv \partial x^*/\partial z^g$ are negative when g(q,x) is strictly concave, $g_{qx}>0$ and $p>z^g$.[1] Assuming $C'(Q)>0$ and noting from (3.2) that $g_x(x^*,q^*) = r/(p-z^g)$, we conclude that, provided $p < 1 + rx^{*\prime}/(C'(Q)q^{*\prime})$,

$$z^g = \frac{p}{1 + rx^{*\prime}/(C'(Q)\,q^{*\prime})} \tag{3.9}$$ **Error! Switch argument not specified.**

satisfies (3.8) and is the optimal fee level.

However, this is a second best efficiency, because the output fee and the zero price of water may distort input/output decisions. The outcome attained under output pricing, thus, is likely to fall short of that under marginal cost pricing.

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[1] To see this, total differentiate the first order conditions (3.2a-b) with respect to z^g, setting $z_w=z_x=0$ and using $g_q=0$ and $g_x=r/(p-z^g)$, to obtain

$$g_{xx}x^{*\prime} + g_{xq}q^{*\prime} = r/(p-z^g)^2 \quad \text{and} \quad g_{xqx}x^{*\prime} + g_{qq}q^{*\prime} = 0,$$

or, written compactly,

$$\begin{pmatrix} g_{xx} & g_{xq} \\ g_{qx} & g_{qq} \end{pmatrix}\begin{pmatrix} x^{*\prime} \\ q^{*\prime} \end{pmatrix} = \begin{pmatrix} r/(p-z^g)^2 \\ 0 \end{pmatrix}.$$ **Error! Main Document Only.Error! Main Document Only.**

Applying Cramer rule yields

$$x^{*\prime} = \det\begin{pmatrix} r/(p-z^g)^2 & g_{xq} \\ 0 & g_{qq} \end{pmatrix} / \det\begin{pmatrix} g_{xx} & g_{xq} \\ g_{qx} & g_{qq} \end{pmatrix}, \text{and } \ q^{*\prime} = \det\begin{pmatrix} g_{xx} & r/(p-z^g)^2 \\ g_{qx} & 0 \end{pmatrix} / \det\begin{pmatrix} g_{xx} & g_{xq} \\ g_{qx} & g_{qq} \end{pmatrix}$$

The strict concavity of g ensures that the denominator is positive, and $g_{qq}<0$, $g_{qx}>0$, and $p-z^g>0$ imply that the numerators are both negative.

Moreover, the restrictions needed to achieve the second best efficiency (identical per hectare production technologies g_i across farmers and complimentarity relation between water and another input of production) are avoided by the marginal cost pricing rule when water is priced directly.

It should be noted, however, that the benefit measure B abstracts from agency cost and the cost of collecting information associated with implementing the water pricing policies. The advantage of output pricing is that it does away with the need to measure water inputs of individual farmers, which in many developing countries is an expensive (or even impossible) task. Output, on the other hand, is easier to measure.

In the input pricing method, z^w, z^g and z^a are set equal to zero and only z^x is used. With a few obvious modifications, the analysis of this case follows that of the output pricing method. As in the previous case, the benefit under input pricing policy is smaller than that under marginal cost pricing. The performance of the input pricing method relative to that of the output pricing varies from case to case, depending on the production technology g(x,q).

3.5. Per area pricing

Here z^w, z^g and z^x vanish and only z^a is used: Farmers pay a fixed fee per hectare for the right to receive irrigation water; once this fee is paid, water is supplied upon request, free of charge. In the single crop case, the per hectare input demands are independent of the fee z^a and water demand exceeds that under volumetric pricing for any positive water price z^w. Thus, the demand for irrigation water is larger than that under the marginal cost pricing rule and the resulting allocation is inefficient.

Yet this scheme is easy to administer and, unlike the volumetric method, does not require the water conveyance facilities to be metered. Moreover, in the multiple crop case, it is possible to influence water demand directly by differential fee schemes, in which per-hectare fees vary from crop to crop, that affect farmers' crop choice. Under certain circumstances in the multiple crop case, farmers may select only one crop of the possible set, or a mix of crops. Factors affecting this choice may be behavioral--level of risk aversion of the farmer, or technical--availability of and substitution between factors of production other than water.

