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The Economics of Conjunctive Ground and Surface Water Irrigation Systems: Basic Principles and Empirical Evidence from Southern California

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1. Introduction

Agriculture production in California depends on irrigation water derived from ground and surface water sources conjunctively. The term "conjunctive ground and surface water system" is applied to a number of systems; they differ according to the ground and surface water sources. Surface water may consist of stream flows emanating from aquifers, surface reservoirs and 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 costs included). Conjunctive systems, viewed in this larger context, contain all possible cases; the term "conjunctive" signifies that the ground and the surface water sources are two components of *one* system and should be analyzed as such.

The management of a conjunctive water system was initially investigated by Oscar Burt (1964). Tsur (1990, 1991), and Tsur and Graham-Tomasi (1991) have extended this theory to account for uncertain surface water supplies. Surface water supplies derived from rainfall and snowmelt fluctuate randomly from year to year and within a year. Groundwater stocks, on the other hand, are relatively stable because the uncertainties they involve, e.g., random recharge levels, take long time to express their influence and hence annual fluctuations tend to be averaged out (smoothed) over time. Thus, groundwater performs a dual function, increasing the quantity and reducing the variability of irrigation water. The variability-reducing role of groundwater carries an economic value, which is designated as the stabilization value (or buffer value in a dynamic context) of groundwater.

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 that a decision-maker wishes to evaluate such a project using a benefit-cost approach. Clearly, determining the value of groundwater assuming that surface water is stable at the mean is much simpler than when uncertainty is incorporated. However, if the stabilization value is large relative to the overall value of groundwater, use of the simpler stable approach provides a poor approximation to true benefits and could seriously bias assessments of groundwater development projects. Studying the case of the Israeli Negev region, Tsur (1990) found that the stabilization value of groundwater is substantial. Our empirical investigation below provides further evidence to the importance of this concept: in some cases, the stabilization value amounts to more than 50 percent of the total value groundwater. Assuming that surface water supplies are stable at the mean, therefore, would seriously bias assessments of groundwater benefits.

In this chapter we apply this principles to the California situation. For the sake of concreteness, we focus on a particular district: the Arvin-Edison Water Storage District of Kern county, located at the southeastern edge of San Joaquin valley. We have chosen this district because it implements sophisticated conjunctive management practices and offers rich data on these activities. Section 2 lays down the basic principles underlying the management of a conjunctive irrigation system. Section 3 applies these principles to the above mentioned district. Section 4 evaluates the role of conjunctive water management under future scenarios involving reduction in surface water entitlements for irrigation. Special attention is given to the role of irrigation efficiency in mitigating the adverse affects such reductions have on farmers welfare. Section 5 discusses implications for conjunctive water policy in California and suggests further research.

2. Principles

The analysis of a conjunctive irrigation system may involve one period only, in which case it is called static, or many periods, in which case it is dynamic. Dynamic models also consider effects of current decisions on future outcomes; static models consider only current outcomes. The analysis depends on whether surface water supplies are stable or fluctuate stochastically from year to year and within a year. We discuss each case separately, starting with

2.1. The simplest case: Single period and stable surface water supply

Consider an agricultural region (say, a water district) that enjoys a stable (fixed) supply of surface water S. The region's farmers grow J crops, indexed $j = 1,2,\ldots,J$. let $F_j(w)$ represent the water response function of crop j; this function attaches total yield to each quantity of water w applied for irrigating crop j. Typically, F_j increases with w (more water gives higher yield) at a diminishing rate (the effect on yield of a small increase in w diminishes as w increases). These properties are expressed in mathematical notation as: $F'_j(w) \equiv \partial F_j(w)/\partial w > 0$ ($F_j(w)$ is increasing) and $F''_j(w) \equiv \partial^2 F_j(w)/\partial w^2 < 0$ ($F_j(w)$ is concave). The revenue generated by crop j when irrigated with w acre-feet of water is $Y_j(w) = p_j F_j(w)$, where p_j

represents the output price of crop j, assumed fixed.

The value of the marginal productivity of water is the change in revenue generated by increasing water application by one (marginal) unit. It is measured by $Y_j'(w) = p_j F_j'(w)$. Due to the diminishing marginal productivity of water, Y_j' slopes downwards. Profit-seeking farmers will demand an additional unit of water as long as the revenue this unit generates exceeds its price. This translates into the following rule: when the price of water is p, crop j's growers will demand the quantity w(p) satisfying $Y_j'(w(p)) = p$. As the water price p varies, so does the water demand and the derived demand for irrigation water by crop j's growers is formed. The region's derived demand for irrigation water is obtained by horizontally summing the derived demand curves over all crops, j=1,2,...,J. This curve is denoted by $Y'(\cdot)$; the case J = 2 is illustrated in Figure 1.

Figure 1

Groundwater, when available, needs to be pumped from the ground and is usually more expensive than surface water. This may not always be the case, as surface water which is imported from a remote region can be more expensive than groundwater pumped from a local aquifer, but it holds in the case under study—the San Joaquin valley in California. When surface water is rationed, groundwater will be demanded by irrigators (to augment surface water) to the extent that the cost of groundwater does not exceed the value of marginal productivity of irrigation water. Let the supply cost (the price) of surface water be denoted by p_s and that of groundwater by p_g; that surface water is cheaper than groundwater means $p_s < p_g$. If the available supply of surface water S is limited such that $Y'(S) > p_g$, groundwater will be demanded at the quantity g satisfying $Y'(S+g) = p_g$.

Figure 2 provides a graphical view. The profit, i.e., the revenue minus the water cost, is measured by the area {$acdep_s$}. The surface water S contributes to profit the area {$abep_s$} and the groundwater g contributes the area {bcd}; the latter constitutes the value of groundwater. Suppose that the pumping cost of groundwater decreases to the level p_g' due, for instance, to a recharge program that elevates the groundwater table in the aquifer. The demand for groundwater increases to the level g' satisfying $Y'(S+g') = p_g'$ (see Figure 2) and the value of groundwater (i.e., the contribution of groundwater to total profit) changes to the area {bc'd'}. Thus, the net benefit associated with a recharge program due to the changes in groundwater cost from p_g to p_g' is the area (bc'd') minus the area {bcd}. Such benefits are calculated in the empirical analysis below.

Figure 2

Alternatively, if the derived demand for irrigation water shifts upward, say from Y' to $\tilde{Y}'$ (Figure 2), the demand for groundwater (of price p_g) changes to the level $\tilde{g}$ satisfying $\tilde{Y}'(S+\tilde{g}) = p_g$ and the value of groundwater changes to the area {$\tilde{b}\tilde{c}d$}. The derived demand for irrigation water may shift due, for instance, to the development of an improved variety of some of the crops, due to the application of a better cultivation method, due to the introduction of an improved and cheaper fertilizer, or as a result of the adoption of an efficient irrigation method. Here, we shall be concerned only with the latter possibility, namely, when water productivity increases as a result of adoption of efficient irrigation techniques. We can thus measure directly the benefit generated by an increase in irrigation efficiency: for the case depicted in Figure 2, this is given by the area {$\tilde{b}\tilde{c}d$} minus the area {bcd}.

2.2. Single period and stochastic surface water supply

When the quantity of surface water available for irrigation fluctuates randomly from year to year according to precipitation, S is a random variable. In the absence of groundwater, growers use the realized amount of surface water and enjoy the profit $Y(S) - p_s \cdot S$, which fluctuates randomly from year to year according to the realized surface water supplies. When groundwater is available at a price p_g, growers augment the available surface water supplies by the groundwater quantity g that satisfies $Y'(S+g) = p_g$, provided $Y'(S) > p_g$; when surface water is plentiful so that $Y'(S) \leq p_g$, no groundwater will be demanded.

