AN ECONOMIC ANALYSIS OF SUPPLEMENTARY IRRIGATION IN SKÅNE

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FOREWORD

Since the inception of the International Institute for Applied Systems Analysis (IIASA), the problems of water resource systems have been important research subjects in the Institute's resources and environment program. As water demands become larger proportions of available supply, the importance of responsive and efficient water resources management increases. This management function must be supported by analyses of increasing detail and comprehensiveness, including economic and social evaluation of development alternatives; and these analyses must use mathematical modeling techniques to generate inputs for planning, design, and operating decisions.

In 1978 IIASA began a series of regional water management studies with a view to integrating its continuing work on water demand with other work on water supply. One of these, which was carried out in collaboration with the Swedish National Environment Protection Board and the Lund Institute of Technology, dealt with water management in the southwestern Skåne region of Sweden.

The work in Skåne showed that one of the most important issues affecting water management is supplementary irrigation. This report examines the economics of this use in Skåne. It answers some fundamental questions, not only for agricultural development, but also for the overall water management strategy in this region. It also shows how the problem of supplementary irrigation can be looked at from an economic standpoint.

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Chairman
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SUMMARY

This report analyzes the water demand for supplementary irrigation in Skåne. Using water balance models, recent IIASA studies of Skåne demonstrated that agricultural water use could be a critical factor in future water management decisions in this region, and raised questions about possible economic effects:

- *What is the potential demand for irrigation water at current (1978) crop prices and irrigation costs?*
- *What effect would this level of irrigation have on the market for irrigated crops, and how would the changed market conditions in turn affect the demand for irrigation?*
- *What effect would a significant increase in the cost of irrigation have on the quantity of water used for that purpose?*

This report responds to these questions. However, for several reasons, the answers are tentative. The data on which they are based are seriously incomplete. The quantitative analysis determines only the demand for water per hectare of crop area; the analysis that determines the land areas planted in different crops is strictly qualitative. The estimates presented cover only two of the crops irrigated in Skåne: table potatoes and sugar beets.

Subject to these important caveats, the analysis shows that, at roughly current crop prices and water costs, irrigation demands may indeed be as great as those calculated using simple water balance models. The analysis thus supports the conclusion of related IIASA studies that potential water supply and demand in this region could become seriously out of balance.

The analysis also shows that irrigation would have little effect on the market for irrigated crops. Hence, there would be little hope that this kind of feedback effect would contribute much to closing the gap between potential demand and supply.

The sole remaining options for balancing supply and potential demand are reallocating water from other users and/or expanding the capacity of the water supply system. In all

cases, the result would be a substantial increase in the opportunity cost of irrigation. The analysis shows that the demand for irrigation probably would be reduced substantially if irrigation costs were increased to reflect the opportunity costs of reallocating existing supplies or of expanding capacity.

The conclusions of this report thus reinforce those from other studies conducted as a part of IIASA's analysis of regional water management in Skåne. Agricultural water demand is an important – perhaps even the critical – factor in future planning and management of the water supply system in this region.

1 INTRODUCTION

Recent work at IIASA (Arthur 1980, and Strzepek 1981) raises the possibility that future use of water for supplementary irrigation in Skåne will severely stress the current water resources of that region. Arthur showed that the irrigation rules now being recommended to farmers in Skåne would result in average irrigation water usage on irrigated acreage of from 86 to 194 millimeters per hectare (mm/ha), depending upon the crop. Strzepek converted these average figures into totals for the regions of the Kävlinge River Basin, added estimates of water demands for other purposes, and compared these totals to the estimated water yield of the basin. He found that the water supply system frequently did not yield enough water to satisfy all demands simultaneously.†

These calculations portend a serious imbalance of water supply and potential demand in Skåne. They certainly indicate that a thorough analysis of potential irrigation water demands in this region is in order. Any such analysis should include an examination of the effects of economic factors such as crop prices and irrigation costs.

Figure 1 shows the major relationships and variables that should be considered in a complete investigation. Broadly speaking, irrigation demands are derived from market demand for crops which can be produced using irrigation water, and other inputs such as fertilizer and seed.†† In outlining the system, it is useful to think of price and output determination as a cyclical series of four steps, as shown in Figure 1.

1. Demands for crops, along with relationships that describe the ways in which inputs can be combined to produce crop outputs, result in demands for inputs.
2. Demands for inputs, together with input supplies determine input prices and quantities of inputs used for crop production. For example, these relationships determine the quantities of land planted in each crop, and the quantities of seed, water, and fertilizer applied to each hectare.

†In a simulation covering 75 years, Strzepek (1981) found that, in 83 percent of the years, the yield of the basin would be insufficient to meet the sum of potential irrigation usage [calculated by multiplying the usages per hectare reported in Arthur (1980) by corresponding crop areas in 1976, and multiplying this result by the Malmöhus County Board of Agriculture's estimates of the percentages of crop areas that potentially will be irrigated in Malmöhus County], 1976 levels of municipal and industrial demand, and water-quality-related stream-flow regulations.

††Section 2 gives a more complete explanation of the economic relationships shown in Figure 1.

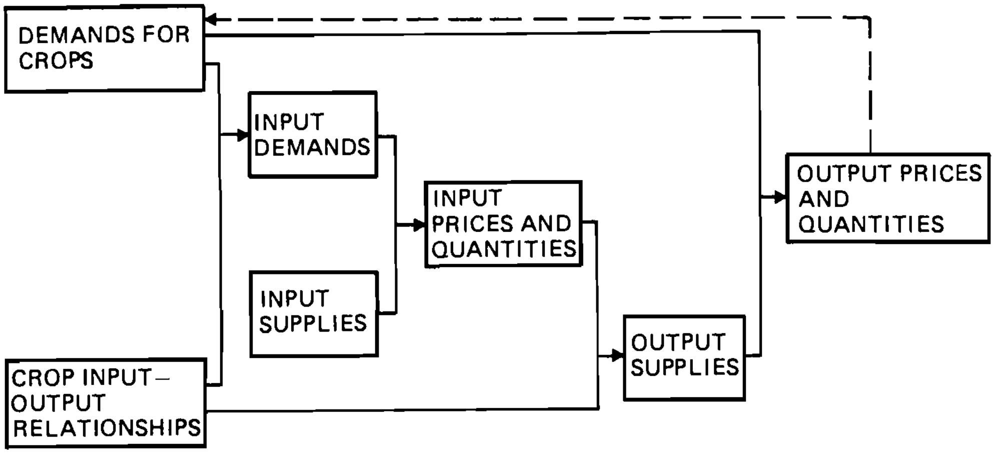

FIGURE 1 Economic determinants of irrigation usage.

3. Input quantities and prices, together with crop production input–output relationships, determine crop supplies.
4. Crop supplies and demands interact to produce market prices and quantities of crops.

An important implication of Figure 1 is that input and output prices and quantities in related markets are interdependent. In general, effects occurring in one market have ramifications in all other markets. For example, increased use of irrigation water to produce, say, potatoes would increase the yield and production of potatoes; this in turn may lead to a decrease in the price of potatoes, which would reduce the land area planted in potatoes and the demands for nonland inputs, including irrigation water. In the absence of additional shocks, the final outcome would be a readjustment of prices and quantities in all markets. Any complete investigation on the balance of water supply and demand must attempt to account for all important market adjustment mechanisms that could help this balance.

In spite of its seeming comprehensiveness, Figure 1 simplifies the market adjustment process in two important respects. First, some adjustment mechanisms have been omitted. For example, we have ignored the role that prices play in influencing the state of the technical arts for transforming inputs into outputs. In general, when scarcities arise, the search begins for technologies that will economize on the use of scarce resources. If water were scarce, agronomists would seek crop varieties less critically affected by water. We have ignored this type of linkage mechanism in Figure 1, since it generally occurs only over relatively long periods of time whereas our concern here is with the relatively immediate future.

A second simplification is that Figure 1 does not explicitly show the many nonmarket factors that affect the determination of prices and quantities. One might imagine these factors as being represented by the white space on the page that engulfs the forces explicitly represented. This image would be appropriate. Nonmarket factors, such as price supports, or restrictions on the quantity of land planted in a particular crop, modulate and in some instances overwhelm the market forces represented in the diagram. These nonmarket factors are particularly important in Swedish agriculture today, as we see in subsequent sections of this report.

Although Figure 1 is a simplified representation of market adjustment processes, an examination of all of the factors indicated in it is well beyond our means. Given the information at our disposal, the most that can be attempted is a partial analysis of the influence of economic and selected nonmarket factors on the demand for irrigation water in Skåne.

In particular, this report attempts to answer three questions. First, what would be the level of potential demand for irrigation water at current crop prices and irrigation costs? The estimates presented by Arthur (1980) are based on application of irrigation rules that are designed to maximize yield. These rules do not take into account economic factors such as the cost of irrigation, incremental yields due to irrigation, and additional farm income associated with incremental yields. When these other factors are accounted for, what level of demand for irrigation would be expected?

Second, what effect would irrigation have on the market for irrigated crops, and how would these altered market conditions affect the demand for irrigation? The range of possible market effects, depending upon particular conditions in the relevant markets and the agricultural policies that apply to them, includes expanded crop production accompanied by constant or falling prices, and possible increases in the cost of crop price support programs. The nature and magnitude of these market effects are extremely important to the balance of water supply and demand. Depending upon the form they take and the size they assume, crop market effects could either tend to moderate or to intensify the demand for irrigation water.

Third, what effect would a significant increase in the cost of irrigation have on the quantity of water demanded? Balancing supply and demand may well require that existing water supplies be reallocated and/or that capacity be expanded. In all instances, the cost of additional water may be substantially above current water costs, and this increase in cost, if allowed to affect irrigation decisions, could also help to balance supply and demand.

Our answers to these questions are tentative for several reasons. The data on which our estimates and analyses are based are seriously incomplete. We analyze quantitatively only the determination of the demand for water per hectare of crop area; our analysis of the determination of land areas planted in different crops is strictly qualitative. Our quantitative estimates cover only two of the crops – table potatoes and sugar beets – that are irrigated in Skåne.

Subject to these important caveats, our analysis shows that the levels of irrigation water demand projected by Arthur (1980) are consistent with the levels of demand one would project based upon an economic model of irrigation water demand, assuming 1978 crop prices and irrigation costs.† Our analysis thus supports the conclusion that, at current (1978) crop prices and water costs, water supply and potential water demand in Skåne could become seriously out of balance.

Our analysis also shows that the effects of irrigation on crop markets probably would contribute little to closing the gap between water supply and potential water demand. We

†1978 is the latest year for which the relevant published economic data were available at IIASA.

show that even if crop prices fell as a result of increased production, the resulting price decreases probably would not have much of an effect on irrigation water demand. If crop price supports restrained any tendency of prices to fall, this adjustment mechanism would be of no help in rebalancing water supply and demand.