3.6. Additional pricing methods

Tiered pricing: This pricing method is common when water demand has periodical (seasonal, daily) variations and water supply is insufficient to meet demand at all times. During low demand periods, when supply exceeds demand, the marginal cost pricing rule achieves (short-run) efficiency (see the discussion of the volumetric method above). During peak demand periods, supply is insufficient to meet demand and the constraint $Q \leq \overline{Q}$ is binding. The water price then should account for water scarcity and is increased by the shadow price of this constraint. Formally, the problem is to maximize (3.5) subject to $Q(z^w) \leq \overline{Q}$. The Lagrangian is

$$L(z^w) = \sum_{i=1}^{n} \textbf{Error! Switch argument not specified.} L_i[pg_i(x_i^*(z^w), q_i^*(z^w)) - rx_i^*(z^w)] - C(Q(z^w)) - \mu(Q(z^w) - \overline{Q})$$

and the necessary condition (3.6), when z^* is substituted for $pg_{qi}(q_i(z_w^*))$, changes to

$$\sum_{i=1}^{n} \textbf{Error! Switch argument not specified.} L_i[z^w - \{C'(Q(z^w)) + \mu\}]\, q_i' \textbf{ Error! Switch argument not specified.}(z^w) = 0,\ \mu \geq 0,\ Q(z^w) - \overline{Q} \leq 0,\ \mu(Q(z^w) - \overline{Q}) = 0$$

During low demand periods, the water supply constraint is not binding, i.e., $Q(z^w) - \overline{Q} < 0$, so that $\mu = 0$ and water is priced at the marginal cost. During peak demand periods, when the water constraint is binding, $\mu > 0$ and water is priced above marginal cost. Such a tiered pricing scheme is a straightforward extension of the single rate marginal cost pricing rule to cases of periodic changes in water demand or water supply or both.

Another tiered pricing method sets the price $\$z_1/m^3$ for the first Q_1 m^3 of water supplied, $\$z_2/m^3$ ($z_2 > z_1$) for the next Q_2 m^3, $\$z_3/m^3$ ($z_3 > z_2$) for the following Q_3 m^3 and so on. If the different water rates are set along the marginal supply curve, it can be shown that this method amounts to discriminating water prices in favor of irrigators (i.e., water consumers). The water supply agency is thus striped of some of its operating profits that could be gained under a single-rate-marginal-pricing policy. For short run efficiency, this reallocation of income has no impact on the overall benefit. In the long run, the reduced profits of the water supplier may be insufficient to cover capital and other fixed costs and long-run considerations have to be incorporated.

Two part tariff: By introducing the admission fixed charge that serves to balance the budget of the water supply agency, this method extends the short run marginal cost pricing rule to account for long run fixed costs considerations. The implementation of the annual admission charge as a Pigouvian poll tax avoids the distortionary effects of other taxing forms. The two part tariff method has therefore been considered as capable of achieving long run efficiency (see Feldstein [1972a-b], and Laffont and Tirole [1993, pp.19-34]).

Water markets: The basic premise of modern economics is that markets, under certain conditions, achieve first-best efficiency. These "certain conditions" include competitive environment (no single agent can affect outcomes), fully informed agents operating under certainty, no externalities, and no increasing returns to scale in production. In the case of water, these conditions are frequently violated. Water is expensive to transport, hence water markets tend to be localized, consisting of a limited number of participants, some of whom may be able to influence outcomes. Water supply is in many cases uncertain. Water resources (e.g., aquifers) may be shared by many users that inflict externalities on each other (e.g., groundwater pumping of one farmer reduces the water level and increases pumping costs to other farmers). Water supply systems, like other public utilities, may exhibit increasing returns to scale. For these reasons, water markets are unlikely to attain a first-best efficient allocation.

Yet, even when distorted, the sub-optimal outcomes of water markets may outperform the other pricing methods when administration, implementation and information costs are taken into consideration. So far, all the pricing methods discussed are operated via some kind of a central (national, regional, district, village) water agency. Such an operation is costly both in terms of administering it and in terms of the information it requires (e.g., regulators may need data on farmers production technologies, inputs and outputs). Water markets do away with these agency (or transaction) costs, thus may, on the whole, achieve a better outcome then any of the other pricing methods. Water markets are only recently beginning to emerge and more experience is needed to assess their performance compared to centralized mechanisms.

3.7. Summary of the efficiency analysis

A *volumetric* scheme that uses the marginal cost pricing rule achieves, when information is costless, first-best (the maximum attainable total benefit) efficiency in the short run. The *output* and *input* pricing methods can achieve second best efficiency in the short run, as the output/input taxes may distort output/input decisions; they are, however, easy to implement and do not require data on water used by farmers. The *tiered* pricing method can achieve first best efficiency in the short run, and a *two part tariff* scheme can achieve that in the long run. *Per area* pricing can affect water input through its effect on crop choices but is inefficient, since once the crop has been chosen, the water fee has no effect on water demand. It is however easy to implement and administer and requires minimal information. *Water markets* achieve first best efficiency when properly operated. When distorted they may still be desirable when agency (monitoring, implementing, data collecting) costs are taken into account.

