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The Stabilization Value of Groundwater and Conjunctive Water Management Under Uncertainty

by

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The Stabilization Value of Groundwater and Conjunctive Water Management under Uncertainty*

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The importance of managing ground and surface water conjunctively increases with water scarcity and with inter- and intra-temporal fluctuations in precipitations. Both factors are becoming critical in many parts of the world: the former due to increased water demand associated with economic and population growth; the latter due to climate change. A conjunctive ground and surface water system appears in a number of forms, which differ according to the ground and surface water sources. Surface water may consist of stream flows emanating from aquifers, surface reservoirs or lakes, snowmelt, rainfall or any combination of these. It may be stable or stochastically fluctuate over time. Groundwater sources – aquifers – may be non-replenishable or replenishable, deep or shallow, confined or unconfined. The two cases in which only surface water or only groundwater is used lie on both ends of the conjunctive spectrum; these extreme cases occur when one source is always cheaper than the other (scarcity cost included). Conjunctive systems, viewed in this larger context, characterize most irrigation systems worldwide. The term conjunctive signifies that the ground and surface water sources are two components of one system and should be managed as such.

The analysis of conjunctive water systems was pioneered by Oscar Burt more than 40 years ago. More recently, Tsur, Tsur and Graham-Tomasi, Provencher and Burt, and Knapp and Olson extended the theory to account for stochastic, dynamic and multiaquifer considerations. The underlying idea is simple. Surface water sources derived from rainfall and snowmelt typically fluctuate randomly from year to year and

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within a year. Groundwater stocks, on the other hand, are relatively stable because the slow subsurface flows tend to smooth out intra- and inter-temporal fluctuations. Groundwater thus performs a dual function, *increasing* the mean and *reducing* the variability of total water supply. The value of groundwater is usually attributed to its first – mean increasing – role, while its variability reducing role is ignored. Yet the latter role carries an economic value, which is designated as the stabilization value (or buffer values in the dynamic context) of groundwater, which could be substantial.

Why should we be interested in the stabilization value as a distinct concept? Suppose that a groundwater development project can be implemented at some cost and the decision whether or not to undertake the project is based on a cost-benefit criterion. Clearly, determining the benefit generated by the groundwater project assuming that surface water is stable at the mean, while easier to obtain, ignores the stochastic fluctuations of surface water and the ensuing stabilization role of groundwater. If the economic value associated with this role – the stabilization value – is non-negligible, compared to the value of the resource due to increasing the mean water supply, this simpler approach leads to a serious underestimation of the groundwater benefit and bias assessment of the groundwater projects. Empirical studies (Tsur) reveal substantial stabilization value of groundwater.

Here we discuss implications of the stabilizing role of ground water for conjunctive ground and surface water policies. Applying the analysis to Coimbatore Water District in Tmil Nadu, India reveals a substantial stabilization value. We conclude with some remarks regarding the important role of conjunctive water management policies in a world of increasing food demands and declining irrigation water supplies.

The stabilization value of groundwater revisited

Suppose that crop production requires only water and let $f(x)$ be the per-hectare yield-water response function, with x representing water input (the empirical application employs an extended version with multiples outputs and inputs). The water response function $f(x)$ is assumed increasing and strictly concave over the appropriate range of water input, reflecting the diminishing marginal productivity property. Let $R(x) = pf(x)$ represent revenue per hectare when output price is p (assumed exogenous to farmers). Following the properties of the yield-water response function, $f(x)$, the revenue function, $R(x)$, is increasing and strictly concave in water input.

Let S represent available surface water supply (e.g., annual rainfall), assumed to fluctuate randomly according to some probability distribution function $F(S)$. (We ignore intra-seasonal variations of surface water and consider only variations in total supply of surface water during a year.) When surface water (rainfall, stream flows emanating from snow melt) is the only source of irrigation water, the revenue (which is also profit in this case) $R(S)$ also fluctuates randomly around its mean $R_m=E\{R(S)\}$, where E represents expectation with respect to the distribution of S. If rainfall could be stabilized at the mean $S_m=E\{S\}$, the revenue would have changed to $R(S_m)$. Since $R(\cdot)$ is strictly concave, we have (Jensen's inequality)

$$E\{R(S)\} < R(S_m). \qquad (1)$$

Let S_{ce} be the Certainty-Equivalent water input satisfying

$$E\{R(S)\} = R(S_{ce}), \qquad (2)$$

i.e., S_{ce} is the constant annual surface water that leaves farmers indifferent between receiving it with certainty (every year) and facing the uncertain rainfall S with distribution $F(S)$. Since $R(\cdot)$ is increasing, (1) and (2) imply $S_{ce}<S_m$. (Growers are

assumed to be risk neutral and the divergence between S_{ce} and S_m stems from the concavity of the revenue function.)