The sole remaining options for balancing supply and demand for water are reallocation of water from other users (e.g., residential, commercial, industrial, environmental, and recreational users), and/or expansion of the capacity of the water supply system. In all cases, the result is likely to be a substantial increase in the opportunity cost of irrigation. Where balancing is effected through reallocation, these costs may take the form of inconvenience or even hardship on other water users as they reduce their water usage. Although total costs of system operation may not seem to go up, this loss of opportunity to use water – or opportunity cost – is a very real and probably substantial cost, and should be considered in analyzing this alternative for balancing supply and demand. Of course, the costs of expanded capacity are easier to identify and obviously are large.

Our analysis suggests that the demand for supplementary irrigation probably would be reduced substantially if irrigation costs were increased to reflect the opportunity costs of reallocation of existing supplies or capacity expansion. This conclusion is strengthened if possible irrigation-induced crop price decreases are considered simultaneously.

It is tempting to reach beyond these conclusions concerning the prospective demand for irrigation water and to make conclusions about appropriate public policy. For example, some readers might conclude: "These results show that potential water demand will exceed water supply. Therefore we must reallocate water or expand capacity." Or other readers might conclude: "These results show that if prices reflecting the full opportunity cost of resources were to prevail, there would be no imbalance between water supply and potential demand. Reallocation to agriculture or capacity expansion are economic wastes, and should not be undertaken."

Readers should resist making conclusions about public policy: conclusions concerning what should or should not be done depend upon the objectives of Swedish public policy. We make no attempt here either to identify these objectives or to reach any conclusions concerning appropriate policy.

In Section 2 of this report, the basic model for our analysis is developed. This model involves two important, and perhaps controversial, approximations. The first is an approximation of the relationship between water input and crop yield via a function that relates yield to total seasonal water inputs. The second is an approximation of irrigation decision-making under uncertainty. Section 2 explains the basis for these approximations and their effects on the results of our analysis.

Section 3 presents empirical estimates of the parameters required to estimate irrigation water demands for two crops, table potatoes and sugar beets. These crops are considered by Swedish agricultural experts to be the best candidates for expanded use of supplementary irrigation in Skåne. Three kinds of parameter estimates are presented. First, parameters of empirical distributions of precipitation over the growing seasons for these crops are estimated from historical data on precipitation measured at Lund. Our statistical analyses of these data show that the probability distribution of precipitation during the growing season for each crop can be approximated conveniently and satisfactorily by the Weibull distribution. Second, empirical estimates of seasonal water input–yield relationships are presented for table potatoes and sugar beets. These relationships are based upon the reported results of irrigation experiments conducted in southern Sweden. Very few data points were available for this purpose, so the estimated yield relationships presented here are subject to a great, although unquantified, amount of uncertainty. Third, estimates of the fixed and variable costs of irrigation are reported. The derivation of these estimates is described in detail in Appendix A.

Section 4 presents estimates of the demand for irrigation water for table potatoes and sugar beets using the model presented in Section 2 and the parameter estimates reported in Section 3. Expected demands of approximately 87 mm/ha for both crops are obtained, assuming that 1978 crop prices and irrigation costs prevail. These estimates are reasonably close to those reported in Arthur (1980).

Section 4 also examines the contribution of irrigation to farm income. This contribution, again assuming 1978 crop prices and irrigation cost levels, is found to be more than sufficient to cover the fixed costs associated with irrigation. However, for reasons that are explained in Section 2, our estimates of contribution to farm income tend to overstate the contributions that could in fact be expected. Nonetheless, when adjustments are made for this overstatement, the conclusion stands that irrigation is profitable at 1978 crop price and irrigation cost levels.†

In Section 5 we consider the possible effects of irrigation on crop markets and "feedback" effects on irrigation demand. As previously noted, increased yields, other things being equal, could result in decreased crop prices. These price decreases, in turn, could moderate the demand for irrigation water. Section 5 presents some very rough estimates of the extent to which crop prices might fall as a result of irrigation in Skåne, assuming other factors remain constant. Our analysis shows that even sizeable price decreases probably would not result in a substantial decrease in the quantity of irrigation water demanded.

Section 6 examines the effect of markedly higher variable costs of irrigation on the quantity of irrigation water that would be demanded. Our calculations suggest that increases in costs to levels that would reflect either the opportunity cost of reallocating existing water supplies or the costs of capacity expansion would reduce substantially the quantity of water demanded per hectare. This result is reinforced if the simultaneous effects of increased crop yields on crop markets and an increase in the cost of water are considered. We conclude that increasing irrigation costs, e.g., through imposition of a charge on the use of water for irrigation, to reflect the opportunity cost of the water resources involved would make a substantial contribution to redressing the potential imbalance between water supply and demand in Skåne.

Section 7 offers some general but nonetheless qualified conclusions. Our analysis supports the conclusion that use of water for supplementary irrigation in Skåne is profitable at roughly current prices and costs. Growing awareness of this undoubtedly accounts, in part, for the recent rapid adoption of irrigation techniques among farmers in the region. Our results on the combined effects of crop price changes in response to increased yields and increases in the cost of irrigation suggest that economic factors could come into play that would reduce or eliminate altogether the opportunities to employ supplementary irrigation profitably, and thereby markedly reduce the potential demand for irrigation water.

†Anderson (1980) developed an approximation that may be used to adjust estimates of the contribution of irrigation to farm income to eliminate, approximately, the overstatement.

2 THE MODEL

As noted in Section 1, water is demanded for irrigation because irrigation increases crop yields and, consequently, farm income. Thus, one important factor in calculating how much water is likely to be demanded is the quantitative relationship between water inputs, yield increases, and farm income increases.

Another important factor in estimating irrigation demand is the extent to which precipitation satisfies the water requirements of crops. There are three important aspects of the relationship between precipitation and irrigation demand. First, precipitation varies randomly. During some periods, precipitation is relatively great, and the need to supplement it with irrigation is correspondingly reduced; during other periods precipitation is relatively low, and the need to supplement it is great. As a consequence, irrigation demand also varies randomly. Second, farmers do not know exactly how much crop-usable water precipitation will yield. Thus, irrigation decisions must be made in the presence of uncertainty about the quantity of water that will be supplied by precipitation. Third, the effectiveness of precipitation in promoting crop growth varies, depending upon a number of other conditions.

This section explains how we model the relationship between water inputs and crop yields, and how we treat the various aspects of precipitation as a source of water input. The actual relationships between these variables are complex and our modeling of them is therefore at best approximate.

2.1 The Relationship between Water Input and Crop Yield

In general, the effect of water inputs on crop yields depends upon the crop variety, the type of soil, solar radiation, and upon the temporal pattern of application of the water. It also depends upon other soil and climatic factors, and upon subtle genetic differences in plants.

Several detailed models of crop–water relationships that attempt to incorporate one or more of these factors have been developed. In most of these models, the fundamental premises are that each crop variety has a genetically determined maximum potential yield (denoted by Y_M), and that actual yields below this maximum potential yield are the results of water stresses on the crop. The models differ primarily in the mathematical form given the water stress–crop yield relationship, and in the variables chosen to characterize this relationship.

Four basic concepts have been found to be useful in describing and modeling the effect of water on plant growth. The first concept is *permanent wilting point*. This is the moisture content of a given soil at which the leaves of a given type of plant growing in that soil become permanently wilted. This happens when the moisture in the soil falls to levels so low that the rate of transpiration exceeds the rate at which the plant is able to extract water from the soil.

The second concept is *field capacity*. This is defined as the quantity of water held in the root zone by the soil against gravity when the soil is allowed to drain freely. Clearly field capacity also depends upon both soil type and crop.

The third concept is *soil moisture tension*. This is the force with which water adheres to soil particles. The higher the moisture tension, the greater the force with which moisture is "bound" to the soil.

The fourth and final concept is *evapotranspiration*. This is the evaporation of water from soil and the transpiration of water by plants.

These four concepts are related to one another. For example, the closer a given soil layer is to field capacity, the lower the soil moisture tension in this layer, and the greater the rate of evapotranspiration. The higher the soil moisture tension, the greater the difficulty plants have in making use of this moisture and the lower the rate of evapotranspiration. The permanent wilting point is reached when plants are no longer able to overcome the forces that bind moisture to the soil.

There are two main theories concerning the precise nature of the relationship between water availability and plant growth. The first theory, which has been called the *equal availability theory*, holds that variations in soil moisture between the permanent wilting point and field capacity have no effect on yield (Veihmayer and Hendrickson 1955). This theory implies that the aim of irrigation, ignoring cost factors and other constraints, should be to maintain just enough water in the field to insure that available water does not fall below the permanent wilting point.

The second theory holds that the rate of plant growth is inversely related to the level of soil moisture tension in the root zone of the plant (Hagan, Vaadia, and Russel 1959). High levels of tension retard plant growth, and completely terminate it at the permanent wilting point.

One of the earliest formulations of production functions for irrigated agriculture based upon these theories is due to Moore (1961). Moore noted that the agronomic theories described above imply that there is a relationship between the percentage of the maximum growth rate that is attained by a plant and the percentage of available moisture (i.e., the moisture between field capacity and the permanent wilting point) that is depleted in the field in which the plant is growing. Figure 2 illustrates the form of the relationship posited

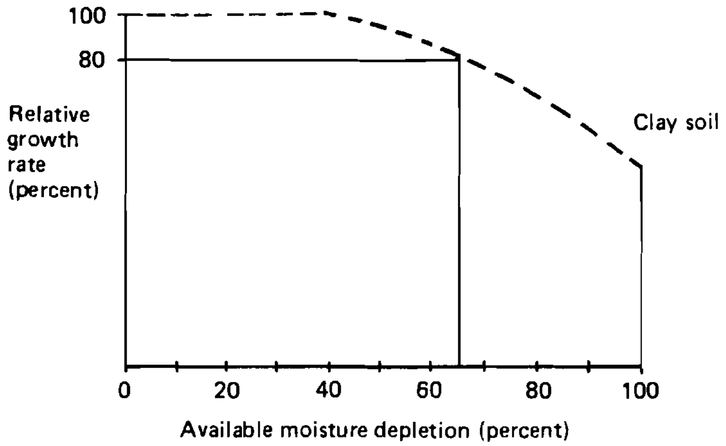

FIGURE 2 Relationship between soil moisture and plant growth.

by Moore in an hypothetical case. This figure shows that at 65 percent depletion of available moisture in clay soil, the growth rate of the plant is 80 percent of the maximum attainable by the plant. The rate of decrease of the growth rate percentage curve depends upon the effect of variations in water availabilities between field capacity and the permanent wilting point. Under the equal availability hypothesis, the curve would be flat at 100 percent of the maximum growth rate until 100 percent depletion is reached. Under the hypothesis that growth rates decline with depletion, the curve would begin to decline at lower depletion percentages.

