SPATIAL WATER MANAGEMENT UNDER ALTERNATIVE INSTITUTIONAL ARRANGEMENTS

by

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ABSTRACT

This paper examines the impact of alternative institutional arrangements in the generation, distribution and allocation of water. More specifically, it develops a spatial framework to address what happens to aggregate water use, output and prices as well as to the pattern of water allocation, technology investments and quasi-rents over space under alternative market structures such as an output monopoly, a water-users' association, a public utility and a project without government intervention. The analytical results are illustrated with data from California agriculture and suggest that if government intervention is costly, an output or input monopoly may be a preferred second-best alternative to a decentralized project under high output elasticities.

Keywords: water institutions, spatial models, conveyance, market structure

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1. INTRODUCTION

Most water projects suffer from high losses in distribution canals and in individual farms. It has been estimated that on average, these two sources result in 65 per cent of the water being lost before reaching the root zone of the plant. Principles for optimal investment in reducing conveyance losses and in increasing on-farm efficiency have been developed in earlier work (see Chakravorty and Roumasset (1991), Chakravorty, Hochman and Zilberman (1995)). These papers suggest that market mechanisms will in general not ensure optimal investment in water transmission and have compared socially optimal allocation with sub-optimal regimes under water markets and other uniform pricing schemes. They have shown that substantial gains in economic benefits and "equitable" distribution of benefits over space could be achieved through centralized conveyance investments by a water utility.

This paper extends the above analysis to investigate the economic impacts of alternative market structures. In particular, the spatial allocation of investment and production under a monopoly, and under a decentralized, competitive regime are compared with the socially optimal. In the theoretical literature on externalities, it is well known that a monopoly may be less-efficient than a competitive system. This paper provides a concrete application of the above theory to water management and examines the spatial impacts of alternative market structures. An illustration with data from California agriculture shows the order of magnitude differences in output, water use and rents. It is concluded that for regions producing agricultural output characterized by high demand elasticities (e.g., export high-valued crops) monopoly in water distribution may be preferred to a decentralized regime.

2. THE MODEL

The model consider here is a more general form of the one developed by Chakravorty, Hochman and Zilberman (1995), henceforth referred to as CHZ. It is a simple one-period (i.e., one cropping season), model of a water project with no uncertainty. Water is supplied by the utility from a point source (e.g., a dam or a diversion) into a canal. Identical firms are located over a continuum on either side of the canal on land of uniform quality. Firms at location x draw water from the canal, where x is distance measured from the source. Let $r(=0)$ be the opportunity rent per unit area of agricultural land. Define α to be the constant width of the project area.

Let z_0 denote the amount of water supplied from the source. The cost of supplying z_0 units of water is $g(z_0)$, assumed to be an increasing, twice differentiable, convex function, $g'(z_0)>0, g''(z_0)>0$. The quantity of water delivered (per unit land area) to a firm at location x is $q(x)$, with $q(x)\geq 0$. The fraction of water lost in conveyance per unit length of canal is given by the function $a(x)$, with $a(x)\geq 0$. Let $z(x)$ be the residual quantity of water flowing in the canal through location x, $z(x)\geq 0$. Then

$$z'(x) = - q(x)\alpha - a(x)z(x) \qquad (1)$$

where the right-hand side terms indicate, respectively, water delivered and water lost in conveyance at location x. It suggests that $z'(x) \leq 0$, i.e., the residual flow of water in the canal decreases away from the source. Let X be the length of the canal. Then

$$z_0 = \int_0^X [q(x)\alpha + a(x)z(x)]dx. \tag{2}$$

From (1) and (2), $z(X)=0$, i.e., the flow of water in the canal reduces to zero at the project boundary. The loss function $a(x)$ depends on $k(x)$, defined as the maintenance expenditures per unit surface area of the canal, which can vary with location. If $k(x)=0$ (e.g., unlined canals), then the fraction of water lost $a(x)$ equals the base loss rate a_0, where $a_0 \in [0,1]$. If $k(x)>0$ (e.g., concrete-lined canals), then $a(x)<a_0$. Let the reduction in the conveyance loss rate obtained by investing $k(x)$ be given by $m(k(x))$. Then

$$a(x) = a_0 - m(k(x)). \tag{3}$$

Assume $m(\bullet)$ to be an increasing, twice differentiable function with decreasing returns to scale in k, the last limit suggests that marginal returns to conveyance investments approach infinity with decrease in k. Let $a(x)=a_0$ when $k=0$, i.e., investing zero dollars reduces conveyance losses to zero (e.g., metal piping). From (3), $a(x) \in [0,a_0]$.

Annualized investments in conveyance at each location x are assumed to be given by

$u(z,k) = v(z)k$ where $v(\bullet)$ denotes the canal perimeter which increases with the amount of water z flowing in the canal. Since z can be taken to represent the cross-sectional area, we assume that the perimeter is an increasing, concave function of z, i.e., $v'(z)>0,$ $v''(z)<0$. This formulation generates a distinction between investment in canal quality given by the function $k(x)$, and the cost of carrying a given volume of flow denoted by the multiplicative component $v(z)$. This specification also implies increasing returns to scale in conveyance investments.

Firms invest in technology (e.g., drip or sprinkler irrigation) that conserves water on their land and thereby increases the efficiency of the water delivered, $q(x)$. Let $I(x)$ denote firm-specific investment in water conservation. Then $h(I)$ gives the proportion of water delivered that actually reaches the plant, assumed to be increasing, twice differentiable and concave, i.e., the price of I is unity. Also let $e(x)= qh(I)$ where $e(x)$ is "effective water," i.e., the amount of water actually applied to the crop. Similar distinctions between 'delivered' and 'applied' input use have been made elsewhere (e.g., for energy-conserving appliances, see Repetto (1986)). Then the production technology for each firm is given by $f(e)$ which is assumed to exhibit constant returns to scale with respect to land and other production inputs. Let $f(\bullet)$ be twice differentiable with $f(\bullet)>0;$ $\partial f/\partial q>0;$ $\partial f/\partial I>0;$ $\partial^2 f/\partial q^2<0$ and $\partial^2 f/\partial I^2<0$ which in turn yields $f'(e)>0,$ $f''(e)<0$. Let e be bounded from above, i.e., there exists a maximal evapotranspiration rate beyond which the plant begins to wilt (Vaux (1983)). In order to ensure strict concavity of the production function, the elasticity of marginal product ($\eta_f'=f''e/f'$) is assumed to be in the range $-\infty < \eta_f' < -1$. This condition is sufficient for the Hessian to be strictly positive.