Table 2: Comparison of key variables of various pricing methods

Pricing Scheme	Implementation	Efficiency Achieved	Time Horizon of Efficiency	Ability to Control Demand
Volumetric	Complicated	First-best	Short-run	Easy
Output	Relatively easy	Second-best	Short-run	Relatively easy
Input	Easy	Second-best	Short-run	Elatively easy
Per area	Easiest	None	N/A	Hard
Tiered	Relatively complicated	First-best	Short-run	Relatively easy
Two part	Relatively complicated	First-best	Long-run	Relatively easy
Water Market	Difficult without pre-estableshed institutions	First-best	Short-run	N/A

4. Equity Measures

Equity is a vague concept that changes colors, shapes and meanings depending on the particular object according to which it is measured (opportunities, needs, incomes, utilities). It has therefore been pushed aside from mainstream economics (and its associated policy prescriptions), overshadowed by less subjective efficiency concepts. Yet, it appears reasonable to require that policies aimed at allocating publicly owned natural resources will not eschew equity considerations altogether. How then are such considerations to be incorporated within water allocation policies? To address this question, we begin with a brief primer (based on Sen, 1973) of economic inequality concepts and their measurements. We then discuss how these concepts can be used to evaluate equity consequences of departure from marginal cost pricing towards the other pricing schemes discussed above.

Inequality measures can be either *descriptive* or *normative*. Descriptive measures simply evaluate the dispersion of the income profile by means of some descriptive statistic. Normative measures are derived from some underlying social welfare function.

4.1. Descriptive measures of income inequality

A widely used measure of dispersion is the variance

$$V = \frac{1}{n}\textbf{Error! Switch argument not specified.}\sum_{i=1}^{n}\textbf{Error! Switch argument not specified.}(y_i-\mu)^2, \tag{4.1}$$

where $\mu = \sum_{i=1}^{n} y_i/n$ is mean income. V equals zero when income is equally divided, and it attains the level $(n-1)\mu^2$ under maximum inequality, when the entire income $\sum_{i=1}^{n} y_i$ goes to one person and the other members get zero income. A weakness of V is its sensitivity to relative shifts in income: an income profile $y' = \beta y$ for some scalar β has a variance $V' = \beta^2 V$. Thus, an income profile that grows proportionally over time is considered less unequal at early stages of growth, when incomes are low, then at later stages when the society is richer.

The coefficient of variation

$C = \sqrt{V}$ **Error! Switch argument not specified.**/μ

avoids this property**.** C possesses the undesirable property of assigning the same impact to income transfers between rich-poor pairs with the same income disparity, regardless of their actual income level (e.g.,, the change in C as a result of a transfer from a person with income 10 to a person with income 1 is the same as a transfer from a person with income 1000 to one with income 991).

A measure that does away with this property is the standard deviation of logarithms defined, for y > 0, as

$H = \left(\frac{1}{n}\sum_{i=1}^{n}(\log y_i - \log\mu)^2\right)^{1/2}$. **Error! Switch argument not specified.Error! Switch argument not specified.Error! Switch argument not specified.** (4.3)

A related index was proposed by Theil (1967), drawing on the idea of entropy in information theory. When normalized to lie between zero and unity, Theil's entropy index has the form

$T = \frac{1}{n\mu\log(n)}$ **Error! Switch argument not specified.** $\sum_{i=1}^{n}$ **Error! Switch argument not specified.**$y_i\log(\frac{y_i}{\mu}$**Error! Switch argument not specified.**). (4.4)

Another inequality measure that uses income/mean ratios is Atkinson's (1970) Cobb-Douglas index

$$A = 1 - \prod_{i=1}^{n}\left(\frac{y_i}{\mu}\right)^{1/n} \qquad (4.5)$$

All the above measures involve income comparisons relative to the mean, which may seem somewhat arbitrary. The Gini coefficient, on the other hand, involves comparison between all income pairs. Ordering incomes so that $y_1 \geq y_2 \geq \ldots \geq y_n$, the Gini coefficient, normalized to lie between zero and unity, takes the following equivalent forms:

$$G = \frac{1}{2n^2\mu}\textbf{Error! Switch argument not specified.}\sum_{i=1}^{n}\textbf{Error! Switch argument not specified.}\sum_{j=1}^{n}\textbf{Error! Switch argument not specified.}\left|y_i - y_j\right|$$

$$= 1 - \frac{1}{n^2\mu}\textbf{Error! Switch argument not specified.}\sum_{i=1}^{n}\textbf{Error! Switch argument not specified.}\sum_{j=1}^{n}\textbf{Error! Switch argument not specified.}\mathrm{Min}\{y_i, y_j\}$$

$$= 1 + 1/n - \frac{2}{n^2\mu}\textbf{Error! Switch argument not specified.}\sum_{i=1}^{n}\textbf{Error! Switch argument not specified.}\, i \cdot y_i. \tag{4.6}$$

Despite the limitations (mentioned above) of some of the indexes, they all satisfy two important properties: (a) renaming members does not change the inequality measure (this has been referred to as the symmetry or anonymity property); and (b) an income transfer from rich to poor, everything else remains the same, decreases the inequality measure.