Based upon variants of Moore's theory, several investigators have specified and/or estimated empirical relationships between water inputs – as measured by one or more of the concepts discussed earlier – and crop yield. For example, Hall and Butcher (1968) developed a model of the water–yield relationship that distinguishes between different stages in a plant's development, with overall growth being determined by multiplication of growth rates at different stages. The form of their model is given in eqn. (1)

$$Y(q) = \prod_{k=1}^{n} \alpha_k(\theta_k)\, Y_M(q_M) \tag{1}$$

where

- q is the total amount of water applied per unit area
- $Y(q)$ is the actual yield corresponding to application of q units of water
- q_M is the water required to maintain soil at field capacity
- $Y_M(q_M)$ is the maximum yield that can be obtained with an unlimited quantity of water
- θ_k is the available soil moisture during stage k
- k is the index of stages of growth
- n is the number of stages of growth
- $\alpha_k(\theta_k)$ is the function representing the effect of moisture deficiency during stage k on total yield

Minhas, Parikh, and Srinivasan (1974) specified the relationship between water and yield shown in eqn. (2)

$$\frac{Y}{Y_M} = \sum_{k=1}^{n} \left\{1 - \left[1 - \left(\frac{E}{E_p}\right)_k^2\right]\right\}^{b_k} \tag{2}$$

where

- $\left(\frac{E}{E_p}\right)_k$ is the ratio of actual evapotranspiration to potential evapotranspiration in stage k
- b_k is the coefficient measuring crop sensitivity to water deficits
- Y is the actual yield

Fitting this equation by regression methods, they determined that over 98 percent of the variation in experimental yields of wheat in India could be explained by the model.†

†Other papers that develop models of the water–yield relationship are Flinn and Musgreave (1967), Jensen (1968), Hiler and Clark (1971), and Hanks (1974).

In general, the literature establishes that it is possible, using yield experiment data, to obtain quite satisfactory empirical relationships between measures of water availability (e.g., available soil moisture depletion, the ratio of actual to potential evapotranspiration) and crop yield. Moreover, this literature holds out the promise that substantial improvements can be made in field-level irrigation management. The use of detailed field-specific and growth stage-specific water–yield relationships to improve irrigation management through sequential control of water inputs is amply illustrated in Burt and Stauber (1971) and Córdova and Bras (1979).

The ideal type of water–crop yield relationship for our examination of irrigation water demand in Skåne would be one that relates total seasonal water inputs (i.e., water inputs over the growing season) to yield. Strictly speaking, this can be done legitimately only if the intraseasonal distribution of water inputs is held fixed. (See Yaron 1971.) Nonetheless, it is possible to derive an approximate relationship between seasonal water input and yield even in cases where the intraseasonal distribution of water inputs is not held strictly fixed. Indeed, this is by far the most common practice in studies of the effects of water inputs on yields. (For example, see Hallgren 1971, and Hexem and Heady 1978.) We shall follow this common practice in further development of the model and in empirical investigations in subsequent sections of the report.

2.2 Precipitation and the Demand for Supplementary Irrigation

As noted at the beginning of Section 2, some portion of the water requirements of crops in Skåne is met by precipitation, with the balance to come from supplementary irrigation. We also noted that three aspects should be considered in examining the effects of precipitation on the demand for irrigation: (1) randomness in precipitation; (2) uncertainty about precipitation at the time irrigation decisions must be made; and (3) randomness in the effectiveness of precipitation in supplying water requirements to crops.

Let us consider each of these aspects in turn. Since we conduct our analysis in terms of the relationship between total water inputs over the growing season and crop yields, we are interested primarily in interseasonal randomness in precipitation. However, as has been discussed and is discussed further, intraseasonal randomness is an important determinant of the effectiveness of precipitation in supplying crop water requirements and, thus, requires some consideration.

Let us consider the implications of interseasonal randomness of precipitation. Let us suppose that there is an optimal (by some criterion as yet unspecified) quantity of total water input for a crop season, denoted by i^*. Let us also suppose that in each crop season, farmers know in advance exactly how much of this optimal level of water input will be supplied by precipitation. Then the quantity of irrigation water demanded would be either the difference between the optimum water input level and the level of precipitation, or zero, whichever is greater.

This situation is easily illustrated. Consider Figure 3, which depicts a hypothetical probability distribution of total precipitation for the season relevant to production of the crop under consideration. As illustrated, precipitation typically may vary over a wide range. The particular shape and position of the distribution depend upon the local climate. In the absence of irrigation, the distribution of the quantity of water input for agriculture and the distribution of precipitation are identical.

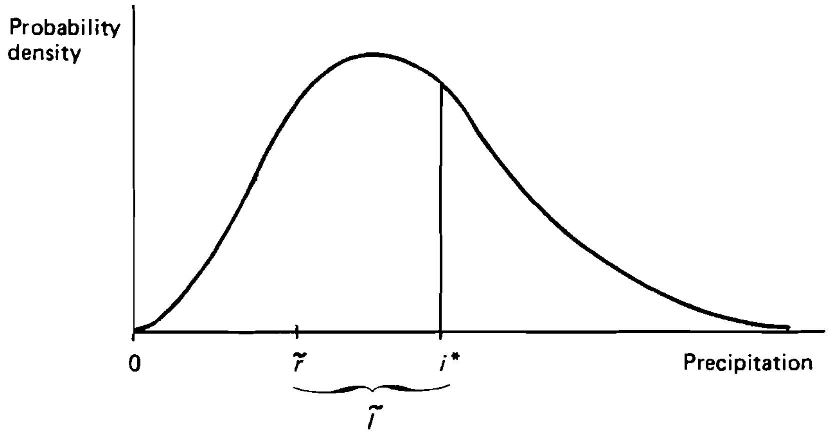

FIGURE 3 The effect of irrigation on the distribution of water.

If irrigation is undertaken, the situation is somewhat different. In any crop season in which precipitation (denoted by $\tilde{r}$) is less than i^*, irrigation water (denoted by $\tilde{I}$) is added to bring total water input up to the level i^*.

Two conclusions emerge concerning the effects of irrigation on water input, assuming perfect foreknowledge of precipitation. First, the quantity of irrigation water demanded will vary randomly from crop season to crop season depending upon the level of precipitation.† This follows from the fact that the quantity of irrigation water applied is adjusted to make up any deficit between the optimal total water input for the crop season i^* and the (random) level of total precipitation for the crop season $\tilde{r}$. Assuming perfect foreknowledge, the quantity of irrigation water applied is always exactly the correct amount needed to make up any gap between the optimal level of water input and precipitation. Second, the effect of irrigation under the perfect foreknowledge assumption is to alter the distribution of water input to the crop by chopping off the left-hand tail of the distribution. For example, if irrigation water is added to insure that available water is always at least i^* mm per hectare, then the probability density of water input if supplementary irrigation were practiced would be the right-hand tail of the precipitation distribution beyond i^*, scaled appropriately to possess the usual properties of a probability density function.

In practice, the irrigation plans applied in Skåne also shift the right-hand tail of the distribution of seasonal water inputs. Arthur (1980) shows that the irrigation operating rules currently being recommended to farmers in Skåne reduce the dispersion of the probability distribution of seasonal water inputs, and, in varying degrees, shift the entire distribution to the right in the direction of increased water inputs. As Arthur (1980) explains,

†The quantity of irrigation water demanded conditional on precipitation is deterministic. However, since precipitation varies from year to year, irrigation is a random variable with a probability distribution that may be derived from the probability distribution of precipitation. This is explained in more detail in Section 2.3.

the reason that this shift occurs is because irrigation decisions must be taken before precipitation is known with certainty.

In the completely general case, it is impossible to say precisely what effect uncertainty about the water input supplied by precipitation would have in an economic model of the quantity of irrigation water demanded. The specific effect would depend upon assumptions about the way in which randomness enters the model (e.g., multiplicative, additive), the information available to farmers at the time irrigation decisions must be made (e.g., precipitation forecasts), and the behavior of the farmers under uncertainty. In the absence of perfect foreknowledge, all that can be said with confidence is that the quantity of irrigation water applied would not in general be exactly the correct amount needed to make up a deficit between a target water input level and the actual level of precipitation. In some cases, more water than required would be added, in other cases, less water than required would be added.

In this analysis, we proceed as if precipitation were known with certainty at the time irrigation decisions are made. Since irrigation operating rules involve sequential control of irrigation water inputs in response to observed precipitation, and since short-term forecasts of precipitation are available, this assumption may be accepted as an approximation.

A third important consequence of the fact that precipitation is random is that its effectiveness as a source of water input varies. This effect is a result of intraseasonal randomness. For example, precipitation that occurs when soil moisture is already at field capacity contributes nothing to the water input of the crop. Indeed, it may cause injury through erosion with the run-off or, in extreme cases, waterlogging. Because precipitation does not come in carefully controlled doses, its effectiveness as a source of water input is generally lower than the effectiveness of irrigation.

Detailed field level models of sequential intraseasonal irrigation management, such as in Córdova and Bras (1979), incorporate hydrological balance models that represent the varying effectiveness of precipitation as a source of water input. Since our analysis is conducted in terms of total water input for the crop season, it is necessary to adopt a slightly different approach to incorporating this effect into our model. In particular, we allow for the difference in effectiveness of irrigation and precipitation as sources of water input by introducing a relative effectiveness parameter B.† This parameter always takes a value in the unit interval, reflecting the fact that precipitation, which is uncontrolled, is no more effective as a source of water input than irrigation. In general, it will be less effective. We shall then compute total effective water input as $W = I + Br$, where W is effective water input, I is irrigation, and r is precipitation.

To summarize, we shall make our calculations as though farmers had perfect foreknowledge about precipitation at the time irrigation decisions must be made. The only source of randomness in our model is thus natural variation in precipitation. While year to year variations in precipitation will influence the quantity of irrigation water demanded, the quantity applied in any year is – assuming perfect foreknowledge – always exactly the correct amount. This has the effect of biasing our demand estimates, although the direction of this bias cannot be determined without more information. However, since perfect foreknowledge also implies that irrigation water is never used needlessly, this assumption

†This parameter is not to be confused with "irrigation" efficiency, which measures the ratios between water inputs and water outputs, along the links in an irrigation system.

also has the effect of making our estimates of the contribution of irrigation to farm income too high.

2.3 The Demand for Irrigation

With these preliminaries, we can now analyze the demand for irrigation. Let us suppose that the relationship between yield per hectare and seasonal effective water input is quadratic as given in eqn. (3)

$$Y = a_1 W - a_2 W^2 \tag{3}$$

This equation is concave in water, and reaches a maximum at $a_1/2a_2$. It is similar in form to many of the functions obtained in empirical studies of water input–crop yield relationships. (For example, see Yaron 1971, Hexem and Heady 1978, and Hallgren 1947.)

Let us also suppose that the variable cost of irrrigation is equal to C monetary units per hectare-millimeter (ignoring fixed costs for the moment), and that the net proceeds to the farmer from sale of one unit of crop are equal to p monetary units. If farm operators incurred costs of C monetary units per hectare-millimeter of irrigation water used, and if they sought to maximize expected farm income, the optimum level of irrigation water usage (assuming that the fixed costs were covered) would be

$$I \geqslant \frac{pa_1 - C}{2a_2 p} - Br = i^* - Br; \qquad I(i^* - Br) = 0 \tag{4}$$

This is the necessary condition of the level of irrigation water input that would maximize farm income (before fixed charges).†

Equation (4) leads to a simple rule for deciding when and how much to irrigate. In particular, if precipitation (adjusted for effectiveness) yielded less water than the amount i^* shown in eqn. (4), profits could be increased by "purchasing" irrigation water until the sum of precipitation (adjusted for effectiveness) plus irrigation water equaled i^*.