Let Y be the aggregate output from the project. It is then given by

$$Y = \int_0^X f(e)\alpha\, dx. \tag{4}$$

Define the total cost of producing a given output level Y as $C(Y)$ which can then be expressed as

$$C(Y) = g(z_0) + \int_0^X [kv(z) + (l(x) + r)\alpha]dx. \tag{5}$$

In (5) the cost of output Y is the sum of the cost of water generation, conveyance, irrigation investment and the rent to land. The utility chooses control functions $q(x)$, $I(x)$, $k(x)$, and values for X and z_0 that maximize aggregate net benefits from the project as follows:

$$\underset{q,l,k,X,z_0}{minimize}\; g(z_0) + \int_0^X [kv(z) + (l(x) + r)\alpha]dx \qquad 6(a)$$

subject to

$$z'(x) = - q(x)\alpha - a(x)z(x) \qquad 6(b)$$

$$Y\,'(x) = f(e)\alpha \qquad 6(c)$$

$$q(x) \geq 0,\ l(x) \geq 0,\ k(x) \geq 0,\ z(x) \geq 0, \qquad 6(d)$$

$$z_o \text{ free},\ z(X) = 0,\ X \geq 0,\ X \text{ free}. \qquad 6(e)$$

Then the Hamiltonian and corresponding Lagrangian are

$H = kv(z) + (l + r)\alpha + \lambda_1(q\alpha + az) - \lambda_2 f(e)\alpha$ 7(a)

$L = H(\bullet) - \lambda_3 z,$ 7(b)

where $\lambda_1(x)$, $\lambda_2(x)$ and $\lambda_3(x)$ are functions associated with 6(b,c) and the state constraint $z(x)\geq 0$ respectively. The necessary conditions for a solution to problem (6a)-(6e) are

$(\lambda_1 - \lambda_2 f'h(l))\alpha \leq 0$ (= 0 if $q > 0$) (8)

$(1 - \lambda_2 f'qh'(l))\alpha \leq 0$ (= 0 if $l > 0$) (9)

$v(z) - \lambda_1 zm'(k) \leq 0$ (= 0 if $k > 0$) (10)

$\lambda_1'(x) = v'(z)k + \lambda_1 a - \lambda_3$

(11)

$\lambda_2'(x) = 0$ (12)

$\lambda_2 = C'(Y)$ (13)

$\lambda_3(x) \geq 0$ (= 0 if $z(x) > 0$) (14)

$\lambda_1(0) = g'(z_0),$ (15)

$\lambda_1(X^-) - \lambda_1(X) = \beta,$ (16)

and

$L(X) = 0$ (17)

where β is a constant. From (1), if $z(x)=0$ at any $x \in [0,X)$, it could not increase from that value. Then the state constraint is never tight except possibly at $x=X$. From the maximum principle, $\lambda_1(x)$ is continuous on $[0,X)$, $\lambda_3(x)=0$ on $[0,X)$ and $q(x)$, $l(x)$ and $k(x)$

are continuous except at $x=X$.

In the above, $\lambda_1(x)$ is interpreted as the shadow price of delivered water at location x. Condition (11) suggests that $\lambda_1'(x) = v'(z)k + \lambda_1 a \ \forall x \in [0,X)$. Because $\lambda_1(0)>0$ by (15), this suggests that $\lambda_1'(x)>0$ for $x \in [0,X)$. Intuitively, the shadow price of delivered water increases away from the source because of the cost of conveyance. In order to simplify the analysis, consider the limiting case of a "flat" canal cross-section in which the elasticity of conveyance, given by $\eta_v(= v'(z)z/v(z))$, equals zero. That is, the ratio of the canal perimeter to cross-sectional area, $v(z)$ is constant. Then (11) yields $\lambda_1'(x) = \lambda a$, or that the shadow price of delivered water increases with distance at the conveyance loss rate.

Substituting the limiting values of $f'(0)$ and $m'(0)$ in (8)-(10) suggests that $q(x)>0$, $I(x)>0$, $k(x)>0$ and the corresponding necessary conditions hold with equality. Their spatial distribution as well as the spatial allocation of effective water and output is characterized as follows:

Proposition 1: ***(a)*** $q'(x)<0$ ***(b)*** $I'(x)>0$ ***(c)*** $k'(x)<0$ ***(d)*** $e'(x)<0$; ***and (e)*** $y'(x)<0$.

Proof: see CHZ.

An increase in the shadow price of water from head (upstream) to tail (downstream) causes a decrease in the amount of water used by each firm, which in turn makes conservation more profitable. So firms situated downstream of the project receive less water, but spend more on conservation relative to those located upstream. The 'price' of effective water $(Pf'(e) = \lambda/h(I))$ increases with distance leading to a decrease in its use, and a fall in output with distance.

Of particular interest is the result that conveyance investments decrease with distance. Although the shadow price of water increases away from the source, the volume of water flowing in the canal decreases at a higher rate. The net effect is a decrease in the "value" of the residual water flowing in the canal, causing a decrease in conveyance expenditures. The assumption $\eta_v=0$ implies that the sectional area to be lined is independent of the volume of flow. If $\eta_v=1$, i.e., there are economies of scale in conveyance (canal perimeter is an increasing, concave function of volume), then it is easy to see that $\eta_m'(k)k'/k = -\lambda'/\lambda <0$ and therefore $k'(x)>0$. Therefore, the presence of increasing returns to scale in conveyance may cause conveyance investments to rise with distance, a somewhat counter-intuitive result.

At the project boundary X, (17) gives

$$L(X) = k(X)v(z(X)) + [I(X) - r]\alpha + \lambda_1(X)[q(X)\alpha + az(X)] - \lambda_2 f(e(X))\alpha - \lambda_3(X)z(X) = 0. \quad (18)$$

Substituting $z(X)=0$ and $v(0)=0$ and rearranging, yields

$$\lambda_2 f(e(X)) - I(X) - \lambda_1 q(X) = r$$

(19)

which implies that net benefits from expanding the land area by one unit must equal the opportunity rent of land, r. Thus the equilibrium value of X is inversely related to r. If $r=0$ (land is in infinite supply), that would imply a greater project area. If r increased with x because say, the downstream locations were closer to an urban center, then X would be smaller. On the other hand if an urban area were closer to the upstream section, then the function $r(x)$ would be negatively sloping and various cases may arise depending on the relative magnitude of the land rent function and $r(x)$. For instance, in regions where $r(x)$ is larger than quasi-rents to land, land is better allocated for residential or commercial use than in farming.

3. ALTERNATIVE INSTITUTIONS FOR WATER MANAGEMENT

In this section we compare the optimal allocation derived above with water allocation and conveyance investments under three different market structures, each of which are explained as follows:

Decentralized Water Market Model: In this model we assume that the water utility is weak and fails to provide optimal conveyance in the project. Thus water losses in the canal are higher and farmers trade in water rights and pay spot shadow prices at each location. The output from the project is sold as a competitive industry. This stylized model is meant to represent typical water projects in developing and developed countries where there is a general failure in operation and maintenance leading to a system of laissez faire (see Wade (1987), Repetto (1986)). A possibly more relevant model may be one with sub-optimal pricing and uniform pricing (e.g., an output tax or land tax) that is unrelated to water use. This would then lead to sub-optimal water use and concentration of production activity closer to the source. However, the selection of institutional arrangements in this paper is driven by normative criteria relating to the performance of alternative institutions that can help upgrade water management and not those that are already in place.