Define K to be the quantity of irrigation water satisfying $Y'(K) = p_g$ (see Figure 3). Then, the demand for groundwater equals K - S or 0 as S < K or $S \geq K$, respectively. Groundwater demand and the benefit it generates, then, depend on the surface water realization. When $S = S_1$ (see Figure 3), irrigators demand $K - S_1$ acre-feet of groundwater that generate the benefit given by the area $\{b_1cd_1\}$. When $S = S_2$, $K - S_2$ acre-feet of groundwater will be demanded (at price p_g) and will generate the benefit measured by area$\{b_2cd_2\}$. The value of groundwater is defined as the mean of the groundwater benefits (taken with respect to S). If S can take the values S_1 or S_2 with equal probability, the value of groundwater equals:

$$\text{area}\{b_1cd_1\}(1/2) + \text{area}\{b_2cd_2\}(1/2).$$

Figure 3

Due to the availability of groundwater, the total amount of water applied for irrigation is stabilized at the level K, despite the fact that surface water fluctuates randomly. Groundwater, thus, serves a dual function. First, it augments the total supply of water available for irrigation. Second, it stabilizes the fluctuations in the supply of irrigation water. The total value of groundwater is the sum of the benefits generated by these two roles. We call the benefit generated by the variability reducing function of groundwater the *stabilization value of groundwater.*

To better understand the stabilization value of groundwater, it helps to think of the move from a situation in which only surface water is available to that with groundwater as occurring in two steps. In the first step the supply of surface water is stabilized at the mean μ by storing the amount $S_2 - \mu$ of surface water during wet years, when $S = S_2$, and withdrawing from the storage the amount $\mu - S_1$ during dry years, when $S = S_1$ (see Figure 3). In the second step, irrigation water is augmented by the amount $K - \mu$ of groundwater. The value associated with the first step is the stabilization value of groundwater.

Consider the stabilization step, in which the supply of surface water is stabilized at the mean μ. Would farmers prefer a stable supply of surface water at the level μ over the original unstable situation in which S fluctuates randomly between S_1 and S_2? Using Figure 3, this question is easily answered graphically. With a stable supply of surface water, farmers obtain the profit measured by area$\{ab_\mu e_\mu p_s\}$ each year. With $S = S_1$ half of the time and $S = S_2$ the other half, farmers earn the profit area$\{ab_1e_1p_s\}(1/2)$ + area$\{ab_2e_2p_s\}(1/2)$ on average. The difference between the average profits in the stable and unstable situations equals area$\{b_1b_\mu e_\mu p_s\}(1/2)$ - area$\{b_\mu b_2e_2e_\mu\}(1/2)$. Because the value of marginal water productivity (the derived demand for water) Y′ slopes downwards, it is seen, observing Figure 3, that the magnitude of area$\{b_1b_\mu e_\mu p_s\}$ exceeds that of area$\{b_\mu b_2e_2e_\mu\}$ and farmers prefer the stable situation. The amount farmers would be willing to pay to move to a stable surface water supply equals

$$0.5 \cdot \text{area}\{b_1 b_\mu e_\mu e_1\} - 0.5 \cdot \text{area}\{b_\mu b_2 e_2 e_\mu\}$$

which constitutes the stabilization value of groundwater. For a more elaborate account of this concept, see Tsur (1990).

The value of groundwater due to its role in increasing the supply of irrigation water from μ to K is evaluated by area$\{b_\mu c d_\mu\}$. The total value of groundwater is the sum of the stabilization value and area$\{b_\mu c d_\mu\}$.

2.3. Dynamic models

Dynamic modeling is needed when actions taken today can affect future outcomes. When present extractions exceed recharge, the groundwater stock will be smaller, scarcer and more expensive to extract tomorrow; thus, dynamic models ought to be used. The literature on intertemporal (dynamic) exploitation of renewable resources in general and groundwater resources in particular is vast (see, for example, Burt, 1964b, Cummings and Winkelman, 1970, Domenico *et al.*, 1968, Feinerman, 1988, Tsur *et al.*, 1989).

A dynamic analysis of a conjunctive irrigation system with stochastic surface water supplies is presented in Tsur and Graham-Tomasi (1991). We summarize the main features of the model. Let G_t denote the aquifer's stock at time t. The stock G_t determines the groundwater depth, which in turn determines the extraction cost p_g. Thus, we write $p_g(G_t)$. Recall that in the static case groundwater was demanded so that $Y'(S+g) = p_g$. In a dynamic analysis, the demand for groundwater at time t, g_t, is determined by the condition

$$Y'(S+g_t) = p_g(G_t) + \lambda_t,$$

where λ_t is the shadow value of groundwater (also known as the *in situ*, unextracted or scarcity value). The shadow price λ_t measures the value of unextracted water and as such encompasses the future cost associated with present extraction decisions. Put differently, λ_t represents the future benefits forgone as a result of extracting a unit of groundwater today. A unit of water left in the aquifer can generate benefit in two ways: first it is available for use in the future; second, it contributes to the stock and hence reduces the cost of future extractions.

The main task of a dynamic analysis is to determine the time path of λ_t. Tsur and Graham-Tomasi (1991) characterize λ_t under two information scenarios regarding the surface water. In the first—the *ex-post* scenario—the demand for groundwater is determined *after* the realization of surface water has been observed; in the second—the *ex-ante* scenario—groundwater must be contracted for in advance, *before* the actual realization of surface water is known. These authors defined the counterpart of the stabilization value of groundwater in the dynamic context and call it the *buffer value* of groundwater. They then showed, by means of numerical examples, that the buffer value can be substantial.

3. A case study: The Arvin-Edison Water Storage District

We turn now to apply some of the concepts discussed above to study the potential of conjunctive ground and surface water policies in Arvin-Edison Water Storage District (AEWSD) of Kern county, located in the southern edge of California's Central Valley. The empirical analysis considers a single year (1987) with the prevailing stochastic surface water supplies. We begin with a short description of the district's water situation.

3.1. Water Sources and Institutions

The district contains over 100,000 acres of cultivated cropland, 60% of which is connected to the AEWSD distribution system (only the area connected to the distribution system is considered). The district receives water from surface water canals and groundwater well fields and makes this water available (undifferentiated by source) to farmers. The surface water is pumped up a hill through Forrest Frick pumping plant and distributed from there to the district's service area. Figure 4 provides a graphical view.

Figure 4: AEWSD surface canals and well fields

The district carries out a groundwater recharge program. Spreading ponds were constructed in selected areas so that surface water could be allowed to seep into the ground and recharge the aquifer in years of surplus surface water (see Figure 4). Since its introduction in 1964, over 500,000 acre feet have been put back into the ground, effectively stabilizing the water table despite increased use.

In order that federal funding be allocated in the construction of recharge and conveyance facilities, knowledge of the demand for the irrigation water was required. As a result, a complex system of contracts for water use was implemented. These contracts commit farmers to purchase a given quantity of water from the district each year. Water contracts are transferred upon sale of farmland, so that water rights become a part of the farmland properties. This means that the district faces a reasonably well known demand for water.

On the supply side, each year the district is given an entitlement to a fixed quantity of surface water by the U.S. Bureau of Reclamation, depending on state-wide water availability. As water availability varies widely year-to-year, so do entitlements, and hence surface water supplies. The district must meet the (known) demands from this stochastic supply and thus operates several pumping stations that extract groundwater to augment surface water supplies when surface water supplies are insufficient to meet demand. If all water demand requests are met with available surface water supplies, the remainder is stored in the spreading ponds (as permitted by ponds' capacity) and used to recharge the aquifer.