How much farmers are willing to pay in order to stabilize surface water supplies at the mean (S_m) rather than facing the (actual) uncertain supplies S? The answer is simply the difference in revenues between the two situations: $R(S_m) - E\{R(S)\}$. We call this the Stabilization Value (SV) and, using (2), express it as

$$SV \equiv R(S_m) - E\{R(S)\} = R(S_m) - R(S_{ce}). \tag{3}$$

In Figure 1, SV is given by the area HCS_mS_{ce}.

To gain insight on how SV depends on the distribution of rainfall, we take a second order Taylor expansion of $R(S)$ around $R(S_m)$ and approximate $E\{R(S)\}$ by

$$E\{R(S)\} \cong R(S_m) + 0.5R''(S_m)\sigma^2$$

where $\sigma^2 = E\{(S - S_m)^2\}$ is the variance of S. By combining (3) and the above equation, we obtain

$$SV \cong -0.5R''(S_m)\sigma^2. \tag{4}$$

We see from (4) that SV increases wit σ^2 (the variance of rainfall) and with $-R''(S_m)$ = the steepness of the marginal revenue function (the derived demand for water) evaluated at S_m (the average surface water supply). Thus SV increases with rainfall variability (σ^2) and with the steepness of the derived demand for water at the mean rainfall S_m. Typically the derived demand for water is convex (i.e., the 3rd derivative of $R(\cdot)$ is positive – see the examples in Tsur et al. and the application below). In such cases the magnitude of $R''(S_m)$ decreases with S_m, so that SV increases with the variance (σ^2) and decreases with the mean (S_m) of surface water supplies. We note that the purpose of approximation (4) is to shed light on how SV depends on the distribution of surface water (particularly its mean and variance) but not for evaluation.

Suppose now that water from a groundwater source becomes available for irrigation at a constant unit cost z (\$ m^{-3}) and assume further that the rainfall distribution and z are such that some groundwater will be demanded also during rainy years, i.e., $R'(S_{max}) > z$, where S_{max} is maximal surface water supply (or the upper support of the distribution of S). We consider the situation in which groundwater pumping decisions are made after the rainfall realization is observed. (Tsur analyzed the stabilization value under this assumption. Tsur and Graham-Tomasi called it 'ex post' and considered also the case in which groundwater pumping decisions are made before the realization of S is observed, which they refer to as the 'ex ante'.) In this case, profit-seeking farmers demand the constant (stabilized) water input $x(z)$ satisfying $R'(x(z)) = z$ by augmenting the rainfall realization S with the amount of groundwater $g = x(z)–S$ (see Figure 1).

The introduction of groundwater has, in effect, lead to a stabilized water supply. We can imagine it occurring in two steps: first, surface water is stabilized at the mean S_m; second the surface water supply is augmented by the amount $g_m=x(z)–S_m$ of groundwater. The economic value associated with the first (stabilizing) step is the Stabilization Value of groundwater and is given by SV of equation (3). The economic value associated with the second step is the value due to the increase in the mean water supply from S_m to $x(z)$ and is denoted the Augmentation Value (AV) of groundwater:

$$AV = [R(x(z)) – R(S_m)] – z[x(z) – S_m] \qquad (5)$$

The total value of groundwater is the sum $SV+AV$. Notice that the price of groundwater z affects AV but not SV.

In Figure 1, the total revenue is the area AEx_zO and the average groundwater cost is $E\{z\cdot(x(z)-S)\}=z\cdot(x(z)-S_m)$ = area $GEx(z)S_m$. The average profit is thus the area $AEGS_mO$. The total value of groundwater is the area $HEGS_mS_{ce}$, of which SV = area HCS_mS_{ce} and AV = area CEG. In general, S_{ce} decreases with the variability of rainfall, as can be seen from (2) and (4). Thus, a mean-preserving spread of the rainfall distribution, which increases variance while keeping the mean intact, will increase the *SV* of groundwater and vice-versa.