Output Monopoly: Here we investigate the effect of monopolistic behavior in the output market on social welfare as well as aggregate water use and spatial allocation of input use. This behavior could be the outcome, for example, of a water-users' association that maintains the canal structures and supervises the allocation process. The allocation of water within the project is done either through some form of water trading or rationing scheme but what is important is that the project output is marketed as a monopoly. The monopolist buys the aggregate amount of water required from the water district at the marginal cost of water generation.

Input Monopsony: In this model, we focus on the market for water. We assume that the project is a monopsonist buying water from the water district or utility and a competitive industry in the output market. Thus, this may be an example of an especially strong water users' association that has monopoly power in determining the price of the water bought for the project. The point behind choosing the monopsonist is to show the differential impacts of market power in the input and the output markets. This comparison yields insight into the behavior of a middleman in which the project behaves as an input monopsony as well as an output monopoly, although for reasons of brevity, we do not develop this case separately.

Institutional Comparisons

The next step is to develop the apparatus for comparisons across the above institutional settings. Let the consumers' utility function for aggregate output Y from the project be defined by $U(Y)$ where $U(0)=0, U'(Y)>0, U''(Y)<0$. We can now derive equilibrium price and output when the water project is operated as a monopoly in the output market. Within the project for any given level of output Y, both the central planner and the monopolist must solve program 6(a)-6(e). Their total cost of producing a given Y would be identical assuming that the program 6(a)-6(e) has a unique solution, since both a social planner and a monopolist would allocate water efficiently over space. However, aggregate output, water use and output prices will in general not be the same. Denote this common cost function by $C^*(Y)$, where * denotes optimality.

Let the consumers' utility function for aggregate output Y from the project be defined by $U(Y)$ where it is assumed that $U(0)=0, U'(Y)>0, U''(Y)<0$. We can now derive equilibrium price and output when the irrigation project is operated as a monopoly in the output market. The monopolist either buys water at marginal cost from the water development authority or develops the water generation capacity within the project. In either case, the monopolist invests optimally in conveyance and chooses the profit-maximizing output and price. The monopolist's cost minimization program is identical to (9), so the relevant cost function faced by the monopolist is $C^*(Y)$. Monopoly output Y_m is chosen to maximize profits Π^m as follows:

$$Maximize\ \Pi^m = pY - C^*(Y) \tag{20}$$

and Y_m solves

$$MR(Y) - C^{*\prime}(Y) = 0 \tag{21}$$

and

$$MR'(Y) - C^{*\prime\prime}(Y) < 0 \tag{22}$$

where p is the output price of the agricultural commodity. Let p_m be the output price under monopoly. Then $p_m = U'(Y_m)$.

Let the corresponding cost function under a water market be $C_w(Y)$. Purely competitive (or decentralized) behavior will result when individual farmers act competitively. Farmers purchase water from the water utility at its marginal cost at source, and choose optimal amounts of water and on-farm technology. The optimization problem for a farmer at location *'x'* is given by

$$\underset{q,I,k}{Maximize}\ \pi^w = [pf(qh(I)) - \lambda_0 q - I]\alpha - k \tag{23}$$

where π^w represents competitive profits at *'x'*. It is clear from (23) that in a decentralized, competitive regime, the individual farmer will not invest in conveyance, and since the maximization problem is independent of *'x'*, conveyance expenditures under competition are zero at each *'x'*. Let us denote the cost function for aggregate output under competition as $C_w(Y)$. Equilibrium aggregate output Y_w and price p_w in competition are then obtained as follows:

$$Y_w \in \underset{Y}{\operatorname{argmax}}\ U(Y) - C_w(Y) \tag{24}$$

and solves

$$U'(Y) - C_w'(Y) = 0 \tag{25}$$

and

$$U''(Y) - C_w''(Y) < 0. \tag{26}$$

Then the following proposition establishes the relationship between $C^*(Y)$ and $C_w(Y)$:

Proposition 2: (a) $C^*(Y)<C_w(Y)$ (b) $C^{*\prime}(Y)>0$ (c) $C^{*\prime\prime}(Y)>0$ (d) $C_w'(Y)>C^{*\prime}(Y)$ and (e) $C_w''(Y)>C^{*\prime\prime}(Y)$.

Proof: (a) The cost function $C^*(Y)$ is optimal by definition while the function $C_w(Y)$ is the total cost of producing output Y under the additional restriction that $k(x)$ is identically equal to zero. By the envelop theorem, $C^*(Y)$ must be smaller than $C_w(Y)$.

(b) Follows directly from complementary slackness, i.e., the shadow price of aggregate output must be non-negative (see Repetto (1986)).

(c) $C''(Y) > 0$ follows from the comparative statics results derived from the sufficient second order conditions for cost minimization for the problem 6(a-e) (see Silberberg (1991)). The details are available in a technical appendix from the authors. Intuitively, as output increases, a higher aggregate stock of water is used, which in turn implies a higher marginal cost of water generation $(g'(z_0))$ which increases the marginal cost of output.

(d,e) These results too follow directly from the application of the envelop theorem to the two cost functions $C^*(Y)$ and $C_w(Y)$. The cost function $C_w(Y)$ is tangential and lies everywhere above the unrestricted cost function $C^*(Y)$. Thus the first and second derivatives of the former are greater in the neighborhood of the minimum point of the restricted cost function than the corresponding derivatives of the unrestricted cost function.

In summary, the above proposition states that the cost of producing a unit of output under the competitive system in which conveyance investments are fixed to be zero must be greater than in the optimal system. Since the marginal cost of output is increasing, the marginal cost of output for the competitive model is higher than the optimal. Fig.1 shows the marginal cost functions in the optimal and competitive case, $C^{*\prime}(Y)$ and $C_w'(Y)$. Both the socially optimal irrigation project and the monopolist operate with the marginal cost function $C^{*\prime}(Y)$. The socially optimal price P^{**} and output Y^{**} are obtained at the point of intersection of the demand function D and $C^{*\prime}(Y)$. The competitive price P_w and quantity Y_w are given by intersecting demand with $C_w'(Y)$. The monopolist equates marginal revenue $MR(Y)$ with $C^{*\prime}(Y)$ to give price P_m and quantity Y_m. The figure has been drawn such that the monopolist produces a higher quantity and charges a lower price than the competitive case. However, it is easy to see that the converse could happen under alternative parameter values.