3.2. Water costs

The cost of surface water includes (a) the cost of purchasing the entitlement quantity, and (b) the cost of operating Forrest Frick Pumping Plant (which moves water up to the distribution system). In 1987, the purchase cost of surface water was \$5.63/AF. Pumping the water through Forrest Frick added \$10/AF. Total surface water cost was \$15.63/AF.

Groundwater cost consists of the cost of extraction and of operating well fields. In 1987, groundwater cost was about \$28.67/AF. Costs of maintaining the distribution system must be paid regardless of the source (or presence) of the irrigation water; these are fixed costs and are not included in the marginal cost of water supply.

Data on surface water supplies and groundwater extractions were obtained via personal communication with Mr. Steven Collup of the District. Costs of purchasing surface water were calculated by dividing total expenditures by total imports of surface water. Costs of groundwater with the recharge program include only the energy cost for extraction (\$0.034/KWH in 1987) and were also supplied by Mr. Collup. The pumping cost calculated as the average (weighted according to production) of all the district well fields.

We also calculated groundwater costs in absence of the recharge program, which amount to \$41.14/AF in 1987 prices. These are costs required to extract water from the estimated depth of groundwater had recharge activities never been implemented. The estimated depth was calculated by the district (Arvin-Edison Water Storage District, 1992, Figure 9).

Surface water supplies during the period 1968-1991 are recorded in Table 1 and illustrated graphically in Figure 5. These data are used to estimate the distribution of surface water supplies by assuming that the random surface water supply can take each of these realizations with equal probability (this amounts to using the empirical distribution of surface water supplies to estimate the true unknown distribution). Given a realization of surface water, the supply schedule for irrigation water consists of a bi-level step function, in which the first (lower) step is formed by the available surface water supplies and the second step by the complimentary demand for groundwater. Figure 6 gives a typical supply schedule.

Table 1

Figure 5 Figure 6

3.3. The demand side: The value of marginal productivity of water

It does not make much sense to consider the derived demand for irrigation water when farmers are bounded in their water demand by predetermined contracts. The value of the marginal productivity of irrigation water (discussed in Section 2), however, is a well defined concept, independent of restrictions on water demand. The design of water institutions involves the endowment of property rights, the definition of water contracts, and rules for trading in them is beyond the scope of this chapter. Here, we take the mechanism of water allocation in AEWSD as given.

Due to lack of input/output data, the water response functions of the district's various crops cannot be estimated. We thus resort to an approximation procedure, implemented along the following steps. The seven major crops grown in the region are grapes, potatoes, cotton, vegetables, orchard, citrus and alfalfa. For each crop, data on acreage, total revenue, and cost of production net of water cost are available; Table 2 reports the data corresponding to 1987. Subtracting the cost of production from total revenue and dividing the result by the number of acres gives the profit per acre net of water cost for each crop. Per acre water requirement for each crop are taken as suggested by agronomist and are reported in Table 2 (data on actual water application by farmers are not available). Dividing the profit per acre (net of water cost) by the water requirement per acre, we obtain the average value of an acre-foot of irrigation water for each of the seven crops. The production technology of each crop is assumed to be of fixed proportions (a Leontief technology). Therefore, each crop's average value of a unit of irrigation water also equals the marginal value. The value of marginal productivity of water is constant within each crop but varies from crop to crop. These values are recorded in the 8th column of Table 2 and depicted graphically in Figure 7. A cell in this histogram corresponds to a particular crop; its height represents the value of an acre-foot of irrigation water and its width gives the total water applied to irrigate this crop.

By arranging the crops in descending order of value of irrigation water and smoothing the steps, an approximate of the value of marginal productivity of irrigation water function is obtained.

Table 2

Figure 7

3.4. Merging supply and demand: Calculating profits, the value of groundwater and the stabilization value of groundwater

For a given surface water realization S, the associated demand for groundwater is the quantity g such that S + g intersect the value of marginal productivity of irrigation water, represented by the histogram of Figure 7. The profit associated with S + g is evaluated as the area between the marginal value histogram and the supply schedule (Figure 6) corresponding to the realized S. Calculating this profit for each realization of S gives a profit distribution induced by the surface water distribution of Table 1.

Let S_t, t=1,2,...,24, denote the surface water realizations during the 24 years recorded in Table 1. Let g_t be the groundwater demand associated with S_t and $\Pi(S_t+g_t)$ the corresponding profit. Columns 1, 3 and 5 of Table 3 present these quantities. Column 2 records the profits in the absence of groundwater, denoted $\Pi(S_t)$. The value of groundwater when surface water supply is S_t equals $\Pi(S_t+g_t)$ - $\Pi(S_t)$ and is recorded in Column 6. The average $\frac{1}{24} \sum_{t=1}^{24} [\Pi(S_t+g_t)-\Pi(S_t)]$ constitutes the value of groundwater. The penultimate row of Table 3 gives the averages of all entries above it in each column. The value of groundwater, given on the sixth entry of this row, equals $1,045,006.

The last row of Table 3 gives groundwater demand and profits assuming that surface water supply is stable at the mean, i.e. S = 122,085 acre-feet. The profit with groundwater minus the profit without groundwater, which gives the value of groundwater had surface water been stable at the mean (the sixth entry on the last row) equals $556,483

The difference $1,045,006 - $556,483 = *$488,523* is the stabilization value of groundwater. This is the value of groundwater (in 1987) due only to its role in stabilizing the supply of irrigation water (disregarding its other role in increasing average supply of irrigation water). It is seen that the stabilization value of groundwater amounts to 47 percent of the total value of groundwater. Assuming that surface water supplies are stable at the mean would bias assessments of groundwater benefits downward by 47 percent; this can lead to serious mistakes in policy making based on cost-benefit evaluations of groundwater projects.

Table 3

3.5. The value of the recharge program

In the absence of the recharge program, it was discussed above, the groundwater table would have been deeper and the cost of groundwater higher. Based on estimates of groundwater levels (Arvin-Edison Water District, 1992, Figure 9), we have calculated the supply cost of groundwater without recharge in 1987 to be $41.14/AF (compare that with the prevailing cost of $28.67/AF).

Repeating the calculations of Table 3 with the groundwater cost of $41.14/AF, we find that, without the recharge program, total value of groundwater would have been $716,735. Subtracting this from the value of groundwater with recharge—$1,045,006 as reported in Table 3—we obtain that the recharge program contributed $328,271 in 1987 alone. This should be compared with the annual cost of of the recharge program which consists of the interest and operation and maintenance costs.

4. Some future (hypothetical) scenarios

Irrigators compete for the limited amount of surface water with the ever growing demand of urban dwellers—both for domestic and industrial uses—and with the increased demand of instream flows for environmental purposes. How water is to be reallocated between these sectors is not of our concern. Here we only note that this competition can lead to a reduction in surface water entitlement allocated to irrigation in the future. It is of interest, then, to calculate the effects of such (hypothetical) reductions on the welfare of agricultural producers and to investigate the role of conjunctive ground and surface water allocation policies. We consider two (hypothetical) scenarios, in which surface water entitlements are reduced by 25 and 50 percent. A reduction in surface water entitlement affects the distribution of surface water supplies. The new distribution is obtained by multiplying each of the surface water realization (Tables 1) by the reduction factor (e.g., a 25 percent reduction entails multiplying surface water realizations by 0.75).