Our irrigation rule may be expressed thus

$$\begin{aligned} &\text{if } i^* \geqslant Br, \qquad I = i^* - Br \\ &\text{if } i^* < Br, \qquad I = 0 \end{aligned} \tag{5}$$

where I is irrigation, r is precipitation, B is the precipitation effectiveness parameter, and i^* is the optimality parameter in eqn. (4).

To examine the effect of irrigation on expected farm income, let us denote the probability density function of precipitation by $f(r)$. Then we may represent expected farm income when we follow the irrigation rule given in eqn. (5) above by the eqn. (6):

†Recalling that total water input is $W = I + Br$, and that r is assumed to be known at the time the irrigation decision is made, eqn. (4) is obtained by finding the maximum of the profit function, $\Pi = p[a_1 (I + Br) - a_2 (I + Br)^2] - CI$ with respect to I, requiring that $I \geqslant 0$. Note that i^* in eqn. (4) is defined as $pa_1 - C/2a_2 p$.

$$\Pi = F(i^*/B)\left\{p(a_1 i^* - a_2 i^{*2}) - C\int_0^{i^*/B} \frac{If(r)\,\mathrm{d}r}{F(i^*/B)}\right\}$$
$$+ [1 - F(i^*/B)]\left\{p\left[a_1 B\int_{i^*/B}^{\infty} \frac{rf(r)\,\mathrm{d}r}{1 - F(i^*/B)} - a_2 B^2 \int_{i^*/B}^{\infty} \frac{r^2 f(r)\,\mathrm{d}r}{1 - F(i^*/B)}\right]\right\} \tag{6}$$

where $F(x)$ is the probability that $r \leqslant x$. This equation, as clearly can be seen, has two main terms. The first term gives expected farm income in the event that effective precipitation (i.e., precipitation multiplied by the efficiency parameter B) is less than i^*. In this event, irrigation water is drawn bringing total available water supply to the level i^*, contributing $p(a_1 i^* - a_2 i^{*2})$ to expected income, and

$$C\int_0^{i^*/B} \frac{If(r)\,\mathrm{d}r}{F(i^*/B)}$$

to expected costs (again ignoring fixed costs). If precipitation exceeds i^*, then no irrigation water is drawn, and the contribution to expected farm income in this event is given by

$$p\left[a_1 B\int_{i^*/B}^{\infty} \frac{rf(r)\,\mathrm{d}r}{1 - F(i^*/B)} - a_2 B^2 \int_{i^*/B}^{\infty} \frac{r^2 f(r)\,\mathrm{d}r}{1 - F(i^*/B)}\right]$$

Each term is multiplied by the corresponding probability that the event indicated occurs (i.e., by $F(i^*/B)$ and $1 - F(i^*/B)$ respectively), and the two terms are added together to give expected farm income if irrigation is practiced.

If irrigation is not practiced, the corresponding expression for expected farm income is simply

$$\Pi_0 = F(i^*/B)\left\{p\left[a_1 B\int_0^{i^*/B} \frac{rf(r)\,\mathrm{d}r}{F(i^*/B)} - a_2 B^2 \int_0^{i^*/B} \frac{r^2 f(r)\,\mathrm{d}r}{F(i^*/B)}\right]\right\}$$
$$+ [1 - F(i^*/B)]\left\{p\left[a_1 B\int_{i^*/B}^{\infty} \frac{rf(r)\,\mathrm{d}r}{1 - F(i^*/B)} - a_2 B^2 \int_{i^*/B}^{\infty} \frac{r^2 f(r)\,\mathrm{d}r}{1 - F(i^*/B)}\right]\right\} \tag{7}$$

We have split the integrals in eqn. (7) into ranges in order to facilitate comparison of expected income with and without irrigation.

The increment to expected farm income from irrigation is determined by taking the difference between eqns. (6) and (7). When this is done, the following expression for incremental expected farm income due to irrigation is obtained.

$$\Delta\Pi = F(i^*/B)p\left\{(a_1 i^* - a_2 i^{*2}) - \left[a_1 B\int_0^{i^*/B} \frac{rf(r)\,\mathrm{d}r}{F(i^*/B)} - a_2 B^2 \int_0^{i^*/B} \frac{r^2 f(r)\,\mathrm{d}r}{F(i^*/B)}\right]\right\}$$
$$- C\int_0^{i^*/B} If(r)\,\mathrm{d}r \tag{8}$$

We have thus far ignored fixed costs in our analysis. Equation (8) gives the excess of expected revenues over expected variable costs obtained through irrigation according to the rule described by eqn. (5). Whether or not irrigation would make a net contribution to farm income after fixed costs are deducted thus depends upon the size of the increment calculated according to eqn. (8) relative to the size of fixed costs. If the increment calculated by eqn. (8) is greater than fixed costs, then irrigation would add to expected farm income. If not, then it will not add enough to cover fixed costs, and presumably would not be undertaken.

The model described here shows how irrigation demand per hectare of crop area and the contribution of irrigation to expected farm income may be calculated for any given value of net farm price p and variable cost of irrigation C. From the individual farmer's perspective, our calculations approximate the expected values of optimal irrigation water quantities and farm income assuming constancy in these parameters.

However, as our discussion of Figure 1 suggests demand and income may be different when a regional perspective is adopted. Two factors are important to mention here. First, irrigation increases expected yield of crops. These yield increases may, for example, affect crop market prices and quantities. That is, when the actions of all farmers in the region taken together are considered, we must allow for the possibility that the crop market conditions assumed in the derivation of individual farmer's irrigation demands change. In Section 5 we show how crop market effects could alter the results of the analysis.

A second factor mentioned in our discussion of Figure 1 is the possibility that expansion of the demand for some factor of production (irrigation water in this case) could necessitate an increase in the price charged for this factor. This possibility is discussed in Section 6, where the effects of increases in irrigation costs on irrigation water demand are considered.

3 PARAMETER ESTIMATES

Three types of parameter estimates are required in order to use the relationships developed in Section 2 to estimate the demand for irrigation water. These are estimates of the parameters of the probability distributions of precipitation over relevant time periods, estimates of the parameters of function relating seasonal water input to yield, and estimates of the fixed and variable costs of irrigation. Estimates of these parameters are presented in this section.

3.1 Precipitation Distributions

Probability density functions for precipitation over relevant time periods (see Table 1) were fitted to 75 years of data on precipitation at Lund. Inspection of the precipitation

TABLE 1 Periods for seasonal water input distributions.

Crop	Period
Potatoes	16 June–31 Aug
Sugar beets	1 July–15 Sept

SOURCE: Arthur 1980.

data (keeping in mind the expressions in Section 2 that require numerical calculation) suggested fitting Weibull densities to the data.

Using this form of density, the results reported in Table 2 were obtained. As can be seen from the table, the estimated densities fit the data well. The coefficients of determination are all relatively high, and chi-square tests fail to reject the hypotheses that the data were generated by Weibull densities with the parameter values reported. For example, in the case of the distribution of "potato season" precipitation, the probability of obtaining a chi-square statistic less than or equal to that obtained, when the null hypothesis is true, is 0.6080. This means that we could reject the null hypothesis only at significance levels of about 40 percent.

TABLE 2 Estimates of parameters of Weibull densities $g(r) = \gamma_0 \gamma_1 r^{(\gamma_1 - 1)} e^{-\gamma_0 r^{\gamma_1}}$

Crop	Density parameters	R^2	Chi-square $\bar{\chi}^2$	Probability $P_6(\chi^2 < \bar{\chi}^2)$
Potatoes	$\gamma_0 = 0.96 \times 10^{-10}$	0.9498	14.8(14)	0.6080
	$\gamma_1 = 3.9818$			
Sugar beets	$\gamma_0 = 3.1 \times 10^{-10}$	0.9714	11.2(14)	0.3297
	$\gamma_1 = 4.1827$			

Taken together, the results reported in Table 2 indicate that our empirically estimated Weibull densities provide a good approximation to the observed distributions of precipitation.

3.2 Seasonal Water Input–Yield Functions

Seasonal water input–crop yield functions were fitted to experimental data (Swedish University of Agricultural Sciences 1966–1979; and Johansson and Linnér 1977). Data used to fit the parameters of water input–yield functions were taken from experiments conducted in southern Sweden. Very few experiments were available that could be used for this purpose. The seasonal water input–yield functions reported here therefore should be interpreted as rough approximations at best.

The procedure used in fitting the functions was as follows. Only data from experiments whose aim was to maximize yield were used.† Effective water inputs and yields

†In experiments designed to maximize yield, complementary inputs (e.g., fertilizer) frequently are applied in greater quantities than would be economical. In cases in which this occurs, estimates of the contribution of the treatment to output tend to be biased upward. It is probable, therefore, that our estimates of the incremental output due to irrigation overstate the increments that would actually be observed under normal farm operating conditions. However, we do not believe that this bias is very large in the present case.

were computed from experimental data. If several experiments were available, water inputs and yields were averaged. The parameters of a quadratic seasonal water input–yield function were then estimated by solving the following two equations for a_1 and a_2

$$Y = a_1 W - a_2 W^2$$

$$0 = a_1 - 2a_2 W$$

The efficiency parameter value B was selected for each crop by trial and error to approximate reported average yields with and without irrigation. The results obtained from these calculations are given in Table 3. The first three columns of the table report estimated

TABLE 3 Estimated parameters of water input–yield functions.

Crop	a_1	a_2	B	Expected yield (dt/ha): Without irrigation	Expected yield (dt/ha): With irrigation
Potatoes	3.4826	0.0087	0.65	270.97	349.67
Sugar beets	4.1707	0.0091	0.75	373.72	477.86

values of a_1, a_2, and B. The last two columns report expected yield without irrigation and expected yield with irrigation. Thus, our estimates imply average yields in the absence of irrigation of approximately 270 dt/ha and 375 dt/ha for potatoes and sugar beets, respectively, and average yields with irrigation of approximately 350 dt/ha and 475 dt/ha, respectively.

3.3 Irrigation Costs and Crop Prices

Two types of economic parameters enter into the calculation of the demand for irrigation water. These are irrigation costs and net farm prices.

In Skåne today, there are no charges levied directly on the withdrawal of water from groundwater or surface water sources for irrigation. The water itself is free.† However, this does not mean that irrigation is free to the farmer. The withdrawal and application of irrigation water require investment in equipment and outlays for its operation.

Estimates of the investment and operating costs associated with water withdrawal and application are given in Table 4. As can be seen from the table, investment costs are estimated to be about 735 Swedish Kroner (skr) per hectare irrigated per year, and variable costs are estimated to be about 4 skr per hectare-millimeter.

†Swedish water law stipulates that water may be withdrawn only in amounts that will not harm the public's right to water, and establishes certain general controls on quantities of water that may be withdrawn for specific purposes without special permission. For example, withdrawals from groundwater for irrigation purposes are limited to 300 m^3 per 24 hours without special permission.

TABLE 4 Estimated irrigation costs.

	Estimated cost
Investment	735 (skr per hectare per year)
Operating	4 (skr per mm per hectare)

See Appendix A for explanation of cost estimates.