Ranking Income Profiles Based on the Descriptive Measures: Any two income profiles, say y^1 and y^2, can be ranked according to any of the above indexes: For I=V,C,H,T,A or G,

$I(y^1)$ >, < or = $I(y^2)$ - - -→ {y^1 is more, less or equally unequal as y^2}.

In principle, then, any such descriptive index provides a complete ranking of all possible income profiles.

There are two basic limitations in using descriptive measures to rank income profiles. First, the different measures may contradict each other, in which case ranking depends on the chosen index. This problem is technical in nature and can be mitigated to some extent by considering ranking according to the interaction of some or all of the indexes; e.g., y^1 is at least as egalitarian as y^2 (or y^1 does not exhibit more income inequality than y^2) if $T(y^1) \leq T(y^2)$ and $A(y^1) \leq A(y^2)$ and $G(y^1) \leq G(y^2)$. When two indexes contradict each other for some income profile pairs, these pairs cannot be ranked according to the interaction index (see example in Atkinson, 1970). In technical terms, interaction of indexes generates a quasi-ordering. This may not be considered a drawback, Sen (1973) argues, as completeness may be too much to ask.

Indeed, the widely used inequality ordering rule based on Lorenz curves is incomplete. Under the Lorenz ordering rule, y^1 is more (less) egalitarian than y^2 if its Lorenz curve lies completely above (below) that of y^2; the two are considered equally egalitarian if their Lorenz curves coincide. When the Lorenz curves of y^1 and y^2 intersect, the two income profiles cannot be compared.

The second limitation of using descriptive measures to rank income profiles is more substantial: With the exception of V, descriptive indexes pay no attention to the total income to be allocated. Thus, an income profile y^1 which is twice as large as y^2 ($y^2 = 0.5y^1$) would be ranked as equal by all measures except for V which would rank y^2 above y^1. Yet, when asked to choose between the two profiles, a reasonable person would surly prefer y^1 over y^2 (each member under y^1 receives a higher income than his counterpart under y^2). And a reasonable person would still prefer y^1 over y^2 even when y^1 is slightly less egalitarian than y^2 but its total income is substantially larger than that of y^2. Moreover, often the size of the pie (the total income) is not independent of the rule according to which the pie is divided, as division rules affect production decisions.

Though descriptive measures contain important distributional information, it appears that their limitation is due mainly to their inability to account for inequality vs. total income tradeoffs. This limitation motivates the consideration of normative measures of inequality.

4.2. Normative measures of income inequality

The social welfare function: Underlying all normative indexes is a group welfare function $W(U_1(y_1),U_2(y_2),...,U_n(y_n))$ defined over the n member utilities U_i, which assign a welfare level to any income profile y through the utility members derived from their incomes. (Such group welfare functions escape Arrow’s impossibility verdict and become possible by considering cardinal individual utilities and allowing for interpersonal comparison of utilities; see, Sen, 1973, Chapter 1, and Deaton and Muellbauer, 1980, Chapter 9). To respect individual preferences, W should be increasing in the U_i's. As the individual utilities may be unknown, it is often more convenient to define the group welfare function directly in terms of the income profile y, in which case W(y) is used to represent welfare.

Group welfare functions are required to be *Symmetric* (or anonymous), *quasi- concave* and to be increasing in the y_i's. Symmetry ensures that renaming members leaves W unchanged (the n members are equally important); quasi-concavity implies that a transfer from rich to poor does not decrease W, hence is biased towards egalitarian distributions (Dalton, 1920, was the first to require that the group welfare function should possess this property). Often, *homotheticity* is also imposed (W is homothetic if it can be expressed as a monotone transformation of a linear homogeneous function).

Normative measures of inequality: Given a group welfare function W(y), define the equally-distributed equivalent income y_s as the per capita income that when shared by all members would generate the same welfare level as that derived from the actual income profile (Sen, 1973, p. 42). That is, y_s satisfies $W(y_s,y_s,...,y_s) = W(y_1,y_2,...,y_n)$. Since W is quasi-concave and symmetric, the indifference curves are convex towards the origin and $y_s \leq \mu$. Sen's (1973, p. 42) normative inequality measure is defined as

$$N = 1 - (y_s/\mu). \tag{4.7}$$

Under utilitarian welfare, when $W = \sum_{i=1}^{n} U_i(y_i)$, N is the same as the measure proposed by Atkinson (1970). If, in addition, $U_i(y_i) = y_i$ for all i, then $y_s = \mu$ and $N = 0$ for all income profiles. Indeed, a group welfare function that is concerned with total income only, is the same as the efficiency criterion and is free of any distributional content.