Figure 1 here

In actual practice multiple crops and multiple inputs exist and the derived demand for irrigation water is modified accordingly. The *SV* of groundwater is then calculated as explained above, using the aggregate derived demand for water. The framework can be extended to multiple water storage sources, such as multiple aquifers with varying pumping costs and surface reservoirs. Moreover, some of the water storage sources may also be stochastic. As long as they are not perfectly correlated with rainfall they are capable of affecting the variability of water supply in a way that gives rise to a stabilization value.

Ignoring the rainfall variability, by assuming that rainfall is stable at the mean, amounts to assuming that *SV*=0, which does away with the stabilizing role of groundwater. This may lead to severe undervaluation of groundwater and distort water management policies. Some policy implications are discussed in the next section, followed by an empirical assessment of the stabilization value of groundwater in the Coimbatore water district of Tamil Nadu, India.

Conjunctive management

The stabilization value of groundwater affects water policies in a number of ways. First it affects the optimal extraction decisions of a dynamic exploitation policy. To see this, consider the above conjunctive ground and surface water system over a long period of time. Denote the aquifer's stock at time t by G_t, which evolve in time according to

$$\mathrm{d}G_t/\mathrm{d}t = M(G_t) - g_t, \quad (6)$$

where $M(G)$ is natural recharge, assumed non-increasing and concave in the aquifer's stock G, and time is taken to be continuous. The aquifer management problem entails finding the pumping policy $\{g_t, t \geq 0\}$ that maximizes the value

$$V(G_0) = \max_{\{g_t\}} \int_0^{\infty} [E_t\{R(S_t + g_t)\} - z(G_t) g_t] e^{-rt} dt \qquad (7)$$

subject to (6), given initial stock G_0 and feasibility constraints ($g_t \geq 0$, $G_t \geq 0$), where r is the time rate of discount and pumping cost z(G) may depend on the aquifer's stock. The expectation E_t is conditional on the realization of S_t being observed before the pumping decision g_t is made – a situation called 'ex-post' by Tsur and Graham-Tomasi .

A detailed analysis of this model can be found in Tsur and Graham-Tomasi (1991). Here we just note the condition

$$R'(S_t+g_t) = z(G_t) + V'(G_t) \,, \qquad (8)$$

determining the optimal pumping decision at time t, where $V'(G_t)$ is the incremental value due to marginal chance in the groundwater stock G_t or the shadow price of groundwater (also known as user cost, in-situ value and scarcity value). (The expectation is ignored because the realization S_t is assumed to be observed when g_t is chosen.)

If, however, surface water is assumed stabilized at the mean, the management problem changes to

$$V^m(G_0) = \max_{\{g_t\}} \int_0^{\infty} [R(S_m + g_t) - z(G_t) g_t] e^{-rt} dt \qquad (9)$$

subject to (6) and feasibility (e.g., nonnegativity) constraints and the optimal pumping rule (8) becomes

$$R'(S_m+g_t) = z(G_t) + V^{m\prime}(G_t), \qquad (10)$$

Where $V^{m\prime}(G_t)$ is the groundwater shadow price when S_t is fixed at the mean S_m.

Tsur and Graham-Tomasi showed (under certain conditions) that

$$V'(G_t) > V^{m\prime}(G_t). \tag{11}$$

The shadow price of groundwater under stochastic surface water supplies is larger because of the added role of groundwater in stabilizing water supply and the ensuing economic value that goes with it. Thus, at any given groundwater stock G, water users should pay more for the resource, hence pump less, under stochastic rainfall relative to a stabilized situation.

The Stabilization Value can also have a considerable effect on cost-benefit analyses of groundwater projects. Quite often the mere access to an aquifer requires investment in infrastructure, besides the operational costs associated with water pumping and conveyance. This cost should be compared to the benefit associated with developing the aquifer. Ignoring the stabilization value leads to underestimating the benefit associated with the development project. To see this consider the case where extraction cost z is independent of the stock and the aquifer stock is at a steady state, i.e., average extraction just equals recharge: $E\{g(S)\}=M(G)$. In this case the shadow price of groundwater vanishes at a steady state (see Tsur and Graham-Tomasi) and Condition (8) implies that $S+g(S)=S_m+M(G)$. The value V(G) evaluated at a steady state is thus given by

$$V(G) = \int_0^\infty E\{R(S+g(S)) - zg(S)\}e^{-rt}dt = \int_0^\infty R(S_m + M(G)) - zM(G)e^{-rt}dt$$
$$= \frac{R(S_m + M(G)) - zM(G)}{r} = \frac{R(S_m)}{r} + \frac{R(S_m + M(G)) - R(S_m) - zM(G)}{r}$$