A possible remedy for the increased scarcity of surface water allocated to irrigation is to improve irrigation efficiency. An improvement in irrigation efficiency can come about in many ways, e.g., using a better irrigation technique (central pivot rather than flood, drip rather than sprinkler), or by lining and covering irrigation canals to minimize loss due to seepage and evaporation. Disregarding its source, an increase in irrigation efficiency shifts upward the value of marginal productivity histogram (Figure 7). A 25 percent increase in irrigation efficiency, for example, is represented by increasing the height of each of the histograms by 25 percent (the dotted histogram in Figure 7). The assumption is that farmers will continue to use the same amount of surface water for irrigation, as they are bounded by predetermined contracts, but will enjoy a higher yield.

The profit and groundwater value calculations, carried out above and recorded in Table 3, can be repeated for each situation characterized by particular surface water distribution and a value of marginal productivity of water histogram. The results of these calculations are summarized in Table 4. Along a column of the table, irrigation efficiency is constant and the distribution of surface water varies from actual (no reduction) to a 25 percent reduction and 50 percent reduction. Along a row, surface water distribution remains unchanged and irrigation efficiency changes from actual to 25 percent increase and 50 percent increase. Advancing along a diagonal of the table involves changes in both the distribution of surface water and irrigation efficiency. For each scenario, four numbers are recorded: average profit, value of groundwater, the stabilization value of groundwater, and the share of the stabilization value in the total value of groundwater.

Table 4

The first column of Table 4 reveals that farmers' welfare (total profit) is not very sensitive to surface water supplies: a 50 percent reduction in entitlements caused total profit to decline by 4.7 percent. This may be misleading, as the calculations in Table 4 uses the prevailing groundwater cost of $28.67/AF. It is clear that a reduction in surface water entitlements will increase extractions, as growers use groundwater to substitute part of the lost surface water. As a result, groundwater tables will decline and extraction costs increase. This process continues until a new equilibrium is reached at lower groundwater stocks and higher extraction costs.

We thus calculated the case of a 50 percent reduction in surface water entitlements again, assuming that the cost of groundwater extraction increases to $61/AF. The results are: average profit = $13,623,964; value of groundwater = $887,812; stabilization value of groundwater = $517,521, which constitute 58 percent of the value of groundwater. The 50 percent reduction in surface water entitlements caused growers' profit to decrease by about 20 percent.

This example demonstrates the role of recharge activities that use surplus surface water during wet years to recharge the aquifer. The capacity of the recharge ponds can be increased to fully utilize the surplus in surface water supplies during wet years. When a reduction in surface water entitlements for irrigation is contemplated by policy makers, investment in recharge facilities is one possible mean to mitigate the adverse effects of such policies on farmers.

5. Discussion

The main theme of this chapter is that water allocation policies should consider ground and surface water sources as two components of a single conjunctive system. Often surface water supplies fluctuate considerably from year to year, while groundwater stocks are relatively stable. Groundwater water when used conjunctively with surface water has the additional role of stabilizing the supply of surface water, a role which bears economic value denoted the stabilization value of groundwater.

The empirical analysis of the Arvin-Edison Water Storage District of Kern county, located in the southeastern edge of San Joaquin valley in California, reveals that the stabilization value of groundwater amounts, in some cases, to about 50 percent of the total value of groundwater. This means that avoiding the uncertainty in surface water supplies (i.e., assuming they are stable at the mean) causes a downward bias in groundwater benefits of the same magnitude and seriously bias policy making based on cost-benefit evaluations.

It is found that growers' profit is sensitive to irrigation efficiency: a 25 percent increase in irrigation efficiency caused profit to raise by 39 percent and a 50 percent increase raised profit by as much as 116 percent (see first row of Table 4). Available means to increase irrigation efficiency include the adoption of improved irrigation technologies (Caswel and Zilberman, 1985), or lining irrigation canals to prevent seepage (Peabody *et al.*, 1991). Our empirical analysis suggests that this can be an affective mean to mitigate adverse effects on irrigators of increased surface water scarcity.

An empirical finding that stands out entails the potential role of recharge programs. The increased scarcity of surface water would inevitably make farmers rely more on groundwater and will eventually lead to smaller and deeper groundwater stocks and higher extraction costs. The combination of increased extraction levels at higher costs is crippling. Recharge programs can provide a partial remedy. Recharge activities require investment in facilities such as spreading ponds, so that the surplus of surface water during wet years is fully exploited for recharge purposes. This would result in higher groundwater tables and lower extraction costs. We have found that if the level of groundwater table can be maintained, a 50 percent reduction in surface water entitlements decreases growers' profit by only 5 percent. The same reduction in entitlements coupled with doubling the extraction costs (as the groundwater table declines) leads to a 20 percent decrease in profits.

What holds true for a particular water district is likely to be magnified when the entire state is considered. California's water system is highly integrated. There are considerable economies of scale to be exploited in water storage and banks used as buffer against surface water fluctuations. Indeed, the recent prolonged drought have brought to the emergence of a few highly innovative water institutions. The Emergency Drought Water Bank (Howitt *et al.*, 1992) is one such example (other examples are described in Peabody *et al.*, 1991). Underlying these innovations is the understanding that ground and surface water sources are two components of one conjunctive system and should be managed as such.

This chapter summarizes the main principles of managing conjunctive irrigation systems and demonstrates their importance empirically. Future extensions can enlarge the focus to a county, a region or the state as a whole, and can use dynamic analysis to account for the increased scarcity of water, as urban and environmental demands grow and water stocks are reduced.

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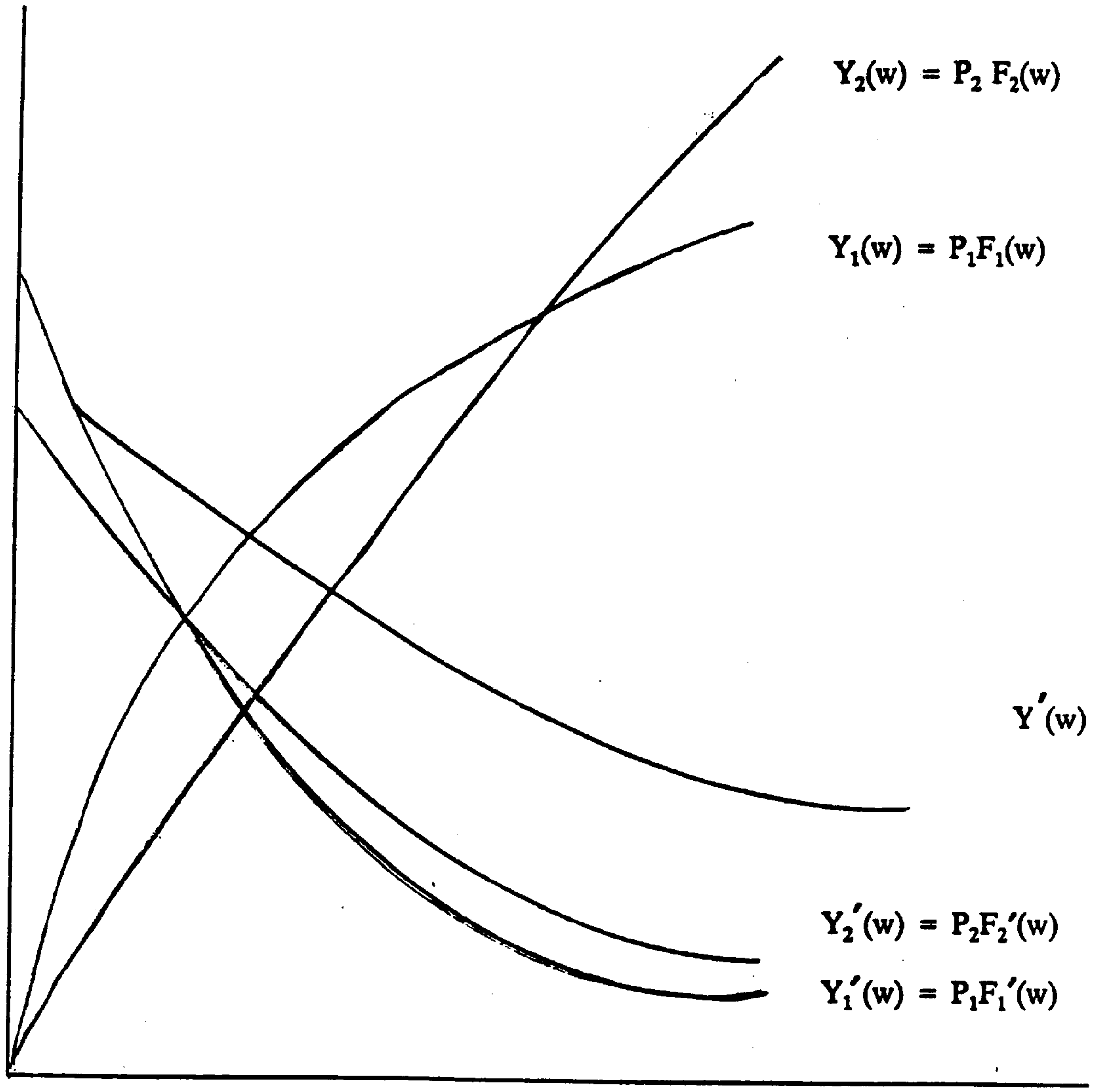
FIGURE 1