The second type of economic parameter required for our calculations is the net farm price of the crops we consider. Net farm price, or producer's price, is equal to the wholesale price for the crop less the cost of harvest, drying, sorting, and transporting the crop to the market. Table 5 reports average wholesale prices, preparation and delivery costs, and net farm prices in 1978 for table potatoes and sugar beets. The net farm prices shown are the prices used in our calculations of irrigation demand in Section 4.

TABLE 5 Wholesale and net farm prices, and preparation and transport costs of table potatoes and sugar beets.

Crop	Wholesale price (skr/dt)	Preparation and transport cost (skr/dt)	Net farm price (skr/dt)
Table potatoes	90	10	80
Sugar beets	16	1	15

4 ESTIMATES OF THE DEMAND FOR IRRIGATION WATER IN SKÅNE

All of the data needed to make the calculations explained in Section 2 are now available. To estimate irrigation demand, we now only require to calculate the expressions developed in Section 2, and certain auxiliary expressions, using the parameter estimates given in Section 3.

4.1 Partial Expectations

Evaluation of the expressions in Section 2 requires that the expectations of certain random variables be taken over a subset of their range. Fortunately this can be done with relative ease given the form of the precipitation densities (Weibull) and water input–yield functions (quadratic) employed here.

Consider first the partial expectation of the first-order term in the seasonal water input–yield relationship,

$$a_1 B \int_0^{i^*/B} r f(r)\,\mathrm{d}r = a_1 B \int_0^{i^*/B} \gamma_0 \gamma_1 r^{\gamma_1} \mathrm{e}^{-\gamma_0 r^{\gamma_1}}$$

Let $t = \gamma_0 r^{\gamma_1}$, then

$$a_1 (1/\gamma_0)^{1/\gamma_1} \int_0^{\gamma_0 (i^*/B)^{\gamma_1}} t^{1/\gamma_1} e^{-t} dt$$

But the integral in this expression is simply the incomplete gamma function with parameters $1/\gamma_1 + 1$ and $\gamma_0(i^*/B)^{\gamma_1}$. Thus, the partial expectations of first-order terms may be evaluated as

$$a_1 (1/\gamma_0)^{1/\gamma_1} \Gamma_I [1/\gamma_1 + 1, \quad \gamma_0 (i^*/B)^{\gamma_1}]$$

where $\Gamma_I(\cdot)$ is the incomplete gamma function.

The partial expectations of second-order terms may be reduced to simple expressions involving incomplete gamma functions by analogous reasoning. The resulting expression for the value of the partial expectation of second-order terms is

$$-a_2 (1/\gamma_0)^{2/\gamma_1} \Gamma_I [2/\gamma_1 + 1, \quad \gamma_0 (i^*/B)^{\gamma_1}]$$

4.2 Estimates of Quantities of Water Demanded

Our basic estimates of quantity of water demanded per irrigated hectare are presented in Table 6. These results are computed using the parameter values reported in Section 3.

Column (1) of Table 6 reports the value of the optimal irrigation parameter i^*, corresponding to 1978 prices and costs, determined according to eqn. (4) in Section 2. The value taken on by this parameter represents the quantity of effective water that maximizes the net contribution of the water input to farm income. At the price and cost combinations used in calculation of the results in Table 6, the quantity of effective water input that maximizes this contribution is only slightly less than the quantity of effective water input that would maximize yield.

Column (2) of Table 6 reports the probability that seasonal precipitation will yield less than the optimal quantity of effective water shown in Column (1). Thus, for example, our estimates imply that in more than 99 percent of the years, irrigation water would have to be applied to both potatoes and sugar beets in order to bring the water inputs up to optimal levels. In less than one percent of the years will precipitation supply the full amount of the optimal water inputs.

Column (3) of Table 6 reports the increases in expected yields that would result from irrigation, computed according to the relationships derived in Section 2. As can be seen by comparing these figures with corresponding estimates of expected yield in the absence of irrigation presented in Table 3, the expected increases are substantial. In the case of both crops, increases in expected yields amount to more than 25 percent of expected yields without irrigation.

Column (4) of Table 6 reports the expected quantity of water demanded for irrigation. This is obtained by evaluating the partial expectation of $i^* - Br$ over the interval $(0, i^*/B)$. Our model implies that expected irrigation demand at 1978 price and cost levels would be about 87 mm/ha for both crops.

TABLE 6 Analysis of water demands per hectare irrigated.

Crop	Period	Production	(1) i^* (mm/ha)	(2) $F(i^*/B)$	(3) $\Delta\bar{Y}$ (dt/ha)	(4) $\bar{I}$ (mm/ha)	(5) $c\bar{I}$ (skr/ha)	(6) $\Delta\bar{\Pi}$ (skr/ha)
Potatoes†	16 June–31 Aug	$a_1 = 3.4826$ $a_2 = 0.0087$	197.28	0.9989	78.63	87.03	348.12	5,942.31
Sugar beets††	1 July–15 Sept	$a_1 = 4.1707$ $a_2 = 0.0091$	214.51	0.9971	102.19	86.65	346.60	1,186.24

Parameters used in calculation:
† Farm price = 80 skr/dt; rainfall effectiveness = 0.65
†† Farm price = 15 skr/dt; rainfall effectiveness = 0.75
Variable cost of irrigation = 4 skr/mm/ha

These estimates are reasonably close to those reported for the same crops in Arthur (1980). This is not really surprising as the irrigation rules simulated by Arthur were derived in part from the same experimental data that were used to fit the water input–yield relationships employed in our calculations. Nonetheless, it is important to note that when current (1978) crop prices and water costs are taken into account, per hectare water demands are approximately the same as those estimated in Arthur's analysis.

Column (6) of Table 6 reports the expected contribution of irrigation to farm income (gross of fixed costs) per hectare. For example, our estimate of the expected contribution of irrigation of potatoes to farm income is about 5,940 skr per hectare irrigated. Since estimated fixed costs of irrigation are less than 800 skr per hectare irrigated (see Table 4), the estimates presented in Table 6 suggest that irrigation of both sugar beets and potatoes would be profitable at 1978 crop prices and irrigation costs.

It should be noted that the contribution to farm income of any single crop need not exceed fixed costs for irrigation to be profitable. This is because crops are grown in rotation, and in different plots on the same farm at the same time. For irrigation to be profitable, it is sufficient if the contribution to farm income from irrigating the mixture of crops is large enough to cover the fixed costs of irrigation.

4.3 Sensitivity of Water Use to Water Cost and Crop Prices

The sensitivity of the basic results presented in Table 6 to changes in crop prices and variable irrigation costs is investigated in Tables 7a and 7b. Table 7a reports estimated water quantity demanded at various combinations of net farm price for potatoes and variable costs of irrigation. The cell of the table corresponding to a net farm price of 75 skr per dt and a variable irrigation cost of 5 skr per mm/ha approximates the assumed values for crop price and irrigation cost used in calculating the results in Table 6.

Table 7a shows two interesting and important patterns. First, at low variable costs of irrigation (i.e., 5 skr/mm/ha), we see that the quantity of water demanded does not respond very much to changes in crop prices. At a net farm price of 35 skr/dt and variable irrigation cost of 5 skr/mm/ha, the estimated per hectare demand for water is 81.7 mm. At a price of 95 skr/dt and variable irrigation cost of 5 skr/mm/ha, demand for water is only about 5 mm/ha greater.

Demand is somewhat more sensitive to crop prices at higher irrigation costs. For example, at a cost of 25 skr/mm/ha, quantity demanded increases from about 49.5 mm/ha at a net farm price of 35 skr/dt to 74.8 mm/ha at a net farm price of 95 skr/dt. The increase in quantity demanded at this level of irrigation cost is thus over 25 mm/ha.

The second important pattern reflected in Table 7a is that sensitivity of quantity demanded to cost is greater at low net farm prices than at high prices. This can clearly be seen by comparing the columns of the table.

Table 7b shows the same general patterns as does Table 7a. Indeed, in some cases in which low crop prices are combined with high irrigation costs, the optimum irrigation parameter i^* is zero [see eqn. (4) in Section 2].

In Tables 7a and 7b, a broken line separates the price–cost combinations which yield a contribution to farm income of less than 800 skr/ha from those which yield this amount or more. Our estimate of fixed costs of irrigation per hectare is approximately 800 skr.

TABLE 7a Analysis of water demands for irrigation of potatoes.

Variable cost of irrigation water† (skr/mm/ha)	Net farm price (skr/dt) 35		55		75		95	
	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)
5	81.70	2325.57	84.68	3892.16	86.07	5462.73	86.88	7034.76
25	49.47	1016.54	63.92	2406.62	70.80	3894.19	74.81	5417.90
45	21.97	316.41	43.90	1330.73	55.75	2629.14	62.84	4041.66
65	5.96	58.85	26.27	634.85	41.36	1659.62	51.11	2902.85

†Note that 1 hectare-millimeter is equal to 10 m^3. Variable cost figures may be converted to skr/m^3 by dividing by 10.

TABLE 7b Analysis of water demands for irrigation of sugar beets.

Variable cost of irrigation water† (skr/mm/ha)	Net farm price (skr/dt) 5		10		15		20	
	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)	$\bar{I}$ (mm/ha)	$\Delta\bar{\Pi}$ (skr/ha)
5	47.52	150.41	73.91	603.54	83.00	1101.42	92.13	2640.64
25	0	0	2.83	7.80	19.75	127.59	56.06	1161.28
45	0	0	0	0	0.46	1.33	25.08	365.39
65	0	0	0	0	0	0	6.92	69.90

†Note that 1 hectare-millimeter is equal to 10 m^3. Variable cost figures may be converted to skr/m^3 by dividing by 10.

Price–cost combinations falling below the broken line fail to yield a contribution to farm income sufficient to cover fixed costs. Price–cost combinations falling above the line do yield a large enough contribution to cover fixed costs. Although it is not necessary for all crops to yield a contribution sufficient to cover irrigation costs in order for irrigation to be profitable, it is necessary that the crop mix yields sufficient income to offset this amount. This means that at least one of the crops irrigated must show a contribution to farm income in excess of fixed costs.

4.4 Remarks

The most important conclusion of the analysis presented here is that explicit consideration of crop prices and irrigation costs does not result in materially lower estimates of per hectare demand for irrigation than those obtained by Arthur. Indeed, the estimated demands per hectare obtained in Section 4.2 are about the same as those reported by Arthur.

This certainly underscores the gravity of the results reported by Strzepek (1981). Consideration of economic factors bearing on individual farmer's irrigation demand decisions does not alter the conclusion that potential water demand and water supply could become seriously out of balance.

The only possible reprieve is that the crop market effects of irrigation could moderate demand. This possibility is considered in Section 5.

5 EFFECT OF IRRIGATION ON CROP MARKETS

Sections 1 and 2 indicated that increased yields due to irrigation could affect the markets for crops. Since the demand estimates presented in Section 4 are based on the assumption of a given set of market conditions, the possibility must be considered that irrigation-induced changes in crop market conditions may result in changes in irrigation demands. Estimating the effect of increased yields in a conceptually correct manner requires a fairly detailed model of the agricultural sector. To support a complete analysis of the effects of irrigation on crop markets and of the feedback effects on irrigation demand, this model would have to explain both factor demands per hectare and the determination of land areas planted in different crops. The model developed in Section 3 explains only irrigation demands per hectare. Without a model that explains crop areas as well, the most that can be done is to estimate roughly the possible ranges of outcomes and to examine how outcomes in these ranges could affect the demand for irrigation water.