5. Equity Performance of Some Water Pricing Methods

We consider a group of farmers identical in all respects except for their land endowment L_i. Let $L = \sum_{i=1}^{n} L_i$ denote total land and $\lambda_i = L_i/L$ be the share of total land owned by farmer i; $\lambda_i \geq 0$ and $\sum_{i=1}^{n} \lambda_i = 1$. Let $\lambda = (\lambda_1,\lambda_2,...,\lambda_n)$ be the land distribution profile. We now look at the group income profiles under the different pricing schemes, compare their corresponding inequality measures and discuss how they perform on the efficiency scale.

5.1. Volumetric pricing

Here farmers pay $\$z^w$ for each m^3 applied for irrigation. So long as all face the same water price z^w, each farmer demands $q(z^w)$ m^3/hectare and obtains the profit $y(z^w)$ (cf. (3.1) and (3.2)). Farmer i's income is $y(z^w)L_i = y(z^w)L\lambda_i$, and the group income profile is given by $y(z^w)L\lambda$. It follows that z^w affects the income profile through the per hectare income $y(z^w)$, which is common to all farmers. Using the definitions of C, H, T, A and G (cf. Eqs. (4.2)-(4.6)), it is seen that they are all independent of proportional shifts in the income profile, hence they are independent of z^w. Income inequality, in this case, is due solely to the land endowment profile λ.

5.2. Per unit area pricing

Here farmers pay a fixed fee of $\$z^a$ for each irrigated hectare. Assume that this fee does not lead to retiring land from production, so that the land distribution λ remains unchanged. Irrigation water will be applied up to the level where its value of marginal productivity vanishes, yielding the same net per hectare income of $y(0)-z^a$ for all farmers. The resulting income profile is $[y(0)-z^a]L\lambda$. As in the case of volumetric pricing, the income profile is proportional to the land profile $L\lambda = (L_1,L_2,...,L_n)$, hence the descriptive inequality measures C, H, T, A and G are independent of the per hectare fee z^a and income inequality is completely determined by land endowment inequality.

This result holds also in the multiple crop case, as the identical farmers will choose the same crop.

5.3. Output pricing

Here $\$z^g$ is paid (as a water fee) for each output unit. The input decision problem is slightly altered. Let g(x,w) be the output obtained using water input w and other inputs x (see footnote 1). Let p and r represent the output price and the price of x, respectively. The per hectare input decisions entail finding the w and x levels that maximize $y = (p-z^g)g(x,w)-rx$. Out of this exercise come the input demand functions $w(z^g)$ and $x(z^g)$ and the indirect per hectare profit $y(z^g) = (p-z^g)g(x(z^g),w(z^g))-rx(z^g)$, where p and r are suppressed as arguments for notational convenience. As in the other two cases, the per hectare profit is the same for all farmers and the income profile associated with z^g is $y(z^g)L\lambda$, which is proportional to the land profile. Again income inequality is independent of water charges.

5.4. Tiered pricing

Here water rates vary with the total amount of water consumed. Consider a dual rate system with a rate of $\$z_1/m^3$ for the first Q m^3 and $\$z_2/m^3$ ($z_1 < z_2$) thereafter. Implementing this pricing method requires specifying how the first (cheaper) Q m^3 are to be allocated. Two possible scenarios are considered: (a) an equal amount of Q/n m^3 is available to each farmer; (b) an amount of $Q\lambda_i$, proportional to farm size, is available to farmer i, i=1,2,...,n.

At a price of $\$z_1/m^3$, farmer i's demand for water is $L_iq(z_1)$ (see (3.1) for the definition of q(z)). But the amount supplied at this price is limited by Q/n or $(L_i/\mu_L)Q/n$ under scenario (a) or (b), respectively, where $\mu_L = \sum_{i=1}^{n} L_i/n$ is the mean farm size. If the cheap water quota is not binding (for any farmer), which happens when Q is sufficiently large, the situation is the same as that of volumetric pricing with a single rate considered above.