$Y'(w)$ is the horizontal sum of $Y_1'(w)$ and $Y_2'(w)$

FIGURE 2

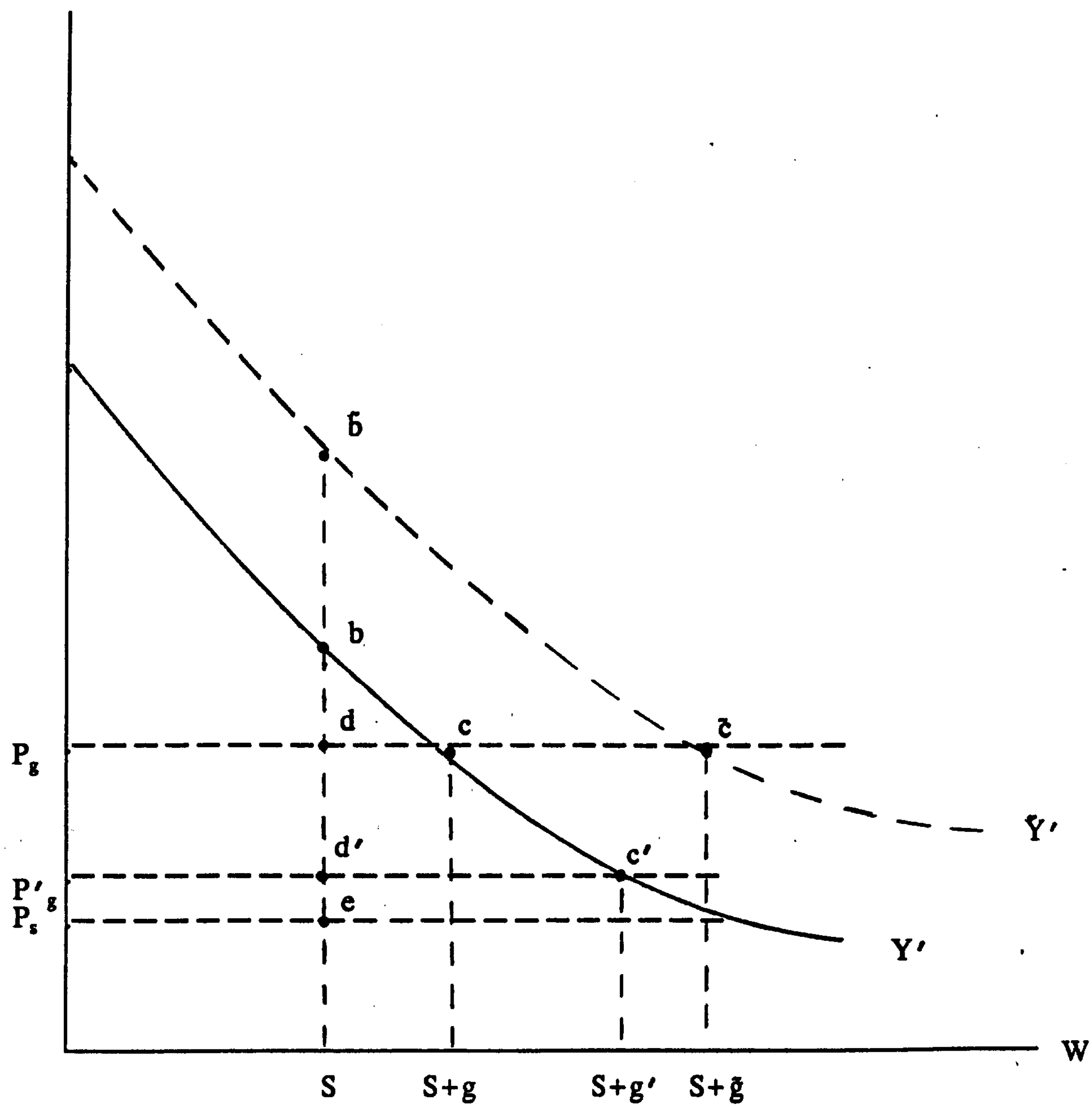