To analyze the possible effects of irrigation on crop markets, let us first consider the basic principles of price and quantity determination in national crop markets. To begin, we assume that the national crop market in question is completely open (i.e., there are no barriers to trade) and perfectly competitive.

Determination of output and price in a competitive open national crop market is shown in Figure 4. Curve D–D represents the domestic demand for the commodity. p_w represents the world price for the commodity, and s_0 represents the domestic supply of the commodity. Ignore the curves p_d and s_1 for the moment.

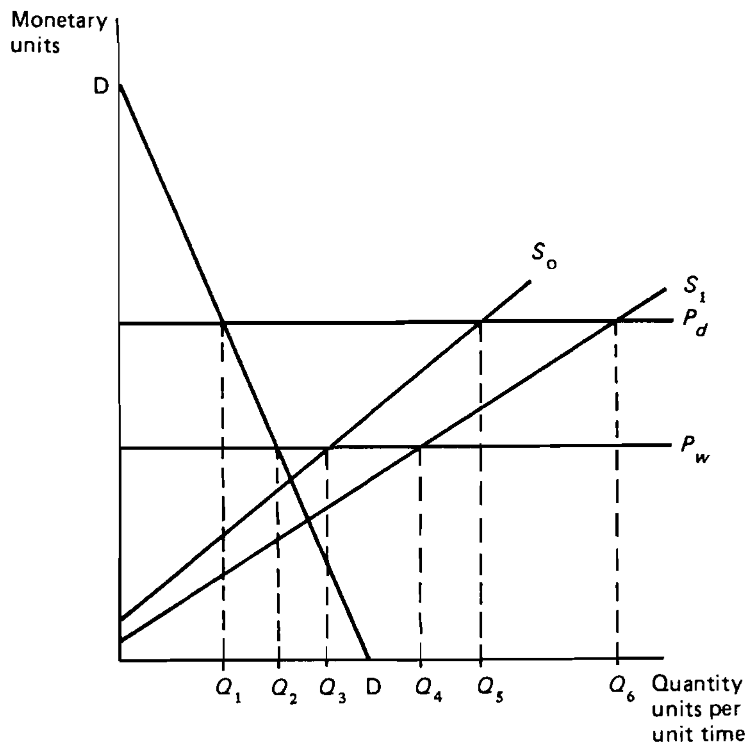

FIGURE 4 Price and output determination in national crop markets.

Under the open competitive market assumption, domestic producers may produce and sell as much output as they wish at the world price p_w. In this situation, domestic producers would produce a quantity corresponding to the point at which the world price curve p_w intersects the domestic supply curve s_0. Output also would be sold domestically at the world price p_w. Hence, domestic producers would produce Q_3 units of output per unit of time, and domestic consumers would purchase Q_2 units of output per unit of time. The difference $Q_3 - Q_2$ would be exported at the world price p_w. If the domestic supply and demand conditions relative to world market price were such that domestic consumers demanded more at the world price than domestic suppliers produced, then the balance would be imported at the world price.

However, the analysis would be somewhat different if domestic prices were supported at p_d, with foreign producers discouraged from selling in the domestic market by an import duty marginally larger than the difference between p_d and p_w. In this case domestic consumption would be Q_1 while domestic production would be Q_5. In this case, exports would not automatically close the gap between domestic production and consumption. The difference between Q_5 and Q_1 would have to be taken up through storage or perhaps through subsidized export. If the latter alternative were chosen, the cost of the subsidy required would be equal to the difference between the domestic and the world price, times the difference between the quantity of the commodity produced and the quantity of the commodity demanded in the domestic market.

Figure 4 also illustrates how an increase in supply – such as might come about with the adoption of irrigation – could affect the crop market. If the market were open and competitive, the effect of an increase in supply would be to increase domestic production and increase domestic exports (or reduce domestic imports). There would be no tendency for market price to change since the increment in output would be negligible in relation to the world market. This is seen in Figure 4 by examining the effect of a shift in supply from s_0 to s_1. Domestic output increases to Q_4, and exports increase to $Q_4 - Q_2$.

If the domestic market were insulated from the world market by tariffs and price supports, the effect of a supply shift would be to exacerbate the problems of dealing with crop surpluses. In the case depicted in Figure 4, the effect of the supply shift to s_1 is to increase by $Q_6 - Q_5$ the surplus of output over domestic consumption that must be dealt with in some fashion. The cost of dealing with this problem depends both upon the size of the surplus and the spread between domestic and world prices.

Market effects, such as those depicted in Figure 4, can have profound feedback effects on irrigation demand per hectare of crop and on the land area planted in the crop. Inspection of eqn.(4) reveals immediately that per hectare irrigation demand varies directly with crop price. It can also be shown that crop area varies directly with crop price (see Appendix B). The effects of crop price changes on per hectare irrigation demand and crop area reinforce one another. Estimates of the effects of price changes on per hectare demand thus tend to understate the full effect of crop price changes on demand.

It can be further shown that if crop price does not change as a result of irrigation, crop area would tend to increase (see Appendix B). Thus, although per hectare irrigation demand would be unaffected in the constant crop price case, total irrigation demand would increase.

Figure 4 conveys the essentials of the situation in Sweden. Sweden has taken policy measures to insulate its agricultural sector from the forces of world market competition. These measures include tariffs, subsidized export and storage programs, and price supports for Swedish farmers designed to insure that prices are adequate to cover costs and that "farmers . . . like others, . . . attain a reasonable income level" (Statens Lantbruks Information 1976).

Sweden today pursues what is termed a "high price" policy for its farm production. The domestic prices of most (although not all) crops are maintained above world levels. The specific levels at which domestic prices are maintained are set in negotiations between the government and various organizations representing producers of the different agricultural commodities. In 1978, the domestic price for table potatoes was about 90 skr per deciton, or about 20 skr per deciton above the world market price. However, the Swedish domestic price for sugar beets was roughly equal to the world market price in that year.

The analysis in Figure 4 demonstrates that, as long as the Swedish domestic price and the world price of sugar beets are approximately equal and the world market is competitive, the effect of increased irrigation of sugar beets is to increase production and, other things being equal, to increase exports. Hence, the sugar beet market conditions assumed in the calculation of per hectare irrigation demands of individual farmers (see Section 4) is not affected by irrigation. Crop market adjustments thus have no effect on demand for irrigation per hectare of sugar beets. Moreover, since irrigation increases the relative profitability of sugar beet production, land area planted in sugar beets can increase. This would result in an increase in *total* water demand, not per hectare water demand, for irrigation of sugar beets.

The effects of irrigation of table potatoes on the Swedish market are less clear-cut. Because of the spread between the Swedish domestic price and the world price of table potatoes, the nature and magnitude of effects on the potato crop market would depend upon the adjustment policy pursued. In this regard, it is useful to consider two limiting cases.

In the first case, we assume that the domestic price of table potatoes is lowered as far as is needed to absorb increased yields. This case could result in elimination of the divergence between domestic and world prices, and a decrease in irrigation water demand per hectare of potatoes.

In the second case, we assume that the 1978 spread between the domestic and the world price of table potatoes is maintained, and that the additional surplus is disposed of via subsidized exports. Of course, this would have the effect of increasing the cost of the price support policy, and, if land area planted in table potatoes increased, increasing total irrigation water demand. However, per hectare irrigation demand of table potatoes is unaffected.

5.1 Price Adjustment

Let us consider the case in which price adjustment alone accommodates the increased supply of table potatoes. Other things being equal, an increase in the yield of table potatoes would tend to cause the price to fall. This is because consumers are induced to buy the larger quantity of crop available only if the price falls. The extent of the price decrease necessary to bring increased crop supply into balance with demand, neglecting other (factor demand) adjustments, can be calculated approximately by using an estimate of the *elasticity of demand*.†

To see how the elasticity of demand can be used to estimate the effect of an increase in yield on crop price, suppose that the elasticity of demand for table potatoes is η and that – as a result of the increase in yield – the quantity of this crop offered for sale increases by n percent. Then the approximate change in the price of table potatoes that would be required to bring supply and demand back into balance would be

$$\Delta p = \frac{1}{\eta}\,\frac{\Delta q}{q}\,p = \frac{1}{\eta}\,np \tag{9}$$

†The elasticity of demand is defined as the percentage change in quantity demanded that would result from a given percentage change in price. The formula for this measure is

$$\text{elasticity} = \frac{\Delta q}{q}\bigg/\frac{\Delta p}{p} = \frac{\Delta q}{\Delta p}\left(\frac{p}{q}\right)$$

where q is the quantity demanded and p is the price.

In a world in which agricultural commodities were freely and competitively traded, the demand facing producers in any country would be highly price elastic (i.e., η would be very large), and increments to output, of the size that would result from irrigation in Skåne, would result in imperceptible downward pressure on prices. Equation (9) is thus completely consistent with our analysis of Figure 4.

Rough estimates of the parameters needed to apply the formula in eqn. (9) and implied estimates of table potato price changes are shown in Table 8. These estimates assume

TABLE 8 Estimated effect of increased yields on table potato prices, assuming no producer adjustment.

(1) Approximate demand elasticity	0.1
(2) Approximate yield increase	0.29
(3) Approximate Skåne share	0.18
(4) Initial wholesale price (skr/dt)	90 (70)
(5) Wholesale price at increased yield (skr/dt)	70
(6) Incremental cost (skr/dt)	10
(7) Farm price at increased yield (skr/dt)	60

that there is no producer response (e.g., reduction in irrigation or reduction in land area planted in table potatoes) to price changes. Thus, they tend to represent upper bounds on the size of the price effect on per hectare irrigation demand that might be expected to follow from irrigation.

Line (1) of Table 8 gives estimates of the price elasticities of Swedish demand for table potatoes.† The elasticity is less than one, that is the domestic demand for this crop is inelastic.

Line (2) gives the estimated increase in per hectare yield obtained when the irrigation plan reflected in Table 6 is applied. Estimated fractional increases are obtained by dividing our estimates of the increases in yield by the estimated yields without irrigation reported in Table 3. Thus, our estimates imply that irrigation will increase expected yields of potatoes by about 29 percent (i.e., $78.70 \div 270.97 \times 100 = 29.01$).

Line (3) gives the fraction of total Swedish production of table potatoes accounted for by the part of Skåne -- Malmöhus County -- which is of interest here. This is the fraction of production which we assume to be affected by irrigation.†† Our estimate of the fraction by which total Swedish production of table potatoes is increased, is thus equal to the product of the fractions in lines (2) and (3) of Table 8.

Line (4) gives the assumed initial (i.e., without irrigation) Swedish wholesale price for table potatoes, and an approximate world market price in parentheses.†††

†Estimate provided by F. Desmond McCarthy, Food and Agriculture Program, IIASA.