Suppose the quotas are binding for some farmers. Consider scenario (b) first. A binding constraint for farmer i means that $L_iq(z_1) > \lambda_iQ = QL_i/L$ or $q(z_1) > Q/L$. Thus, if the quota is binding for one farmer it is binding for all. Define $\alpha = (Q/L)/q(z_1)$; this parameter, which lies between zero and one, represents, for each farmer, the fraction of land that can be irrigated by the cheap water allotted to him. The remaining part, $(1-\alpha)L_i$, can be irrigated by the expensive water, for which the per hectare demand is $q(z_2)$. Farmer i's per hectare demand for water is, on average, $\alpha q(z_1)+(1-\alpha)q(z_2)$, and the associated per hectare profit is $y(z_1,z_2) = f(\alpha q(z_1)+(1-\alpha)q(z_2)) - z_1\alpha q(z_1) - z_2(1-\alpha)q(z_2)$. Farmer i's income is $y(z_1,z_2)L_i$ and the group income profile is $y(z_1,z_2)L\lambda$. As in the above three methods, the income profile is proportional to the land endowment profile, hence income inequality is determined solely by farm size inequality, independent of the water rates z_1 and z_2.

The situation is different under scenario (a), where farmers get an equal share of the cheaper water. To see this, consider the case where n=2 (two farmers), L=1, $\lambda_1=0.25$ and $\lambda_2=0.75$. Suppose further that $q(z_1)=4$ and Q=2. Farmer 1's demand of the cheaper water is $\lambda_1 q(z_1) = 0.25\times4 = 1$, which is fully met by his Q/n = 1 m^3 allotment. Farmer 2's demand of the cheaper water is $0.75\times4 = 3$, which exceeds his 1 m^3 allotment. If $z_2 \geq f'(1)$, farmer 2 will not demand water priced at $\$z_2/m^3$ and will prefer to leave some of his land idle. The result is that both farmers will have identical incomes. The equal allocation of the cheaper water has led to an egalitarian income distribution.

In general, a tiered pricing system coupled with equal allocation of the cheaper water leads to an income profile which is more egalitarian (in the sense of admitting lower inequality measures) than income profiles which are proportional to the land distribution profile λ. This can be verified by showing that the income profile of the tiered system can be accepted from an income profile of a single rate by transferring income from larger farms to smaller ones. Now, the income profile associated with a single water rate has been shown to be proportional to the land distribution profile, and a redistribution of income from richer (larger farm) to poorer (smaller farm) decreases the inequality measures.

5.5. Summary of the equity analysis

When farmers are per hectare identical in production, we find that neither the volumetric, nor the per area, output or input pricing methods have any effect on income inequality: the descriptive inequality measures C, H, T, A and G depend solely on the land distribution profile λ. This property holds for most pricing schemes that involve no quantity regulations. Trying to improve income inequality via water pricing policies by using such pricing methods is doomed to fail. In the absence of capital cost recovery considerations, water rates may as well be set so as to attain efficiency (see Section 3).

Quantity regulation may not always affect income inequality. A tiered pricing method combined with water quotas that are *proportional to farm size* has no effect on income inequality. On the other hand, a tiered pricing method combined with *equal* (per farmer) water quotas generates an income profile which is more egalitarian than income profiles that are proportional to the land distribution profile.

6. Numerical Example

We present here a numerical example to evaluate the performance of some of the pricing schemes discussed above, regarding efficiency of water allocation. We consider a representative farm of 4 hectares (1 hectares = 2.47 acres) with a surface water quota of 1000 acre inches (or 102800 cubic meter). Two crops, cotton and wheat that require water and nitrogen, are considered. Nitrogen can be purchased in the market; water is provided by a water agency. Other inputs are assumed fixed. The farmer's decision problem is as described in Section 3.

We use quadratic approximation for the per-hectare production functions, $g_j(q,x) = \alpha_j+\beta_j q+\gamma_j x+\delta_j q^2+\phi_j x^2+\eta_j qx$, j = cotton or wheat, with the parameter estimates of Hexem and Heady (1978)

Table 3: Parameter estimates of the quadratic production functions for Cotton and Wheat are taken from Hexem and Heady (1978). Yield is measured in Lb/acre*

Coefficient	Cotton	Wheat
Intercept: α	233.71	-10414
Water (acre-inch): β	23.65	852.01
Nitrogen (Lb/acre): γ	0.438	11.6
Water*Water: δ	-0.182	-12.9
Nitrogen*Nitrogen: ϕ	-0.0033	-0.032
Water*Nitrogen: η	0.0209	0.0925
Range of water input	8-40	0-40
Experimental range of nitogen input	0-120	0-200

* Metric conversion: 1 acre-inch = 102.8 cubic meter; 1 Lb = 2.24 Kg; 1 Lb/acre = 1.102 Kg/hectare.

Cost of Production and crop prices, using the state of Hariana in India as an example, were taken from GOI (1993) and are presented in Table 4. Prices are in constant 1993 $US (31.5 Rs = 1 $US).