The following proposition compares monopoly and competitive output and water use:

Proposition 3: ***If $P_m \geq P_w$ then (i) $Y_m \leq Y_w$ (ii) $z_{0m}<z_{0w}$, and (iii) $X_m<X_w$.***

Proof: The proof is obvious from Fig.1. A higher monopoly price implies a lower aggregate output. Since the monopolist is more efficient, it produces a lower (or equal) output relative to competition by using a smaller aggregate water stock at source and distributing it over a smaller project area. However, when $P_m<P_w$, then $Y_m>Y_w$, but the relative sizes of the water stock and acreage are unclear. That is, if competitive output were higher than the monopoly output, the relative order of aggregate output and project area are indeterminate.

Comparing the monopoly and socially optimal models, we obtain:

Proposition 4: ***(i) $P_m>P^{**}$ (ii) $Y_m<Y^{**}$ (iii) $z_{0m}<z_0^{**}$ (iv) $X_m<X^{**}$,***

where '**' denotes the parameters of the socially optimal model.

Proof: Same as above.

The monopoly price (output) is always higher (lower) than optimal. Therefore, an irrigation system under monopoly uses less water and irrigates a smaller area, as compared to a system that maximizes net social benefits. Comparison between the optimal and competitive models yield:

Proposition 5: ***(i) $P_w>P^{**}$ (ii) $Y_w<Y^{**}$.***

Proof: Follows from Proposition 2 and is obvious from Fig.1. Since the marginal cost function under competition is everywhere higher than optimal, it intersects the demand function at a higher price and smaller aggregate output. However, the relative magnitude of water use and acreage in the two models is indeterminate.

The following results examine the impact of the elasticity of demand on monopoly and competitive resource allocation:

Proposition 6: ***(i)*** $dP_m/d|\varepsilon| < 0$ ***(ii)*** $dY_m/d|\varepsilon| > 0$ ***(iii)*** $dz_{0m}/d|\varepsilon| > 0$ ***(iv)*** $dX_m/d|\varepsilon| > 0$ ***(v)*** $dP_w/d|\varepsilon| < 0$ ***(vi)*** $dY_w/d|\varepsilon| < 0$ ***(vii)*** $dz_{0w}/d|\varepsilon| < 0$ ***(viii)*** $dX_w/d|\varepsilon| < 0$.

Proof: The proofs of (iii), (iv), (vi), (vii) and (viii) are omitted because they are similar to the following:

(i) The pricing rule for a monopolist is given by

$P_m(1 + 1/\varepsilon)=C^{*\prime}$ which gives $P_m=C^{*\prime}\varepsilon/(1+\varepsilon)$. Differentiating with respect to ε by using the quotient rule, we obtain

$dP_m/d\varepsilon = C^{*\prime}/(1+\varepsilon)^2 > 0$. Since $\varepsilon<0$, we get the desired result.

(ii) The monopolist sets the output price off the consumer's demand function, or $U'(Y_m)=P_m$. Differentiating totally, we get $U''(Y_m)dY_m/dP_m = 1$ or $dY_m/dP_m < 0$. By the chain rule, using Proposition 6(i), we get $dY_m/d|\varepsilon| > 0$.

(v) The competitive price is set by the condition $P_w=U'(Y_w)$, or $P_w=U''(Y_w)Y_w/\varepsilon$. Differentiating with respect to ε, we get $dP_w/d\varepsilon= -U''(Y_w)Y/\varepsilon > 0$, which gives the result.

The above proposition suggests that as the absolute value of demand elasticity increases, output prices under both the monopolistic and the competitive systems decrease. However, the output under monopoly increases while the competitive output decreases. With increase in absolute elasticity, the monopolist produces more output by using more water and expanding irrigated acreage, while the competitive system shrinks in acreage, and uses a smaller water stock. This asymmetry between competitive and monopoly behavior has major implications for second-best water allocation: if demand elasticity is relatively high (low), monopoly (competitive) behavior in water may be the preferred institutional choice.

Finally, the water monopsonist chooses to buy z_0 units of water to maximize total net benefits as follows:

$$\max_{Z_0} D(z_0) - C'(z_0)z_0 \tag{27}$$

where $D(z_0)$ is the derived demand for the aggregate input of water. The necessary conditions are given by:

$$D'(z_0) = MO(z_0) \tag{28}$$

where MO is the marginal outlay or marginal factor cost of Z_0. The purchase price of water is shown in Fig.2 as *b*. It is easy to see that aggregate water use by the monopsonist will be smaller than optimal, which in turn implies that aggregate output and project area too will be lower than optimal. However, the relative size of water use, output and area in the monopoly and monopsony cases is indeterminate.

4. AN ILLUSTRATION

This section presents a simple illustration of the optimal model and the three cases described in section 3 by using typical cost and demand parameters for Western U.S. agriculture. A quadratic production function for California cotton is derived in terms of effective water e such that a maximum yield of 1,500 lbs. can be obtained when $e=3.0$ acre-feet and a yield of 1,200 lbs. are obtained when $e=2.0$ acre-feet (Hanemann (1987)). Using cotton prices of US$ 0.75 per lb. gives the revenue function

$$pf(e) = - 0.2224 + 1.0944 \bullet e - 0.5984 \bullet e^{2} \quad (29)$$

where revenue is in US$, and e is in m/m^2 of water. Differentiating (29) with respect to e gives the value of marginal product function

$$pf'(e) = 1.0944 - 1.1968 \bullet e. \quad (30)$$

The on-farm conservation function is approximated from cost estimates of investing in irrigation technologies in California as shown in Table 1. When furrow irrigation is applied, it is assumed that there is no investment cost to the farmer so that $h(0)=0.6$, i.e., 60 per cent of the water delivered at the farm-gate reaches the plant. The function $h(I)$ increases at a decreasing rate as more sophisticated technologies such as sprinkler and drip are employed, and is approximated as a continuous function of I as follows:

$$h(I) = 0.6 + 21.67 \bullet I - 333.3 \bullet I^{2} \tag{31}$$

where I is in \$/m^2. Fixed costs for irrigated farming are taken to be \$433 per acre or \$0.107/m^2 (University of California (1988)). A quadratic function for conveyance expenditures was constructed from average lining and piping costs in 17 states in Western United States (U.S. Department of Interior (1979), Table 15, p. 87). An investment of \$200/m length of canal in piped systems results in zero conveyance losses in the system. Concrete lining with an investment of \$100/m attains a loss factor of 10^{-5}/m or a conveyance efficiency of 0.8 over a 20 km length of canal. For simplicity, v is taken to be unity, i.e., a relatively 'flat' canal cross-section. When $k=0$, the loss factor is $4 \bullet 10^{-5}$/m giving an overall conveyance efficiency of 0.2. Thus we get

$$a = 4 \bullet 10^{-5} - (4 \bullet 10^{-7} k - 10^{-9} k^{2}) \tag{32}$$

so that from condition (3), $a_0 = 4 \bullet 10^{-5}$, and

$$m(k) = 4 \bullet 10^{-7} k - 10^{-9} k^{2}, \quad 0 \leq k \leq 200. \tag{33}$$

The conveyance loss figures are consistent with findings from engineering studies (Bos and Nugteren (1974)). The exact loss coefficient, however, would depend on soil characteristics, ambient temperatures, and other environmental factors. The results were found to be generally insensitive to variations in the value of a_0.