FIGURE 3

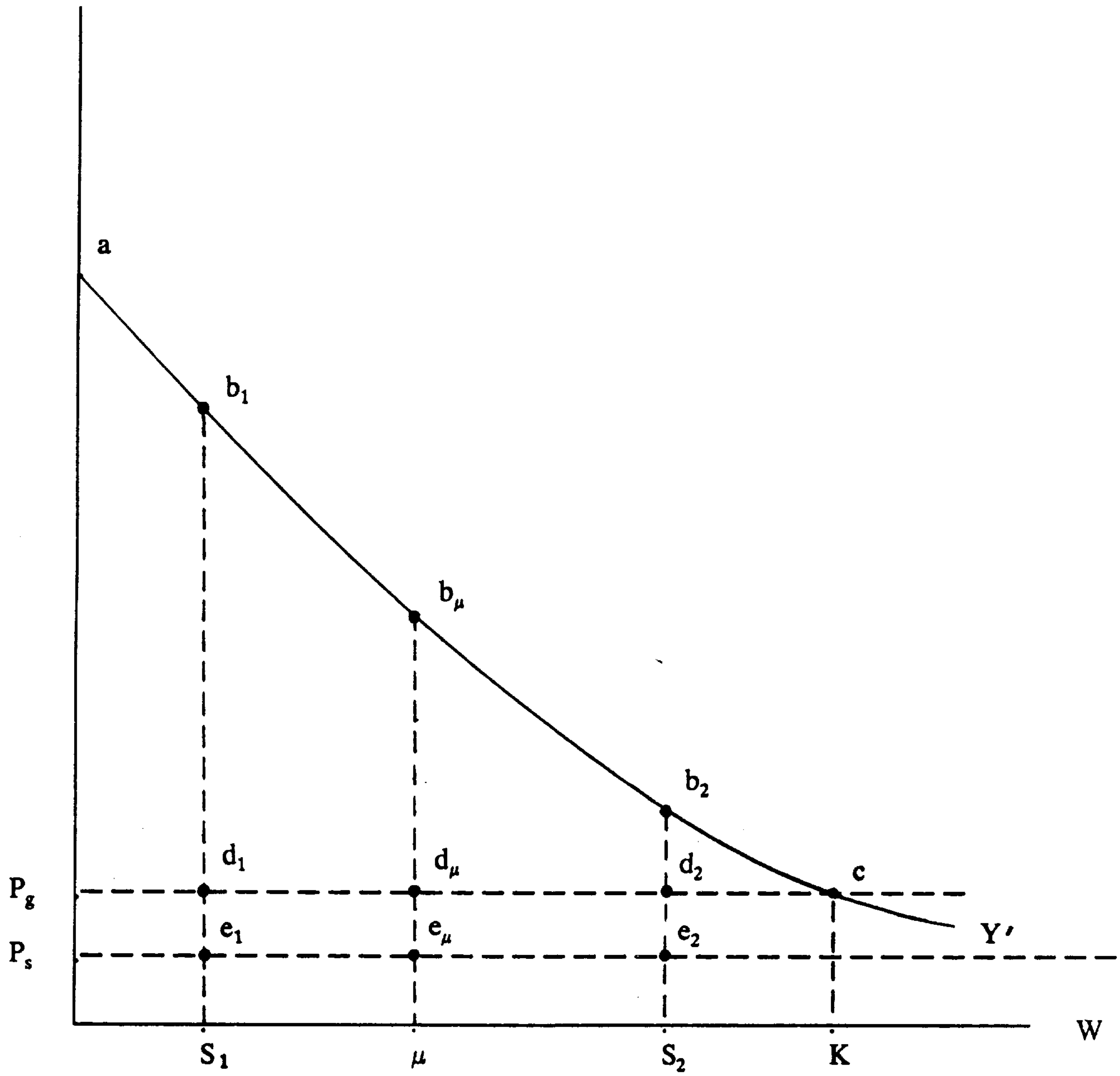
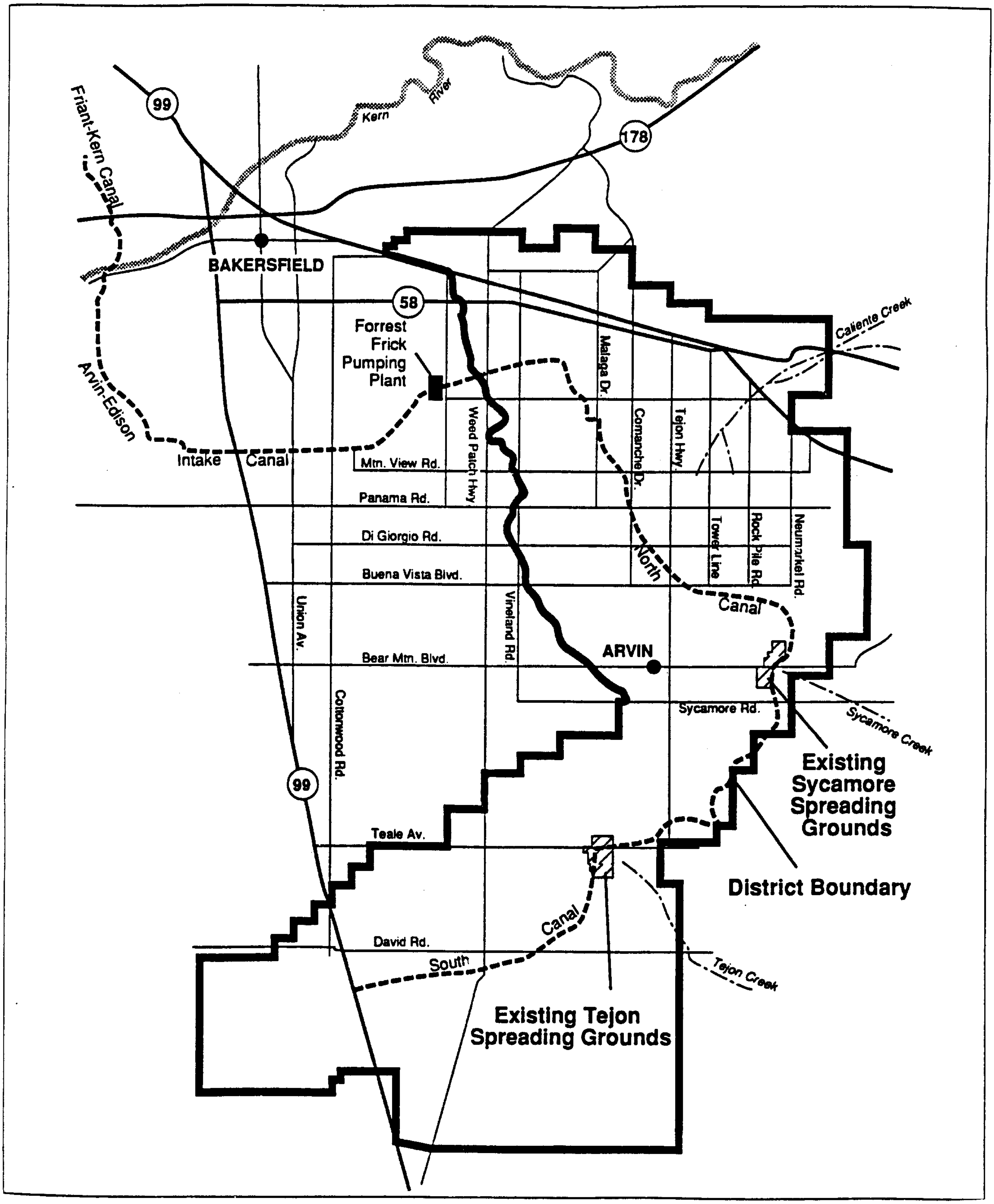