The present value without groundwater is simply

$$V^S = \int_0^\infty E\{R(S)\}e^{-rt}dt = \frac{E\{R(S)\}}{r}.$$

Thus, the benefit associated with developing the aquifer is

$$V(G) - V^S = \frac{R(S_m) - E\{R(S)\}}{r} + \frac{R(S_m + M(G)) - R(S_m) - zM(G)}{r}.$$

The first term on the right-hand side is the present value of the Stabilization Value of ground water. The second term is the present value of the Augmentation Value of groundwater. Assuming stable surface water supplies is equivalent to assuming that SV equals zero, hence biases downward the project's benefit. The magnitude of the bias depends on the magnitude of SV. In 2 applications, the SV as a share of the total value of groundwater was found to be substantial (Tsur). We turn now to calculate the stabilization value of groundwater in the Coimbatore water district, located in Tamil Nadu, India.

Application

Data: Irrigation water is derived from surface reservoirs, filled by the monsoon rains and distributed via a system of canals, and from local aquifers. During the 2001-2002 agricultural year (that extends from July to June) 52.5% of the irrigation water came from surface sources, 45.2% from local wells (groundwater) and the remaining 2.3% from other sources (Palanisami).

There are two monsoon periods: the Southwest monsoon from June to September; and the Northeast monsoon from October to December. The period between January and May is dry, but surface reservoirs allow distributing water throughout the year. The annual rainfall, thus, constitutes the available surface water supplies. Figure 2 shows annual rainfall data (mm) for the periods 1965-1985 and 1991-1999.

Figure 2 here

Due to rising water demands by non-agricultural users, the reservoirs now satisfy about 90% of the irrigated area in normal year and only 60% during dry (low rainfall) years. These shares are expected to worsen (decline) in the future, as urban, industrial and environmental water demands rise. Thus, surface water supplies available for irrigation will on average decline and become more variable (larger variance) in the future (both trends increase the stabilization value of groundwater).

Crop pattern: Table 1 presents the main crops grown in Coimbatore District with their cultivated area, water requirement (m^3 ha^{-1}), yield (100kg ha^{-1}) and price (Rs per 100kg) during the 2001-2002 agricultural year ($1=48.5 Rs in 2002). The main crops (in terms of area) are ground nuts, paddy rice and sugar cane. The cultivation of ground nuts is done during the dry season, while paddy is grown during the monsoon seasons. The only perennial crop is Tapioca (most banana and sugar cane areas are replanted every year in Coimbatore District). The most water intensive crops are sugar cane and banana followed by paddy rice.

Table 1 here

Production inputs and cost: Table 2 lists the input requirements per hectare (other than water) and their costs (Rs ha^{-1}) for the 13 crops listed in Table 1 (since water is assumed the binding constraint and not land, the cost of land is virtually nil). The rightmost column of Table 2 gives the per hectare production cost, excluding water. We turn now to calculate the stabilization value of groundwater in Coimbatore Water District.

Table 2 here

The Stabilization Value: The first step is to obtain the derived demand for irrigation water. The aggregate data presented above do not permit detailed analysis and we follow the approach used in Tsur et al., which utilizes Howitt's PMP method. Table 1 contains data on crop area allocation, yield water requirements and output prices for the 13 crops grown in Coimbatore district. Table 2 contains per hectare input requirements of all production inputs other than water and their cost for these 13 crops. The rightmost column summarizes the per hectare production cost, excluding water. . The data are then processed by the PMP method to yield the derived demand for irrigation depicted in Figure 3.

Figure 3 here

The rainfall data S_t, depicted in Figure 2, are measured in mm. The corresponding surface water supplies are obtained by multiplying S_t by 10 times the irrigated area (77543 ha).[3] The rainfall distribution is taken as the empirical distribution of the observed sample, where each observation receives an equal weight of 1/30 (30 being the number of observations).