A rising long-run marginal cost function for water supply was constructed from average water supply cost data from 18 irrigation projects in the Western United States (Wahl (1985)) as

$$g'(z_0) = 0.003785 + (3.785 \bullet 10^{-11} z_0) \quad (34)$$

where marginal cost is in \$ and z_0 is in cu.m. It gives a marginal cost of 0.003785\$/m^3 (\$4.67 per acre-foot) when $z_0=0$, and marginal cost values in the range 0.068 to 0.16 \$/m^3 (93.34 to 195.9 \$/acre-foot) for the various models analyzed (see Table 2). A linear functional form was assumed to keep the formulation simple. For computational purposes, the width of the rectangular cropped area, α is taken to be 10^5m. The width, of course, does not affect the relative orders of magnitude across models.

A computer algorithm was written that starts by assuming an initial value of output price P and z_0, and computes λ_0 from (15). At $x=0$, (10) gives $m'(k)$. By iterating on k, we compute $k(x)$ that satisfies (33), and (32) gives $a(x)$. Knowing $\lambda_1(0)$, (8) and (9) used simultaneously yield $I(x)$, $q(x)$ and thus $e(x)$, $y(x)$ and $R_L(x)$ respectively. Next, when $x=1$, using $a(0)$ and $\lambda_1(0)$ in the solution to (11) gives $\lambda_1(1)$, and $z(1)$ is obtained from (1) by subtracting the water already used up previously. Again, $\lambda_1(1)$ and $z(1)$ give $k(1)$ from (10) and the cycle is repeated to give $q(1)$, $I(1)$, etc.. The process is continued with increasing values of x until exhaustion of z_0 terminates the cycle, and a new value of z_0 is assumed. Aggregate land rents are calculated for each z_0 by summing over $R_L(x)$ and aggregate rents to water are computed similarly. The algorithm selects the value of z_0

that minimizes total cost (given by (6(a)). For each price P, the corresponding Y is computed to generate the supply function. The equilibrium is computed by solving the supply and demand equations (see below) jointly. The algorithm was modified suitably for the competitive, monopoly and monopsony solutions.

The above models are illustrated by using the functional forms given in section 4. An iso-elastic demand function for the commodity (California cotton) is constructed for elasticity values ranging from -1 to -3 (with intervals of 1) such that at the price of \$0.75, the quantity produced is 17.7×10^8 lbs. The demand function is of the form $Y=DP^{\varepsilon}$ where D is a constant and $\varepsilon<0$. The results are shown in Table 2 and can be summarized as follows:

1. With increase in the elasticity of demand, monopoly output increases while prices decrease, while both price and output under competition decrease. Therefore, at high demand elasticities, monopoly produces more output and charges a lower output price.
2. Irrigated acreage and water use also increases with elasticity under monopoly, while they decrease under a competitive system. Also note that when demand elasticity is unity, both the competitive and the optimal models use roughly the same water, but the latter produces double the output.
3. Land rents at the head reaches decrease with increasing elasticity in both monopoly and competitive systems. However, rents accruing to farmers under monopoly and competition are many times higher than in the optimal model, mainly because of the combined effect of higher output prices and lower water charges (due to a smaller water

stock) in the former models.

4. Welfare effects are highest under the optimal model, closely followed by the competitive model when demand elasticity is unity. Producer surplus decreases with increasing elasticity under both monopoly and competition, since output price decreases, while consumer surplus goes down because of shifts in the demand curve resulting from increasing elasticity. Thus total welfare decreases with increasing output elasticity. In our example, the welfare gains from monopoly always exceed those from competition.

5. Aggregate rents to water are highest in the optimal model. They decrease with elasticity in the competitive case, but increase with increased output elasticity under monopoly. This is because, as elasticity increases, the monopolist produces more output and uses more water, leading to rising shadow prices of water. The reverse is true for the competitive model.

6. Although it is difficult to define the relationship between output monopoly and the input monopsony, the simulation results show that both equilibrium price and the output for each case decrease as elasticity increases. When the elasticity is unity, both output and input monopsonist produce larger consumer surplus and total welfare compared to the competitive model. Except for the unitary elasticity case, output, project area, total welfare water use for the input monopsonist are quite similar to those for the output monopolist. Also, the input monopoly produces higher output and uses more aggregate water than the output monopoly at higher demand elasticities.

5. Concluding Remarks

In this paper we have examined the effect of alternative market structures on irrigation system performance. The behavior of optimal, purely competitive, monopolistic and monopsonistic arrangements were examined under a range of assumptions regarding elasticity of the demand function. The analytical results show that under low demand elasticities, competitive (without conveyance investments) behavior will result in a higher output and lower output price than monopoly. However, when the output elasticities are high, monopoly will produce more output at a lower price. A system that permits intervention in the form of conveyance investments but also maximizes net social benefit would dominate both of the above.

These results yield insights into the performance of alternative water institutions and may be particularly appropriate in countries or regions with weak administrative capacity, i.e., where government intervention in the operation and maintenance of irrigation projects may be costly or difficult to implement. Our results indicate that for crops that are characterized by high demand elasticities, e.g., high-valued crops, or export-oriented agricultural products, a monopolist might be preferred to a competitive system. However, for low-elasticity crops such as those grown in subsistence farming or for domestic consumption, a competitive system is likely to result in lower prices, more output and larger net economic benefits. Farmers' cooperatives, or marketing boards that engage in monopoly behavior in the output market could be viable policy options in the high-elasticity regime. This is consistent with observed behavior, e.g., in the case of plantation crops such as rubber or cocoa, where producers often operate under a marketing cooperative or cartel.

The fact that rents to water increase with absolute value of the elasticity in the case of the monopoly point to the viability of promoting institutions that combine the maintenance and marketing functions in irrigation. Organizations that supply water, and buy the produce from individual farmers might be an economically attractive proposition, especially for high-elasticity crops. Such an arrangement would also reduce administrative costs, since the task of collecting water charges and paying farmers their output price could be integrated into one.