Figure 4: Arvin-Edison Water Storage District



Source: EIP Associates, 1992, Figure 1-1

Fig. 5: Surface Water Supplies 1968-91

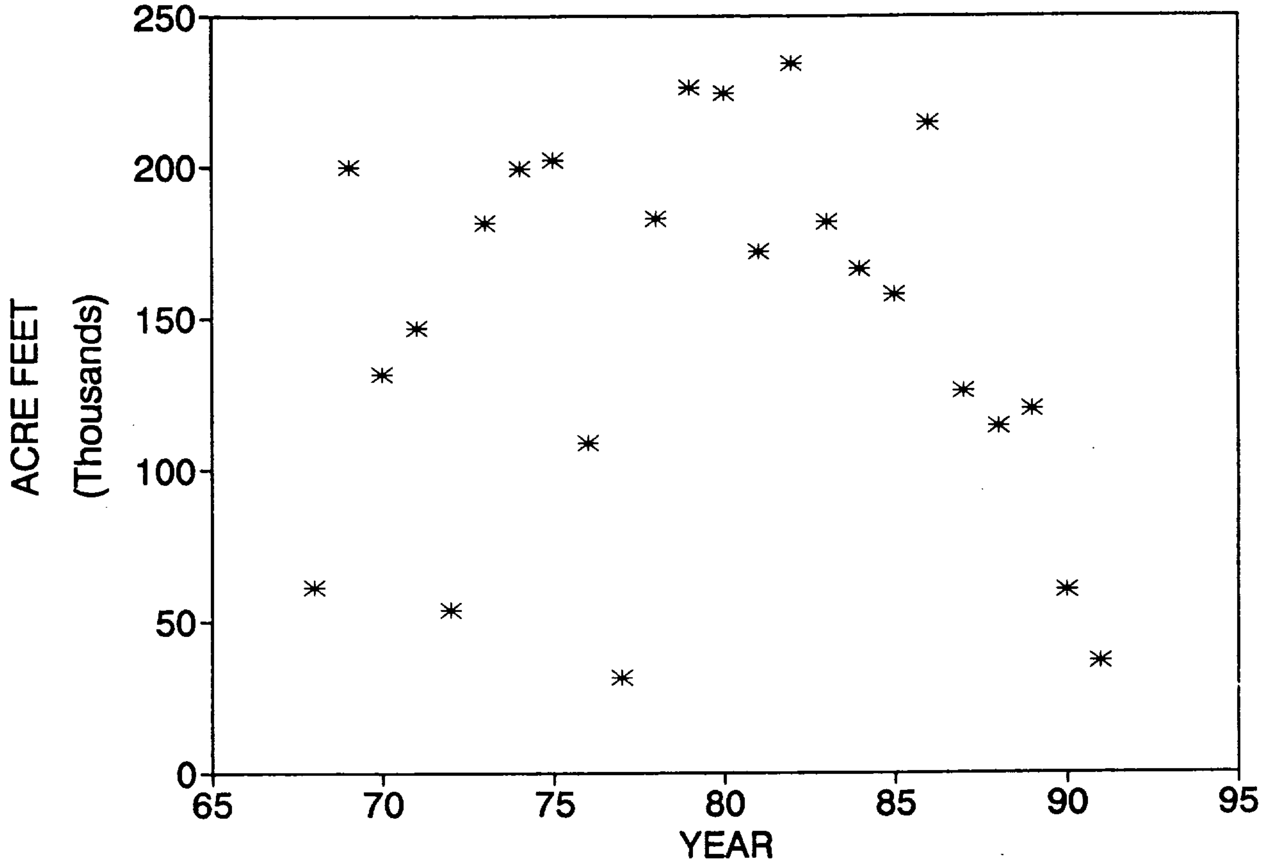
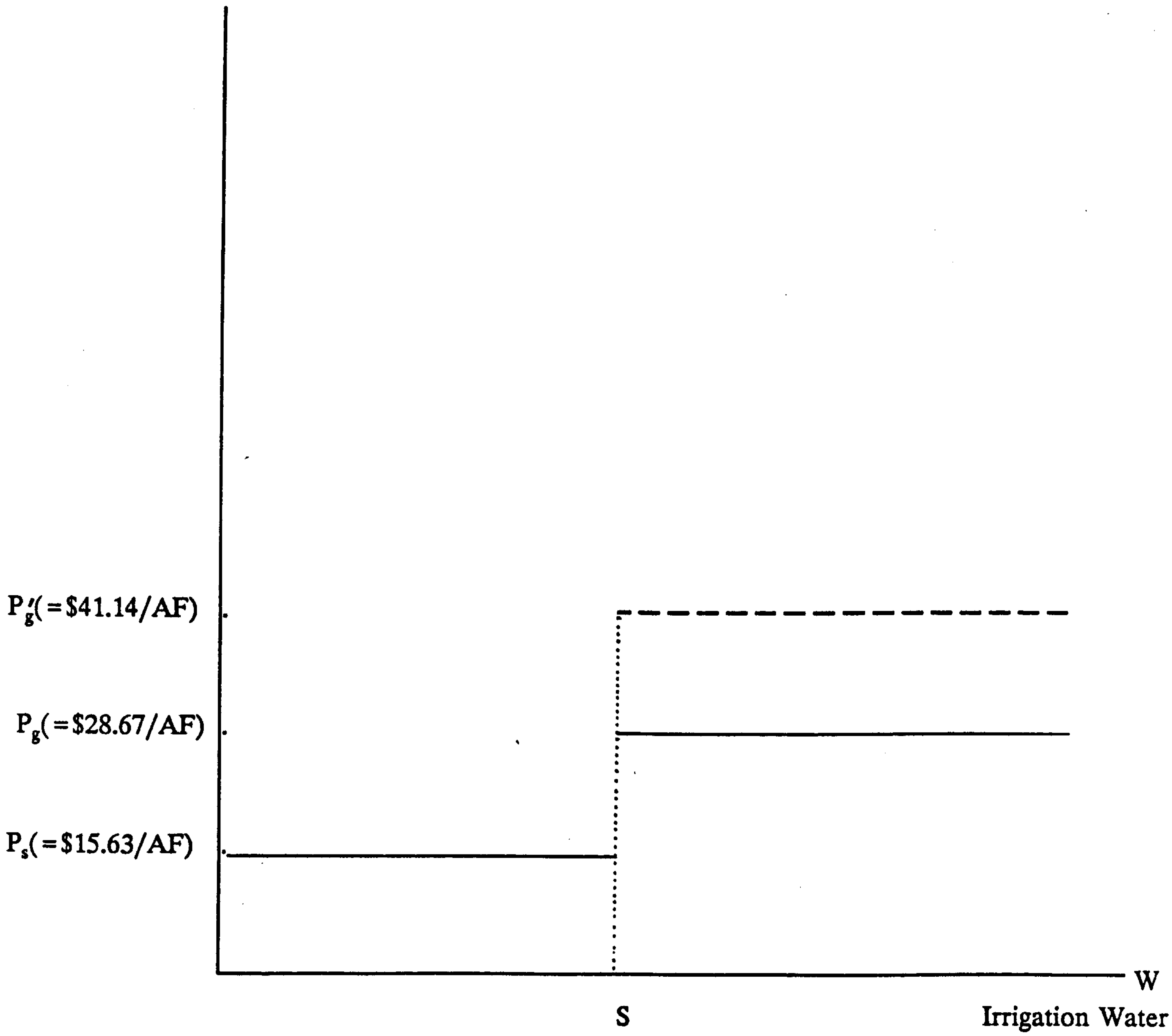


FIGURE 6



A typical supply schedule given S. P_s is cost of surface water in 1987; P_g is actual groundwater cost in 1987 and P_g' is estimated groundwater cost in the absence of the recharge program.