††The Malmöhus County Board of Agriculture estimates that 100 percent of the crop area in potatoes in Malmöhus Country potentially will be irrigated.

†††World price was calculated by dividing the total dollar receipts for exports of potatoes by European nations, by the reported export quantities, and converting to skr. Data for these calculations are taken from Food and Agricultural Organization (1978).

As shown by comparison of these figures, the Swedish wholesale price for potatoes is about 20 skr above the world market price.

Line (5) gives the calculated Swedish wholesale price of table potatoes after the fractional production increases implied by the products of lines (2) and (3). This price is determined by calculating the price decrease implied by eqn. (15), and subtracting this calculated decrease from the initial price shown in line (4).

Line (6) gives the cost per deciton of processing table potatoes for wholesale. This is the difference between wholesale price and net farm price. Subtraction of line (6) from line (5) thus provides an estimate of the net farm price of table potatoes at the increased production level implied by the earlier lines of the table. This estimate is reported in line (7). On *a priori* grounds, the price effects calculated in Table 8 could have significant repercussions on the demand for irrigation water. In particular, significant decreases in the net farm price of potatoes of the magnitude reflected in our calculations in Table 8 could result in substantial reductions in demand for supplementary irrigation.

Juxtaposition of the results presented in Tables 7a and 8 provides some indication of the extent to which the price effects shown in Table 8 could moderate demand. The column of Table 7a which most nearly corresponds to our estimated farm price at increased yields is the column which assumes a net farm price of 55 skr/dt for table potatoes. According to our estimates, irrigation of potatoes would still be profitable by a wide margin (i.e., the contribution to farm income exceeds the fixed costs of irrigation) if irrigation costs remained constant, and the quantity of irrigation water demanded per hectare would be only slightly lower than it would be at 1978 prices.

5.2 Surplus Adjustment

Failing any adjustment of price to reflect the effects of supplementary irrigation on yield and production, additional surpluses of table potatoes would be produced. While the total production of sugar beets would also increase, as noted earlier this additional production could be exported without subsidy under the price and cost conditions assumed in Table 8.

Under our simplifying assumption that land areas planted do not adjust, if the domestic price of table potatoes were held constant, the increase in crop surplus that would have to be disposed of would be

$$\Delta s = A\,\Delta Y \tag{10}$$

where A is crop acreage irrigated, ΔY is the increase in expected yield associated with irrigation, and Δs is the increase in surplus. The cost of disposing of this extra surplus, assuming that it was exported at the world price, would be

$$\text{Export subsidy} = (p_d - p_w)\,\Delta s \tag{11}$$

where p_d and p_w are respectively the domestic and world prices.

When the calculation given in eqn. (10) is carried out we obtain an estimate that the incremental surplus production of table potatoes, assuming that all land planted in table potatoes in Malmöhus County in 1978 were irrigated, would be 316,250 decitons. At a price spread between domestic and world prices of 20 skr per deciton, the cost of disposing of this additional surplus would be 6,325,000 skr.†

5.3 Remarks

Two rather strong assumptions are implicit in the calculations of price adjustments using eqn. (9), and surplus adjustments using eqns. (10) and (11). As shown in Appendix B, these assumptions tend to bias downward our estimate of price that would result from irrigation, bias upward our estimate of the reduction in irrigation demand per hectare that could result from crop price effects, and bias downward our estimate of the increment to surplus that would result if crop prices were maintained.

The first assumption (in reality it is a simplification of our calculations) we have made is that we have not considered the effect of reduced irrigation on prices. That is, as prices fall, irrigation per hectare tends to fall, reducing yields, and relieving some of the downward pressure on prices. We could allow for this moderating effect by reformulating the model presented in Section 2 to take price effects into account. We have not done so because, in view of the other assumptions made, the gains from this refinement would not be worth the extra computation.

The second assumption we have made is that no other adjustments take place. In fact, as is demonstrated in Appendix B, one would expect to see adjustments in areas planted in crops in response to changes in the relative profitability of producing different crops. This would tend to moderate the price adjustments calculated in Section 5.1.

In the surplus adjustment case considered in Section 5.2, one would expect to see the acreage planted in irrigated crops increase since the profitability of these crops relative to other crops is increased, *ceteris paribus* (see Appendix B). The estimate of surplus we present in Section 5.2 thus tends to understate the additional surplus that would have to be disposed of in the pure surplus adjustment case.

These qualifications notwithstanding, it is important to note that one very important conclusion can be drawn from our approximate calculations: crop market effects alone probably would not result in a sufficiently large decrease in the demand for irrigation water in Skåne to rebalance water supply and potential demand in the region. Even the relatively large price decrease for potatoes reflected in Table 8 (which, for reasons discussed above, is larger than we would actually expect to observe) would not substantially reduce per hectare water demand by itself. Only if crop price had a substantial effect on crop acreage would there be any material effect on the total quantity of irrigation water demanded.

† As noted earlier, Swedish agricultural experts estimate that 100 percent of the potato crop in Malmöhus County will be irrigated. The increase in yield used in the above calculations is taken from Table 6, and the 1978 figure of 4,022 hectares of table potatoes is used as the estimate of irrigated crop area.

6 IRRIGATION DEMAND AT HIGHER IRRIGATION COSTS

The evidence examined suggests that water demands at roughly current prices and costs could well be as great as Arthur (1980) and Strzepek (1981) have estimated them to be, and that there is little prospect that irrigation-induced crop market effects would reduce irrigation water demands by very much.

In the calculations presented in Section 4, the cost of irrigation was estimated as the investment in equipment and outlays for operations to withdraw and apply water from surface water and groundwater sources. No cost was attached to the water *per se*. If adequate water supplies were available to meet all demands, the cost of irrigation estimated in this fashion would fairly represent the economic costs of irrigation. If, however, water were scarce relative to demands – as is potentially the case in Skåne if irrigation demands attain the levels projected in Section 4 – the true social cost of irrigation would be somewhat higher than simply the investment and operating costs needed to withdraw and apply it. In order to accommodate irrigation usage, water would have to be reallocated from other uses, or additional capacity would have to be added, and both of these options involve further costs.

Thus, the sole remaining options for rebalancing supply and demand are some reallocation of existing water supplies or the addition of supply capacity. Either option, as is indicated in Section 1, is likely to result in a substantial increase in the opportunity cost of irrigation.

Reallocation of existing water supplies would mean that some current users of water in the region would have to curtail their usage. As noted in Section 1, there may be no increase in water supply system costs occasioned by a reallocation of water from current users. However, there would be an opportunity cost associated with reallocated water. Current users pay on average about 5.5 skr/m^3 for municipal water in Skåne. This means that each cubic meter of water used may be viewed as being worth *at least* 5.5 skr to the user.

If this figure is taken as a benchmark of the opportunity cost of reallocating water from current users, then the implied variable cost of water per hectare irrigated is 55 skr/mm/ha, and the variable cost of irrigation is about 59 skr/mm/ha (i.e., 55 skr/mm/ha for water and 4 skr/mm/ha for operation of irrigation equipment). This is a substantial increase in irrigation costs over current levels (note that we estimate that the variable cost of irrigation is about 4 skr/mm/ha). Moreover, 55 skr/mm/ha may tend to underestimate the true opportunity cost of the reallocated water since it assumes that only the lowest valued uses (i.e., those valued at just 5.5 skr/m^3) are displaced and that no higher valued uses are displaced.

Inspection of the results presented in Tables 7a and 7b shows the dramatic effect that an increase in irrigation costs to 59 skr/mm/ha would have on per hectare irrigation demand. It is unlikely that irrigation of sugar beets, considered in isolation from other crops, would be profitable. Irrigation of table potatoes *might* continue to be profitable, depending upon what is assumed about crop prices. However, even if irrigation of table potatoes remained profitable, it is possible that per hectare irrigation quantities would be reduced between 30 and 50 percent from the levels we would expect at 1978 crop prices and irrigation costs (see Table 7a).

If charges were levied on use of water for irrigation at levels reflecting the opportunity cost of displaced uses, this suggests that the result could – depending upon what happens to crop prices – be a substantial decrease in quantities of water used per hectare for irrigation. The decrease in usage could be sufficient to rebalance demand and supply without additions to existing capacity.

Another option for rebalancing supply and demand is addition to current water supply system capacity. Indeed, system capacity is currently being expanded through construction of the Bolmen project. Taking estimated average cost of water from Bolmen as a measure of the cost of additional capacity, we may approximate the cost of water from expanded capacity between 4 and 5 skr/m^3, or just about the same amount as the cost of reallocating existing supplies. The conclusions stated earlier (i.e., that demands would be significantly reduced at higher cost levels) thus remain valid if the option considered for rebalancing supply and demand is capacity expansion. Note, however, that it is doubtful that any addition to system capacity would be required if agricultural users were charged a price for water that reflected either its opportunity cost or the cost of additional capacity, and if crop prices were established solely by market forces. It is, therefore, doubtful that demands for supplementary irrigation would provide an economic justification for capacity expansion at costs approximating those of the Bolmen project.

These conclusions are reinforced if the effect of increases in irrigation cost on crop areas is considered. In Appendix B it is demonstrated that the effect of an increase in irrigation cost is to reduce crop area. The crop area effect (which we are unable to estimate with the data at our disposal), taken in conjunction with the effects on per hectare demands estimated above, imply a very substantial reduction in total irrigation demand.

We remarked above that Swedish institutions governing the withdrawal and use of water for irrigation provide no mechanism for pricing of the water used. Thus, if prices were to be used in an effort to balance water supply and demand, substantial changes in the current institutional framework for water management might be required.

7 CONCLUSIONS

The following conclusions can be drawn, based upon our analysis.

First, an economic analysis of demand for irrigation water suggests that the per hectare demands for irrigation water for table potatoes and sugar beets, at 1978 crop prices and variable costs of irrigation, are about the same amount as Arthur (1980) estimated. Based on the analysis of Strzepek (1981), we thus conclude that water supply and demand in Skåne could become seriously out of balance.

Second, the feedback effects of increased yields and production on irrigation demand, even under relatively extreme assumptions probably would not reduce the demand for irrigation water enough (if at all) to rebalance demand and supply. This conclusion is obvious if crop prices do not fall – either because they are equal to world price levels or because they are prevented from doing so by crop price supports. Our calculations show that even if prices did fall, and even if market adjustment mechanisms that tend to moderate price decreases were ignored, the fall in prices probably would not reduce demand by more than a modest amount.

Third, if the variable costs of irrigation were increased to levels reflecting the opportunity cost of the water used (e.g., through levying a charge on irrigation water usage) the reduction in demand would be large enough to rebalance demand and existing supply, depending upon what happens to crop prices. If crop prices fell in response to increased yields, quantities of water used can fall between 30 to 50 percent or more from levels that are used under 1978 price and cost conditions. If prices were supported at well-above world price levels, the effect of increased costs on demand would be smaller.