For any water supply *x*, the revenue $R(x)$ is calculated as the area beneath the derived demand curve (Figure 3) to the left of *x*. In this way the revenues $R(S_t)$, t=1,2,…,30, are calculated for each observation (sampled year). The sample average rainfall is $S_m=\Sigma_t S_t/30$ and $R(S_m)$ is calculated as the area beneath the derived demand curve to the left of S_m. Noting equation (3), obtaining *SV* requires the expected revenue $E\{R(S)\}$, which we estimate by the sample mean $\Sigma_t R(S_t)/30$. The Stabilization Value (*SV*) is then estimated by

$$SV = R(S_m) - \sum_{t=1}^{30} R(S_t)/30 . \qquad (12)$$

Calculating the Augmentation Value (*AV*) requires the cost of groundwater (cf. equation (5)), which consists of the pumping and conveyance cost $z(G)$ plus the user cost (or in-situ value) λ (see equation (8)). Obtaining these costs requires solving the dynamic optimization problem (7). This task requires elaborate hydrological and engineering (pumping, conveyance) data and is beyond the present scope. To gain insight on the share of *SV* in the total value of groundwater we calculate

$A = R(\infty) - R(S_m)$,

[3] One mm rainfall over one hectare is equivalent to 10 m^3.

which the AV when the cost of groundwater is zero. Thus, $A > AV$ and $SV/(SV+AV) > SV/(SV+A)$. The share $SV/(SV+A)$ is thus a lower bound on the share of SV in the total value of groundwater.

The empirical results are presented in Table 3. Economic values are measured in Rupees. We see that the stabilization value accounts for more than 25% of the total value of groundwater. Ignoring it, by assuming stable rainfall, would have led to underestimation of the value of groundwater by more than 25%.

Table 3 here

Concluding comments

Population growth and rising living standards lead to rapid increase in the demand for water. Since the average quantity of renewable fresh water available for use in any particular location is constant and water conveyance is an expensive operation, water has become a scarce resource in many parts of the world. Adding the prevalence of deteriorating water quality and the increased awareness for water-related environmental and social problems helps to understand why water resource management has become a critical policy challenge. In the region studied here, surface water has been relocated away from irrigation to meet the growing demands of other sectors in a way that reduces the average quantity of surface water available for irrigation and at the same time increases its variability (the withdrawal for non-agricultural uses is larger during dry years than during wet years).

Worldwide irrigation water still consumes the bulk of the available renewable fresh water resources (over 70 percent). While irrigated agriculture is practiced on only about 18 percent of total cultivable land (267 million hectare in 1997, of which 75 percent are in developing countries), it produces over 40 percent of agricultural output (Gleick, World Bank). Irrigated area is expected to continue to expand in order to meet the food demand of a growing population (FAO), but fresh water resources available for irrigation will at best remain fixed and most likely decline, stressing the need for improved efficiently of irrigation water.

There are ways to increase agricultural output without reliance on fresh water sources, such as improved crop variety (genetically or conventionally modified), appropriate water pricing and increased use of marginal sources (reclaimed, saline water). In this work we focus on conjunctive management of ground and surface water. We note that crop production is affected not only by the quantity of water input but also by how this quantity is distributed within and between growing seasons. Owing to the random nature of precipitations, surface water supplies typically fluctuate randomly while groundwater sources are relatively more stable. The latter, thus, can be used to stabilize the supply of irrigation water, thereby increasing output over and above that expected due the increase in the average quantity of water input.

Applying the analysis to the Coimbatore district in Tamil Nadu, India, we found that the stabilization value of groundwater exceeds 25% of the total value of groundwater. Ignoring the stabilization value (by assuming that surface water is stable at the mean) leads to undervaluing groundwater by more than 25%. Put differently, under the prevailing rainfall variability, conjunctive management of ground and surface water in this region can increase water use efficiency by more than 25%. Groundwater resources are prevalent worldide, yet often mismanaged due to their common property feature. This is particularly true for the region studied here (Palanisami). Understanding the true value of groundwater is a necessary step towards a better management of this resource.