Table 4: Production costs for Cotton and Wheat

	Cotton	Wheat
Output price	$.8/Lb ($1750/ton)	$.15/Lb ($300/ton)
Nitrogen price	$.089/Lb ($.199/Kg)	$.089/Lb ($.199/Kg)
Costs unrel**Error! Switch argument not** to water or nitrogen	$78.5/acre ($196.3/ha)	$45.1/acre ($112.7/ha)

The marginal cost of water supply can be approximated from water charges to industry; these range between Rs60 and Rs500 per thousand cubic meter (equivalent to $0.195-1.633 per acre-inch or $0.0019-0.158/cubic meter). A water fee of $.653 per acre-inch is widely used (World Bank, 1994) and is adopted here as the marginal cost of water supply.

The farmer chooses the cropping pattern and allocates inputs to each crop subject to the land and water constraints, taking all prices and water charges parametrically (see Section 3). The water agency chooses the pricing scheme and the water rates. We shall consider the volumetric (marginal cost) pricing, per unit area pricing, tax on input, and tax on output. Some of these pricing schemes differentiate between crops.

Results are presented in Table 5. In some cases, the water charges are determined such that the proceeds of the water supplier are equal to those collected under volumetric (marginal cost) pricing. This was achieved by solving: Min_{z^T} **Error! Switch argument not specified.**$\{\pi(z^w)-\pi(z^T)\}$ subject to profit maximizing behavior of farmers, where $\pi(z^w)$ is the water agency revenue under the marginal cost pricing rule and $\pi(z^T)$, T=g,x,a, is the agency proceeds under the other schemes.

Following Howitt and Vaux (1994), the marginal cost of water supply is represented by

$$MC(Q) = 115 + 0.000671 \cdot Q,$$

where MC is \$/acre-inch and Q, the quantity of water, is measured in acre-inches. The cost of supplying Q acre-inch of water is thus $115 \cdot Q + 0.000671 \cdot Q^2/2$. The results are presented in Table 5.

Table 5: Results of the efficiency performance of the various pricing schemes (10 ha farm)

Pricing Scheme**E argument not sp**	Water Fees C=Cotton W=Wheat**E argument r**	Crop*	Applied Water m^3/ha**Er argume specifie**	Applied Nitrogen Kg/ha**Er argumen specified**	Farm's Profit $**Error! S argument specified.**	Water Proceeds $	Cost of Water Supply $	Social Gains $
None	0	Cotton	3449.6	348.19	9327.73	0	325.81	9001.98
Volumetric \$/m^3	0.00617	Cotton	3338.7	338.77	8809.87	509.40	308.15	9011.12
Land \$/ha	127.5 CW	Cotton	3449.6	348.19	8817.73	510	325.81	9001.92
Land	500 C	Wheat	1406.2	246.51	7343.66	0	77.13	7266.53
Land	500 CW	Cotton	3449.6	348.19	7327.73	2000	325.81	9001.92
Nitrogen \$/Kg	58 CW	Cotton	3305.8	281.02	8594.82	654.66	303.10	8946.38
Nitrogen	42 CW	Cotton	3344.5	299.1	8776.75	509.19	309.07	8976.87
Output %	11 C	Cotton	3443.5	345.34	8184.91	1142.67	324.82	9002.76
Output	12 C	Wheat	1406.2	246.51	7343.66	0	77.13	7266.53
Output	4.9 C	Cotton	3447.1	347.0	8818.62	509.08	325.4	9002.23
Output	12 CW	Cotton	3442.9	345.05	8081.03	1246.54	324.72	9002.85

*As explained in Section 3, one crop occupies all available land.

The results in Table 5 suggest that the model is sensitive to the water procong scheme. In the simple case analyzed here, only water was considered as a limited factor of production. The model as well could have included other inputs such as labor, credit, etc... As a result, the various solutions in the table suggest only one crop (Corner solutions), while if more constraints would have been effective, the optimal solution could have more than one crop grown. Farm's profit was calculated directly in the objective function that was aimed at maximizing farm's profit. Water proceeds were calculated according to the pricing scheme used, and cost of water supply was calculated based on the cost equation in the text. Social gains were then calculated as the sum of the farm profit and water proceeds minus the cost of water supply.

The results of the nuerical analysis rely on the crops and the functional forms of the production function selected for the analysis. Therefore, the reaults should be viewed as indicative in nature. However, the results of the analysis rank the various procong schemes in an ordinal order that reflects their reative efficiency with regard to the volumetric marginal cost procong scheme.