The analysis on which these conclusions is based contains a number of simplifications and approximations. Even so, in our opinion the results of the analysis can hardly be classified as "simple" or "clear-cut." The actual extent to which supplementary irrigation will be practiced in Skåne clearly will depend upon a number of factors about which we can only speculate. We have seen, for example, that conclusions concerning demand quantities depend upon what one assumes about agricultural commodity price policy. If prices are allowed to adjust to reflect improved yields due to irrigation, water demand may be moderated slightly and the balancing of water supply and demand may be facilitated. If price supports are maintained and additional production is accumulated as surplus, water demand may be amplified as land is reallocated to relatively more profitable irrigated crops, and the potential water supply–demand imbalance may be exacerbated. If institutions are so structured as to confront the farmer with the full social opportunity cost of the water resources he uses, then cost considerations will moderate demands and help balance water supply and demand. If institutions are not so structured, then little help in balancing supply and demand can be expected from this quarter.

What is absolutely clear, from this work and that of Strzepek and Arthur, is that agricultural water demand in Skåne is an important – perhaps even *the critical* – factor in future planning and management of the water supply system in this region. A more detailed investigation which examines and evaluates the assumptions and approximations we have made and the course of Swedish policy with respect to agricultural commodities and water use is thus certainly required. This undoubtedly is our most important conclusion.

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APPENDIX A: ESTIMATED IRRIGATION COSTS

The following estimated irrigation costs were prepared by Lennart de Maré, IIASA. The calculations were based on 1978 costs, 30 hectares were irrigated. All costs are given in skr.

Investments:

	Surface Water (skr)	Groundwater (skr)
Well		30,000
Pump & electric installations	25,000	30,000
Main pipe		
1200 m	30,000	
700 m		17,500
Movable pipe	7,500	7,500
Hydrants	2,500	2,500
Irrigation machine	40,000	40,000
	105,000	127,500

Amortization of investment:

	Well & main pipe (%)	Pump & electric installation, movable pipe (%)	Irrigation machine (%)
Depreciation	5	11	14
Interest	4	4	4
Maintenance	1	5	6
	10	20	24

Other fixed costs:

	skr/yr
Storage, insurance, etc., at irrigation machine	1,500
Electricity (basic fee)	1,200
	2,700

Variable costs and cost factors:

	Factor	Units
Electricity use charge	0.13	Skr/kwhr
Labor cost	35	skr/hr
Tractor cost	17	skr/hr
Electricity use per hour	20.25	kwh/hr
Irrigation factor		
Potatoes	25	mm/ha/irrigation
	2	ha/18 hour-day
Grain sugar beets	35	mm/ha/irrigation
	1.5	ha/18 hour-day
Labor use	1	hr/ha/irrigation
	1.8	hr/irrigation-day
Tractor use	0.3	hr/ha/irrigation
	1	hr/irrigation-day

Irrigation assumptions:

15 ha sugar beets, 2 irrigations, 35 mm/irrigation
15 ha potatoes, 5 irrigations, 25 mm/irrigation

Calculations:

Fixed costs per year:

Surface water

Investment: 0.1 X 32,500 + 0.2 X 32,500 + 0.24 X 40,000 =	19,350
Other fixed:	2,700
	22,050

Groundwater

Investment: 0.1 X 50,000 + 0.2 X 37,500 + 0.24 X 40,000 =	22,100
Other fixed:	2,700
	24,800

Fixed costs per year per hectare:

Surface water: 735
Groundwater: 827

Variable costs per year:

Potato irrigation days:	15/2 X 5 = 37.5	
Sugar beet irrigation days:	15/1.5 X 2 = 20.0	
Total irrigation days/yr	57.5	
	X 18	
Total irrigation hr/yr	1,035	
Electric cost @ 1,035 X 20.25 X 0.13		2,724.64
Labor cost		
Potatoes: 5 X 15 X 35 X 1.0		2,625.00
1.8 X 37.5 X 35		2,362.50
Sugar beets: 2 X 15 X 35 X 1.0		1,050.00
1.8 X 20 X 35		1,260.00
Tractor cost		
Potatoes: 5 X 15 X 17 X 0.3		382.50
1.0 X 37.5 X 17		637.50
Sugar beets: 2 X 15 X 17 X 0.3		153.00
1.0 X 20 X 17		340.00
		11,535.14

Variable costs per nectare-millimeter/yr:

Hectare-millimeters:		
Potatoes:	5 X 15 X 25 =	1,875
Sugar beets:	2 X 15 X 35 =	1,050
		2,925

Variable cost per hectare-millimeter: 11,535.14 ÷ 2,925 = 3.94

APPENDIX B: ANALYSIS OF THE SENSITIVITY OF IRRIGATION DEMAND PER HECTARE AND CROP AREA TO SELECTED PARAMETERS

In Sections 5 and 6 of this report, approximate computations are made of effects of changes in irrigation costs and crop market conditions on the demand for irrigation. Our formal model of irrigation demand (see Section 3) characterizes only the determination of irrigation demand per hectare of crop. Total irrigation demand is the product of demand per unit crop area and total crop area. This appendix qualitatively analyzes the sensitivity of total irrigation demand for a crop to key parameters (irrigation cost and crop price) and shows the effects of changes in these parameters on total demand and per hectare demand.

B.1 Notations and Assumptions

For this purpose, let us denote the production function for a crop by

$$Q = AF(A,w)$$

where Q is total crop output, A is crop area, and F is a function which relates crop yield per unit crop area to total crop area and irrigation water usage per unit crop area, denoted by w. In addition, we assume that the yield function F possesses the following properties:

$$\frac{\partial Q}{\partial A} = AF_1 + F > 0 \qquad \frac{\partial Q}{\partial W} = AF_2 > 0$$

$$\frac{\partial F}{\partial A} = F_1 < 0 \qquad \frac{\partial^2 Q}{\partial W^2} = AF_{22} < 0$$

$$F_{11} > 0 \qquad \frac{\partial^2 Q}{\partial A \partial W} = AF_{12} + F_2 = F_2 = \frac{\partial F}{\partial w} > 0$$

$$\frac{\partial^2 Q}{\partial A^2} = AF_{11} + 2F_1 < 0$$

We have assumed that output is a concave function of inputs, that yield per unit land area declines with increasing land area (as less and less suitable land is brought into production), and that the yield function F is separable in land area and water per unit land area.

We assume that farmers select input levels to maximize farm income. The necessary conditions for this to be achieved are

$$\begin{aligned} &p(AF_1 + F) - r - cw = 0 \\ &pAF_2 - cA = 0 \end{aligned} \tag{B1}$$

where r is the rent per unit area of land, and c is the irrigation cost per unit of water.

B.2 Sensitivity of Factor Demands to Irrigation Cost

Section 6 examines what would happen to irrigation demand per hectare w, if the cost of irrigation increased markedly. Using the extended model described in this appendix, we can also examine the effect of changes in irrigation costs on crop area A and on total water demand, $W = wA$.

To do this, let us first take the total differential of the first-order conditions (B1) we obtain

$$\begin{aligned} &\mathrm{d}p(AF_1 + F) + p(AF_{11} + 2F_1)\mathrm{d}A + (pF_2 - c)\mathrm{d}w - \mathrm{d}r - w\mathrm{d}c = 0 \\ &\mathrm{d}pAF_2 + (pF_2 - c)\mathrm{d}A + pAF_{22}\mathrm{d}w - A\mathrm{d}c = 0 \end{aligned} \tag{B2}$$

Setting $\mathrm{d}p = \mathrm{d}r = 0$, and solving for $\mathrm{d}w/\mathrm{d}c$ and $\mathrm{d}A/\mathrm{d}c$, we obtain

$$\frac{\mathrm{d}w}{\mathrm{d}c} = \frac{A}{pAF_{22}} < 0$$

$$\frac{\mathrm{d}A}{\mathrm{d}c} = \frac{w}{p(AF_{11} + 2F_1)} < 0$$

We conclude that the effect of a change in the cost of irrigation per unit of water applied c is to reduce the quantity of water used per unit of land area w and to reduce the crop area A.

The change in total water usage is given by

$$\frac{\mathrm{d}}{\mathrm{d}c}(wA) = w\frac{\mathrm{d}A}{\mathrm{d}c} + A\frac{\mathrm{d}w}{\mathrm{d}c}$$

and the elasticity of total water demand e with respect to c is given by

$$e_c^T = \frac{c}{A}\,\frac{\mathrm{d}A}{\mathrm{d}c} + \frac{c}{w}\,\frac{\mathrm{d}w}{\mathrm{d}c} = e_c^A + e_c^w$$

We conclude that if irrigation cost c increases, total demand for irrigation falls on two accounts. First, the quantity of water demanded per unit of crop area w falls. Second, crop area A falls. Estimates of the effect of irrigation costs on demand that encompass only effects on irrigation demand per unit land area (as is the case with the estimates presented in Section 6) thus tend to understate the effect of cost on demand.

B.3 Sensitivity of Crop Area to Introduction of Irrigation

We have noted several times that the adoption of irrigation raises the profitability of irrigated crops. Other things being equal, this should result in an increase in crop area. To investigate, let us compare the solutions to the first-order conditions (B1) when w is constrained to be 0 (i.e., the no-irrigation case) and when it takes on the optimal value given by (B1).

Subtracting the first equation of (B1) evaluated at $w = 0$ from the first equation with w set at its optimal value, we obtain

$$\Delta = pAF_1(A,w) - pA^1F_1(A^1,0) + p[F(A,w) - F(A^1,0)] - cw = 0$$

By the concavity of F in w

$$F(A^1,0) < F(A^1,w) - F_2(A^1,w)w$$

and by separability

$$F_2(A^1,w) = F_2(A,w)$$

Substituting into the expression for Δ and making use of the second equation of (B1) to eliminate a term

$$\Delta \geqslant pAF_1(A,w) - pA^1F_1(A^1,0) + p[F(A,w) - F(A^1,w)] \leqslant 0$$

By the convexity of F in A

$$F(A,w) > F(A^1,w) + F_1(A^1,w)(A - A^1)$$

which implies

$$\Delta \geqslant pAF_1(A,w) - pA^1F_1(A^1,0) - pF_1(A^1,w)(A - A^1) = p[F_1(A,w) - F_1(A^1,0)]A \leqslant 0$$

which recalling the separability of F implies

$$A \geqslant A^1$$

Thus, we conclude that the effect of introduction of irrigation is to increase crop area.

This is an important finding. It could mean, for example, that the crop areas assumed in Strzepek's simulations are smaller than might be expected with full adoption of irrigation.

B.4 Sensitivity of Irrigation Demand to Crop Price

Section 5 examines the effect of crop price changes on irrigation demand per unit of crop area. Consideration of the total differential equations (B2) above shows what happens to both demand per unit land area and to crop area. In particular, (B2) implies that

$$\frac{dw}{dp} = AF_2/(pAF_{22}) > 0$$

$$\frac{dA}{dp} = AF_1 + F/(pAF_{11} + 2F_1) > 0$$

and

$$\frac{dW}{dp} = A\frac{dw}{dp} + w\frac{dA}{dp}$$

and

$$e_p^T = \frac{p}{w}\frac{dw}{dp} + \frac{p}{A}\frac{dA}{dp} = e_p^w + e_p^A$$

That is, irrigation demand per unit crop area, and crop area vary directly with crop price.

THE AUTHOR

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