Figure 7 · Value of Marginal Productivity of Water

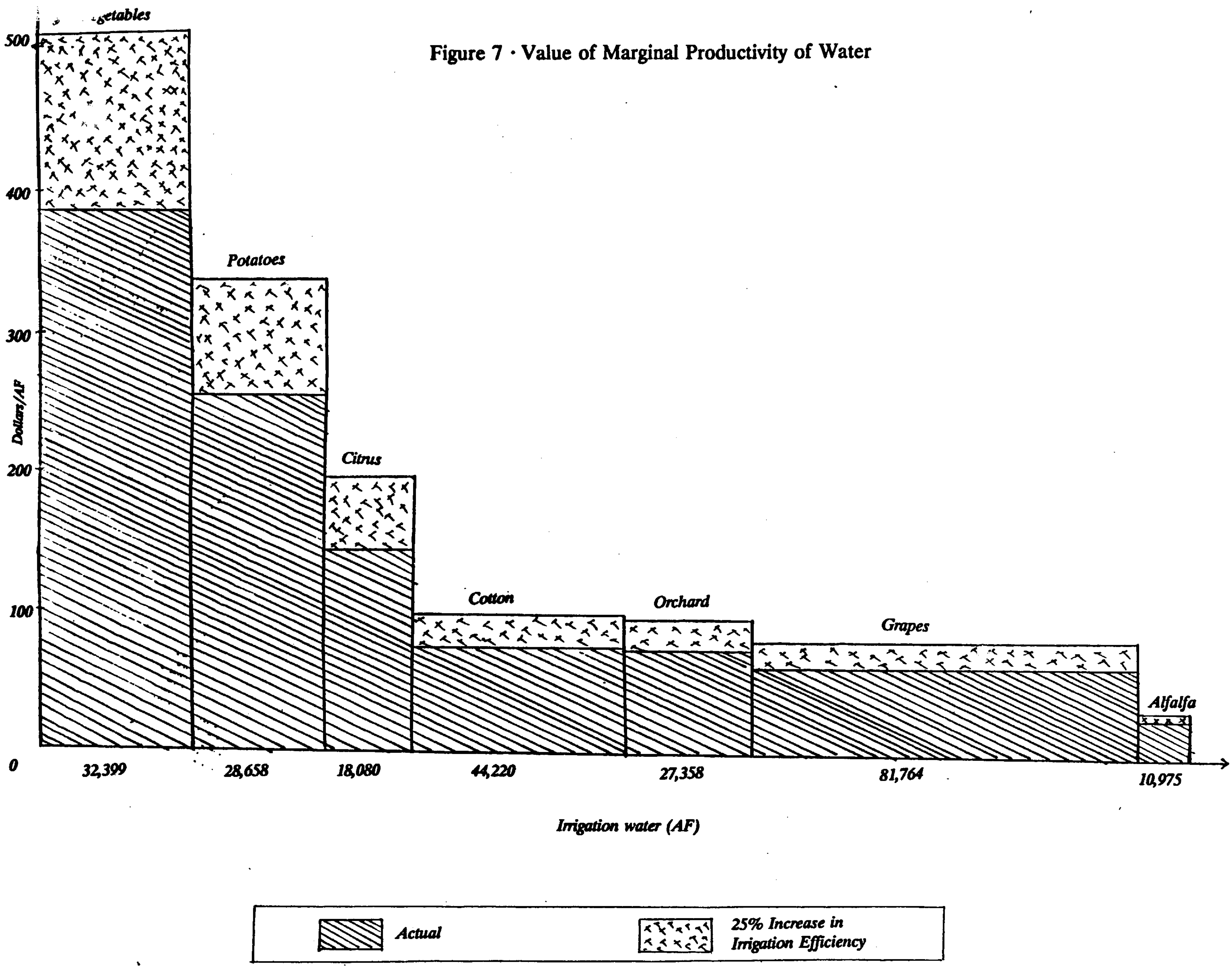


Table 1: SURFACE WATER SUPPLIES 1968-91

YEAR	TOTAL IMPORTS* (acre feet)
68	61015
69	199996
70	131764
71	146753
72	53420
73	181590
74	199845
75	202664
76	108777
77	31563
78	182916
79	225942
80	224093
81	172139
82	234004
83	182325
84	166632
85	158211
86	214124
87	125964
88	114157
89	119680
90	60242
91	36795

(*) Source: Arvin-Edison Water Storage District (1992) and personal communication with Mr. Steven Collup of the district.

TABLE 2: Data used to calculate the Value of Marginal Productivity of Water.

Crop	Area[a] (acres)	Revenue[a] ($)	Revenue per acre ($)	Costs[b] per acre (excluding water cost) ($)	Net Revenue per acre ($)	Water Requirement per acre[c] (AF)	Value of Marginal Productivity of water ($/AF)	Total Water Requirement (AF)
Vegetable	12,806	40,579,299	3,169	2,202	967	2.53	382	32,399
Potatoes	16,376	47,605,032	2,907	2,464	443	1.75	253	28,658
Citrus	7,232	32,345,843	2,999	2,638	361	2.50	144	18,080
Cotton	14,940	13,983,840	936	713	223	3.00	74	44,820
Orchard	10,943	24,729,947	1,515	1,332	183	2.50	73	27,358
Grapes	23,361	59,388,334	1,843	1,632	211	3.50	60	81,764
Alfalfa	2,195	1,353,503	617	486	131	5.00	26	10,975

Sources:

[a] Archibald, 1992, Tables 3.7 and 3.14.

[b] Sample Cost of Production Work Sheets, Kern County/San Joaquin Valley, California; Guerard (1987); Pehrson, J., et.al. (1987); Johnson, S., et.al. (1987); Hirschfelt, D.J., et.al. (1988); Munier, D.J., (1988).

[c] Kern County Water Agency (1991), Table 18.

TABLE 3*: Profits and The Value of Groundwater

Year	Surface Water (1)	Profits $\pi(s)$ (2)	Ground Water (3)	Profits $\pi(s+g)$ (4)	$\pi(s+g)$-P(s) (5)
68	61015	13386021	78832	16256249	2870228
69	144996	17337613	0	17337614	0.464
70	131764	16925576	8083	17178816	253240.4
71	146753	17352505	0	17352505	0
72	53420	12942701	86427	16157210	3214509
73	126590	16696005	13257	17111347	415341.8
74	144845	17336047	0	17336048	0.464
75	147664	17352505	0	17352505	0
76	108777	15905643	31070	16879066	973423.1
77	31563	9999887	108284	15872364	5872477
78	111555	16028902	28292	16915291	886388.4
79	144128	17328612	0	17328612	0.464
80	183661	17352505	0	17352505	0
81	123213	16546168	16634	17067311	521143.2
82	169910	17352505	0	17352505	0
83	156137	17352505	0	17352505	0
84	166311	17352505	0	17352505	0
85	121326	16462442	18521	17042705	580262.9
86	199568	17352505	0	17352505	0
87	125964	16668230	13883	17103184	434954.4
88	114157	16144353	25690	16949221	804867.7
89	119680	16389409	20167	17021241	631832.1
90	60242	13340901	79605	16246169	2905268
91	36795	11224211	103052	15940420	4716210
AVG(6)	122084.8	15922094	26324.88	16967100	1045006
(7)	122085	16496119	17762	17052602	556483.5
STABILIZATION VALUE (8)					488522.7

(*) Information obtained from Steven Collup of the Arvin-Edison district via personal communication
(1) Actual surface water used in irrigation, 1968-92
(2) Profits calculated using surface water only
(3) Groundwater demand based on 1987 prices for each surface water realization
(4) Profits calculated using surface and ground water
(5) Value of groundwater: the difference between profits with and without groundwater
(6) Column averages
(7) Profits calculated using the average surface water quantity
(8) Difference between the average value of groundwater and the value of groundwater calculated at the average surface water supply

TABLE 4: Profits and Stabilization Values under Nine Alternative Scenarios

			IRRIGATION EFFICIENCY		
			ACTUAL	25% INCREASE	50% INCREASE
Surface Water Entitlements to Agriculture	Actual	TP(1)	16967100	23560255	36683611
		VG(2)	1045006	1675370	3463421
		SV(3)	488523	721951	1669805
		SV/VG(4)	0.4675	0.4390	0.4821
	25% Decrease	TP(1)	16652116	23239722	36363309
		VG(2)	1953529	3116760	5493730
		SV(3)	440809	596688	882092
		SV/VG(4)	0.2256	0.1914	0.1606
	50% Decrease	TP(1)	16169401	22733354	82751389
		VG(2)	3433249	5395721	56300341
		SV(3)	564263	758467	-32386674
		SV/VG(4)	0.1644	0.1406	-

(1)Total profits calculated using surface and ground water

(2)Value of groundwater: the difference between profits with and without groundwater

(3)Stabilization value: the difference between the average value of groundwater and the value of groundwater calculated at the average surface water supply.

(4)Stabilization value as a percent of the value of groundwater