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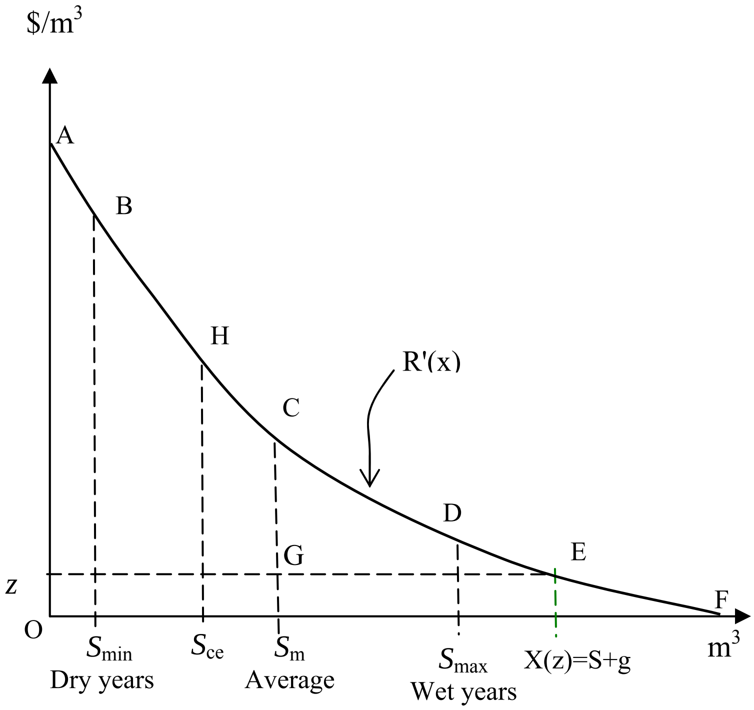

Figure 1: **Rainfall is distributed between S_{min} and S_{max} with mean S_m=E{S}. The derived demand for irrigation water is the value of marginal water productivity $R'(x)$. Areas underneath the derived demand curve represent revenues. z is the unit cost of groundwater. The total revenue is the area AEx_zO and the average groundwater cost is $E\{z(x(z)-S)\}=z(x(z)-S_m)$ = area $GEx(z)S_m$. The average profit is the area $AEGS_mO$. The total value of groundwater is the area $HEGS_mS_{ce}$, of which SV = area HCS_mS_{ce} and AV = area CEG.**

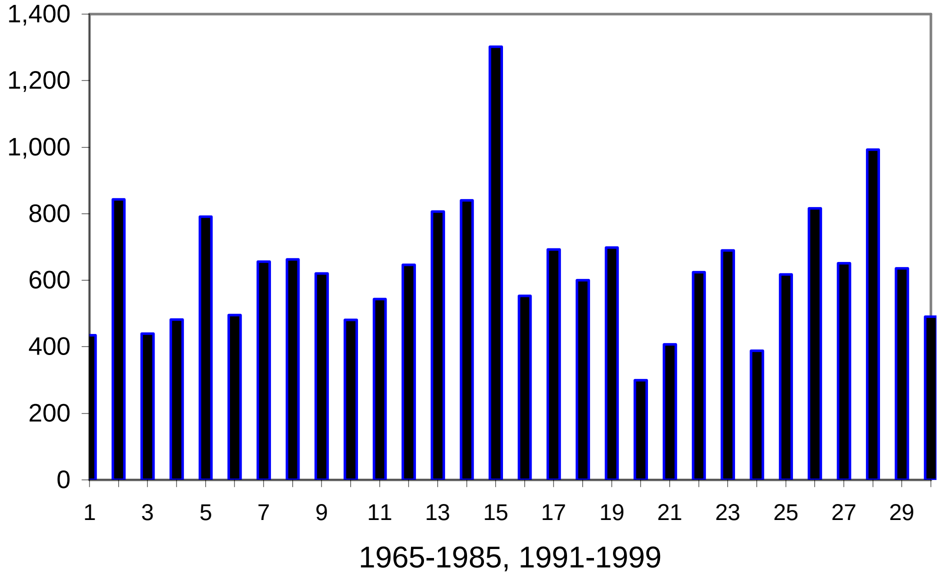

Figure 2: Annual rainfall (mm) in the Coimbatore District during 1965–1985 and 1991–1999.