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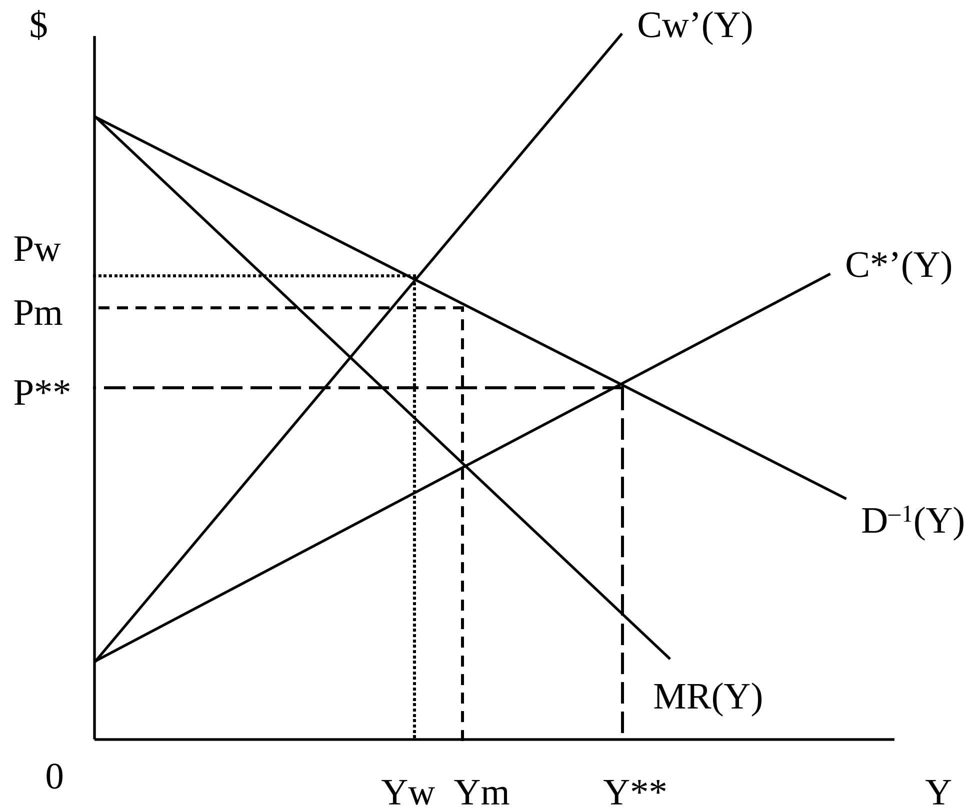

Figure 1. Equilibrium price and quantity
for the optimal, competitive and monopoly case

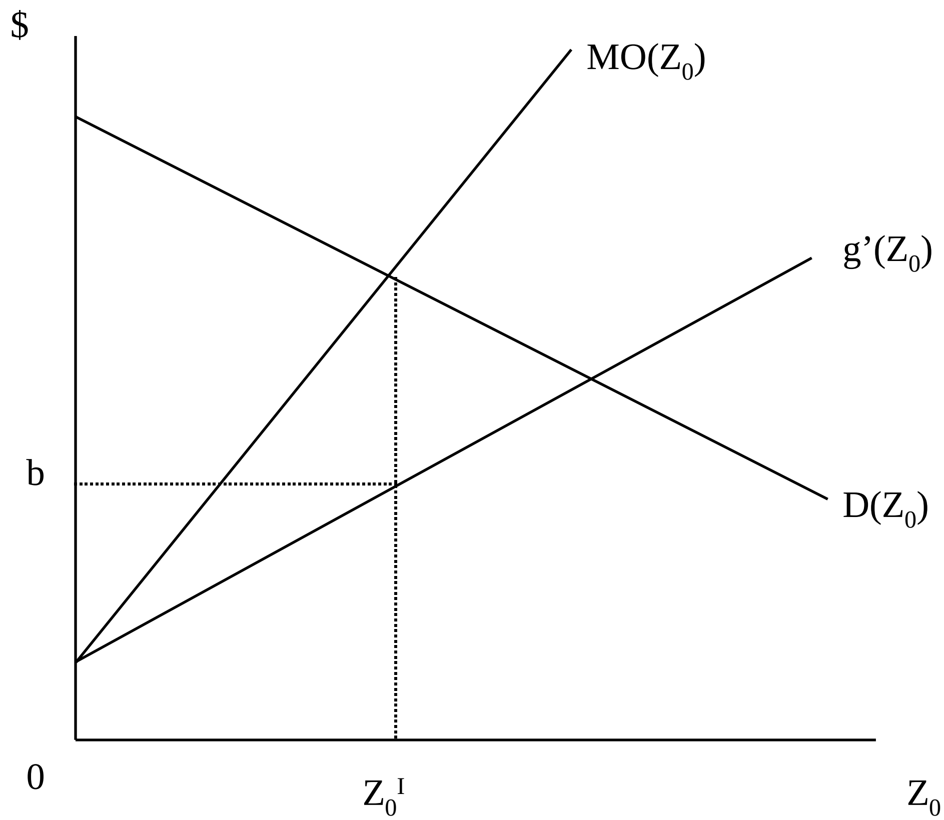

Figure 2. Purchase price of water for the input monopsony

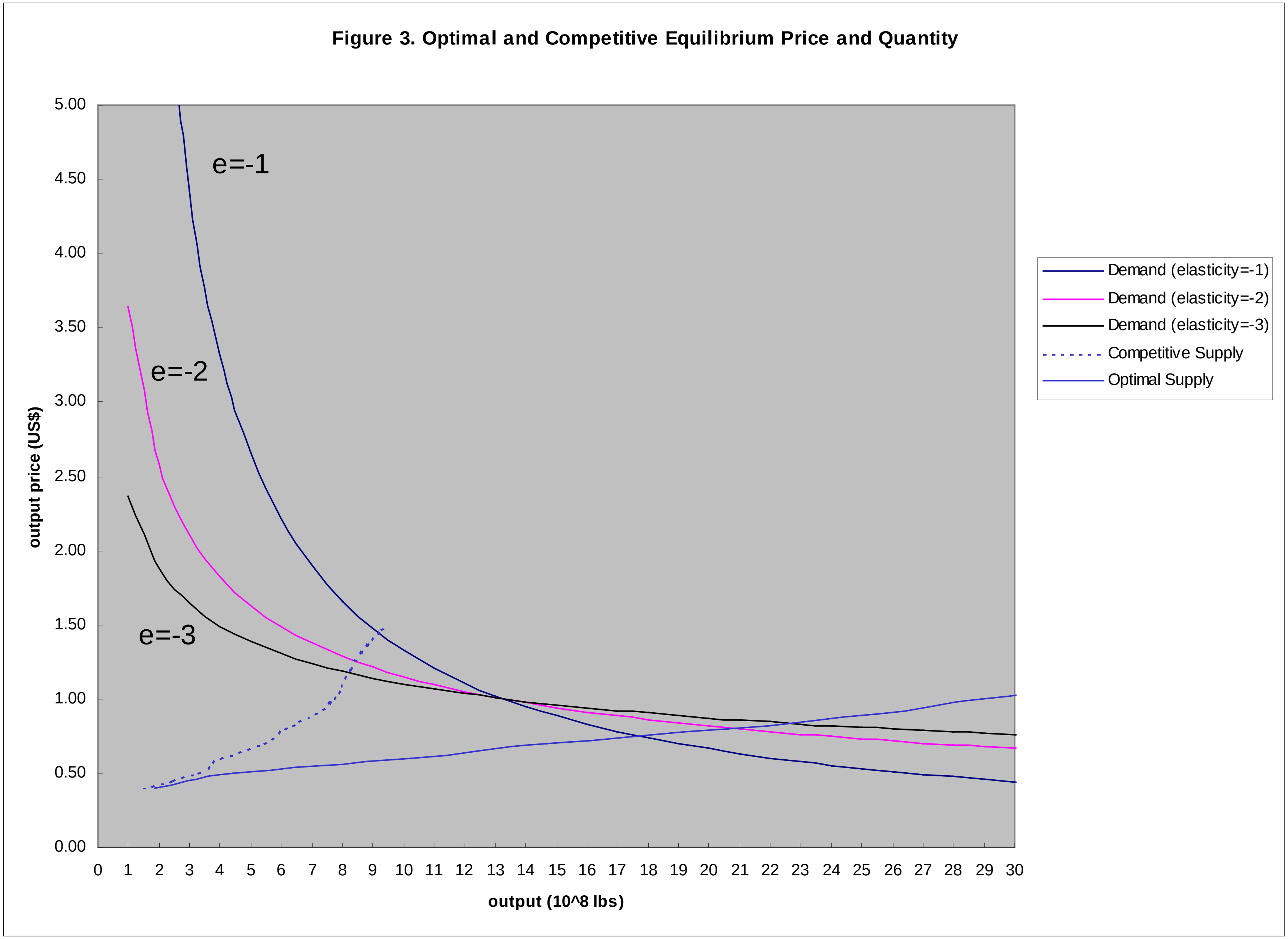
Figure 3. Optimal and Competitive Equilibrium Price and Quantity
output price (US$)
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
output (10^8 lbs)
e=-1
e=-2
e=-3
Demand (elasticity=-1)
Demand (elasticity=-2)
Demand (elasticity=-3)
Competitive Supply
Optimal Supply