As expected, the volumetric pricing is superior, in terms of social gains, to all other schemes. Also, both the input (nitrogen) and output pricing schemes, when optimally selected, outperform the per unit area pricing method. This is as expected because the input and output pricing can achieve second best efficiency (see Section 3) whereas the latter is inefficient. It can be seen also from the example that their are ranges that the output, the input, and the per area schemes are not very responsive (in the social gains) to different tax levels, but do response in terms of water application. Although not significant in this particular example, this effect should be taken into consideration for policy purposes since it may be preferred in situations where water is very scarce, and agricultural activities are very rigid.

The example, however, ignores monitoring and enforcement costs, and per unit area pricing undoubtedly requires the least of such costs. Thus, when transaction (agency) costs are included, the ranking may change.

If the water agency is interested in cost recovery, it can achieve that by appropriate selection of the water rates. A $200/ha land tax provides the agency with the same proceeds collected by using the volumetric scheme, though far from the same efficiency. A nitrogen tax of $42/Lb and a yield tax of 4.9%, both achieve the same level of proceeds as in the case of volumetric pricing.

7. Conclusions

Pricing of water may affect allocation considerations by various users. In this paper we investigated efficiency and equity performance of several irrigation water pricing methods. Main findings of the study are that, in general, efficiency of water use is attainable whenever the pricing method affects the demand for irrigation water. The volumetric, output, input tiered and two-part tariff schemes all satisfy this condition and can achieve efficiency, though the type of efficiency (short or long run, first or second best) vary from one method to the other. These methods also differ in the amount and type of information, and the administrative cost needed in their implementation. Pricing schemes that do not influence water input directly, such as per unit area fee, lead to inefficient allocation. Such methods, however, are in general easier to implement and administer and they require a modest amount of information.

Concerning equity performance, the conclusion is that the extent to which water pricing methods can affect income redistribution is rather limited. Farm income disparities are due mainly to such factors as farm size and location, and soil quality, but not to water (or other input) prices. We found that when farmers are per-hectare identical in production, which is the assumption used in this study, face the same prices, and not affected by quantity quotas on inputs or outputs, the income distribution profile under most water pricing methods is proportional to the initial farm size distribution profile. Since measures of income inequality (with the exception of the variance) are not sensitive to proportional shifts in income, inequality is due solely to the farm size inequality and is independent of the pricing method or water rates used. For a water pricing scheme to influence income distribution, it must involve certain quantity quota rules.

These conclusions lend some support to the view that income redistribution policies should not be carried out via water prices (see, e.g., Seagraves and Easter, 1983); not because it involves wrong doing but because water prices serve as a poor means to reduce income inequality. However, pricing schemes that involve water quota rules can reduce income inequality. We demonstrate this with a two rate tiered pricing scheme combined with equal quotas of the cheaper water.

Appendix: A normative interpretation of descriptive inequality measures

It is possible to interpret the descriptive measures V, C, H, T, A and G as normative measures corresponding to some underlying welfare functions (see Sen, 1973, and Blackorby and Donaldson, 1978). Such interpretations reveal the implicit normative assumptions associated with using any of the descriptive statistics, hence can help in choosing among them in any given situation. This interpretation is carried out as follows.

Consider a linear homogeneous welfare function normalized as

$W(1,1,...,1) = 1$

so that

$W(\mu,\mu,...,\mu) = \mu$ and $W(y_s,y_s,...,y_s) = y_s$.

Now, $\mu = \mu W(1,1,...,1)$ (since $W(1,1,...,1) = 1$)

$= W(\mu,\mu,...,\mu)$ (linear homogeneity)

$\geq W(y_1,y_2,...,y_n)$ (quasi concavity)

so μ is the maximum level of W(y). Noting the definition of N, it is readily verified that the N measure corresponding to the group welfare function

$W_I(y) = \mu(1-I(y))$

is the same as I, I=V,C,H,T,G.

For example, the group welfare functions associated with C, T, A and G are, respectively,

$$W_c(y) = \mu - \left(\sum_{i=1}^{n} (y_i - \mu)^2 / n \right)^{1/2}$$ **Error! Switch argument not specified.**,

$$W_T(y) = \frac{n\mu \log(n\mu) - \sum_{i==1}^{n} y_i \log(y_i)}{n \log(n)},$$

$$W_A(y) = \prod_{i=1}^{n} y_i^{1/n},$$

and

$$W_G(y) = \frac{1}{n^2} y_1 + 3y_2 + \ldots + (2i - 1)y_i + \ldots + (2n - 1)y_n$$ **Error! Switch argument not specified.Error! Switch argument not specified.**, $y_1 \geq y_2 \geq \ldots \geq y_n$.

This normative interpretation allows one to attach some ethical properties to the descriptive statistics (see Blackorby and Donaldson, 1978, pp. 71-76), thereby helps in selecting among them.

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Yacov Tsur

The Hebrew University of Jerusalem

and

The University of Minnesota

and

Ariel Dinar

The World Bank