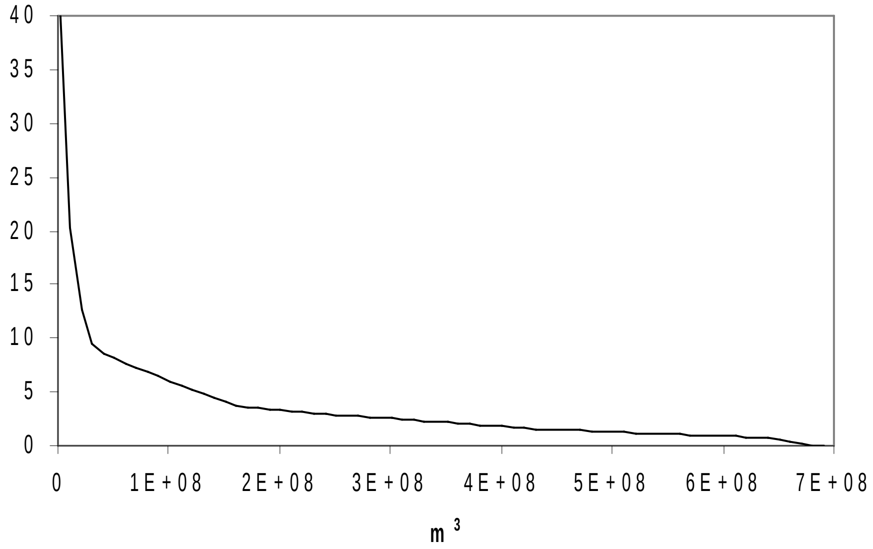

Figure 3: Value of marginal water productivity (Rs m^{-3}) in Coimbatore Water District.

Table 1: Planted area, water requirement, yield and price ($1=48.5 Rs in 2002) for the 13 main crops of Coimbatore District

Crop	Area (hectares)	Water requirement (m^3 ha^{-1})	Yield (100kg/ha)	Price (R/100kg)
Cotton	8576	6000	2.91	8576
Cholam	6451	3500	0.90	6451
Groundnuts	15145	4500	1.39	15145
Sugarcane	12355	20000	6.49	12355
Chilies	2594	5000	21.76	2594
Tomato	5827	5000.00	13.94	5827
Paddy rice	12258	12500	2.26	12258
Tapioca	1214	6000	32.04	1214
Ragi	80	3500	148.58	80
Turmeric	2910	14000	37.41	2910
Banana	7561	20000	17.99	7561
Soya Beans	35	5000	537.77	35
Onion	2537	3000	45.29	2537

Table 2: Per hectare input requirements and costs (Rs ha^{-1}).

	Seeds	Manures	Family men labor	Family women labor	Hired men labor	Hired women labor	Animal power	Machine power	Fertilizers	Pesticides	Per-hactare cost (excluding water)
Cotton	510	778	1730	884	1577	4675	376	1159	1889	1179	14757
Cholam	206	363	661	157	567	562	406	373	212	0	3507
Ground nuts	3028	767	1328	262	1521	2602	664	638	1006	228	12044
Sugar cane	6224	1206	2649	357	14096	7029	651	5238	4585	581	42616
Chilies	705	1903	2730	800	4000	12423	696	2707	4799	1578	32341
Tomato	173	1750	2669	1086	1717	3586	736	633	1813	824	14987
Paddy rice	956	1310	1662	282	2503	3582	933	1746	2394	1440	16808
Tapioca	353	1250	4439	1050	4067	4212	240	2783	2281	40	20715
Ragi	136	683	2152	490	974	2458	568	768	1046	20	9295
Turmeric	9206	2095	2702	367	5888	4690	816	725	2686	607	29782
Banana	5525	727	1859	239	19214	4338	210	1963	1266 3	581	47319
Soya Beans	765	276	892	723	698	1365	441	712	1038	217	7127
Onion	7549	3212	5442	769	5497	8578	1319	3794	3783	2985	42928

Table 3: Groundwater values (except for last row, all values are in Rs).

Symbol	Description	Result
$R(S_m)$	Revenue at the mean	2,395,063,341
$E\{R(S)\}$	Mean revenue	2,342,143,999
$SV= R(S_m)- E\{R(S)\}$	Stabilization Value	52,919,342
$R(\infty)=$	Revenue under unlimited water	2,552,096,009
$A= R(\infty)-R(S_m)$	Upper bound on Augmentation Value AV	157,032,667
$A + SV$	Upper bound on the total value of groundwater	209,952,009
$SV/(A+SV)$	Lower bound on share of SV in total value of groundwater	0.252

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