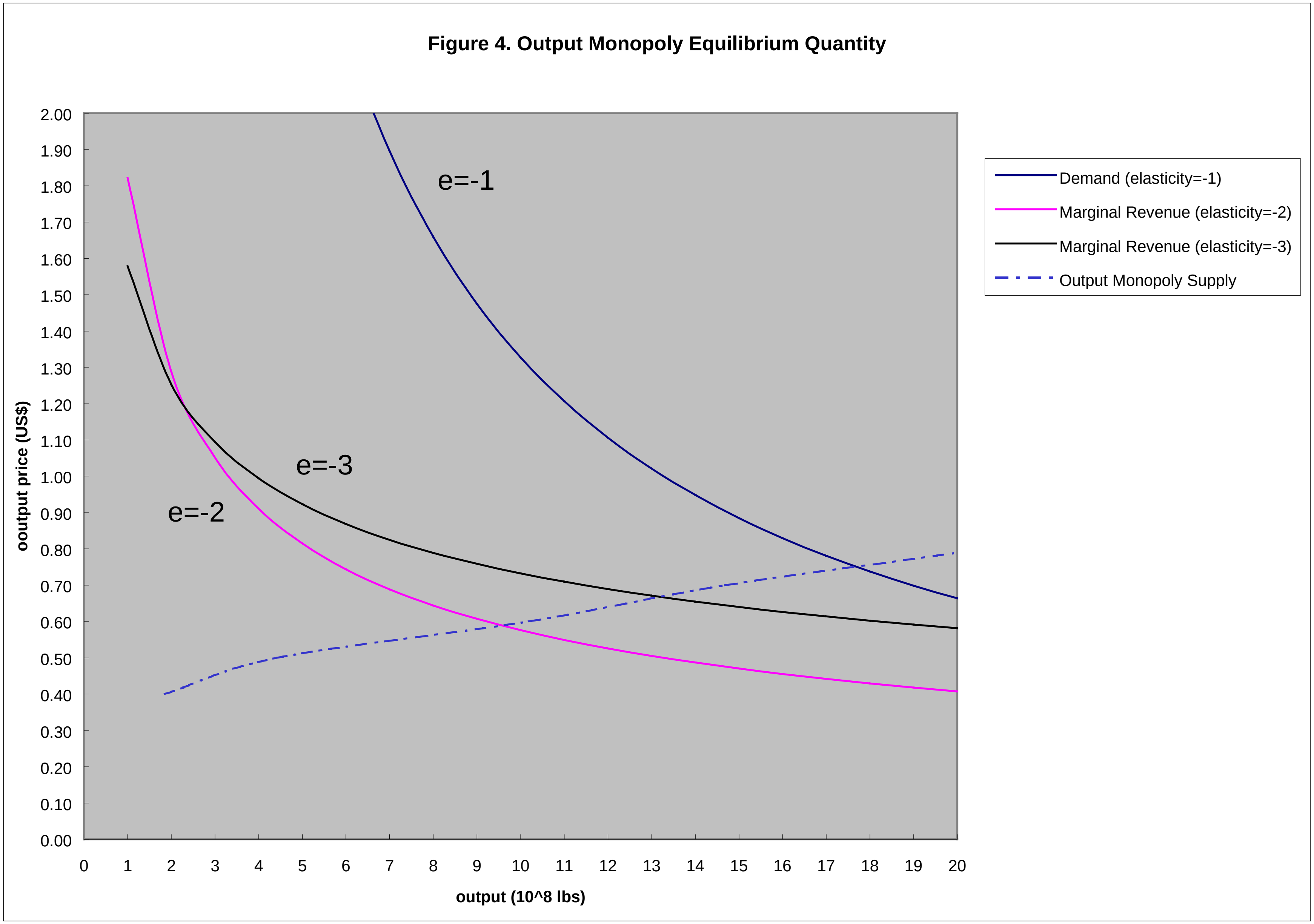
Figure 4. Output Monopoly Equilibrium Quantity
ooutput price (US$)
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
output (10^8 lbs)
e=-1
e=-3
e=-2
Demand (elasticity=-1)
Marginal Revenue (elasticity=-2)
Marginal Revenue (elasticity=-3)
Output Monopoly Supply

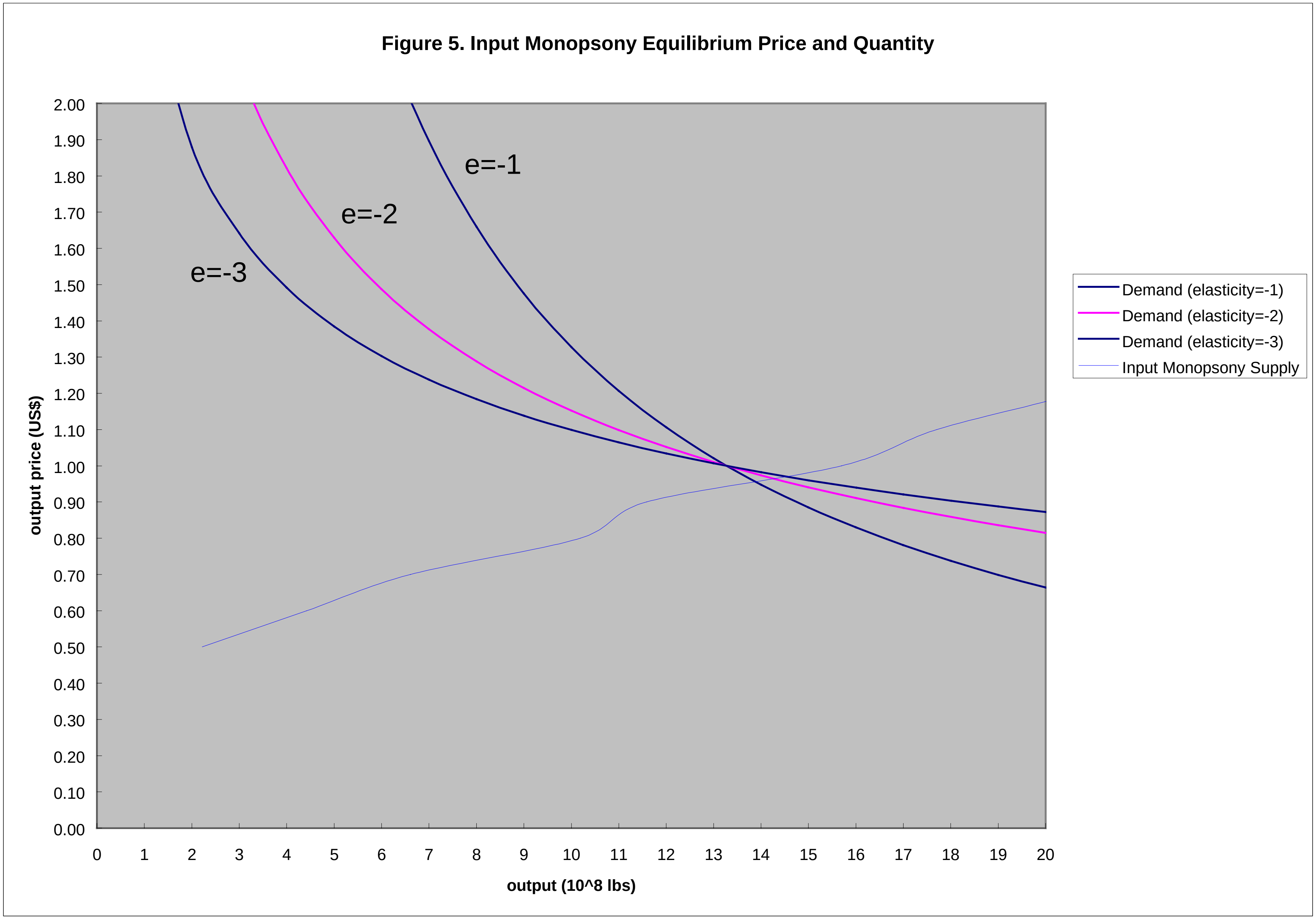
Figure 5. Input Monopsony Equilibrium Price and Quantity
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
output price (US$)
e=-1
e=-2
e=-3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
output (10^8 lbs)
Demand (elasticity=-1)
Demand (elasticity=-2)
Demand (elasticity=-3)
Input Monopsony Supply

TABLE 1: UNIT COST OF ON-FARM TECHNOLOGY [a]

Technology	Cost($/acre)	*h(I)*
Furrow Irrigation	0	0.6
Short-Run Furrow	20	0.7
Hand-move Sprinkler	60	0.8
Drip	120	0.95

[a] Adapted from Hanemman et al. (1987).

TABLE 2. SIMULATION RESULTS

	ε=–1			ε=–2				ε=–3			
	*(=O)	C	I	*	C	I	O	*	C	I	O
P ($)	0.75	1.49	0.96	0.80	1.26	0.97	1.18	0.84	1.18	0.974	1.01
Y (10^8 lbs.)	17.70	8.92	13.89	20.67	8.41	14.28	9.58	22.58	8.16	14.53	13.15
A (10^3 ha)	490	260	430	530	230	360	230	610	230	430	360
Z_0 (10^8 cu.m)	41	35	37	44	31	32	22	49	30.7	37	32
R_L (10^8 $)	0.13	5.00	3.98	0.59	3.52	4.12	5.37	0.56	2.90	4.20	4.65
CS (10^8 $)	25.18	16.07	21.91	13.94	7.88	11.03	8.60	9.14	4.50	7.00	6.24
PS (10^8 $)	3.27	5.91	3.89	4.34	3.92	4.07	6.66	5.19	3.26	4.17	6.38
Total Welfare	28.45	21.98	25.80	18.28	11.80	15.10	15.26	14.33	7.76	11.17	12.62
R_h (10^6 $)	0.271	28.72	9.05	1.09	21.93	11.13	22.38	0.912	19.16	9.55	12.57
R_t (10^6 $)	0.244	4.50	9.03	1.07	5.17	11.10	22.33	0.89	2.92	9.53	12.54
Y_h (10^6 $)	0.354	0.358	0.357	0.281	0.454	0.349	0.431	0.292	0.426	0.348	0.364
Y_t (10^6 $)	0.354	0.277	0.357	0.281	0.393	0.349	0.431	0.292	0.370	0.348	0.364
q_h (m/sq.m.)	0.835	0.863	0.859	0.824	0.891	0.880	0.953	0.802	0.892	0.855	0.880
q_t (m/sq.m.)	0.835	0.608	0.855	1.038	0.916	1.080	1.105	0.801	0.689	0.855	0.880
I_h ($/sq.m.)	0.023	0.022	0.022	0.023	0.020	0.021	0.017	0.024	0.020	0.022	0.021
I_t ($/sq.m.)	0.023	0.027	0.022	0.023	0.026	0.021	0.017	0.024	0.026	0.022	0.021
e_h (m/sq.m.)	0.770	0.790	0.786	0.760	0.802	0.799	0.831	0.744	0.803	0.783	0.799
e_t (m/sq.m.)	0.770	0.572	0.783	0.760	0.644	0.799	0.831	0.744	0.646	0.783	0.799
K_h ($/m.)	199.23	0	199.06	199.33	0	198.75	197.39	199.46	0	199.06	198.75
λ_h ($/cu.m.)	0.1590	0.1363	0.1438	0.1703	0.1211	0.1249	0.0871	0.1893	0.1200	0.1438	0.1249
λ_t ($/cu.m.)	0.1593	0.3855	0.1441	0.1705	0.3039	0.1252	0.0875	0.1895	0.3011	0.1441	0.1252

Notes: *=optimal; C=competitive; I=input monopsony; O=output monopoly; h=head; t=tail.