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IRRIGATION DESIGN AND MANAGEMENT RELATED TO ECONOMICS

KEY WORDS: irrigation system design; optimizing irrigation design; irrigation cost factors; crop production function; irrigation efficiency; water resource management; irrigation.

ABSTRACT: Various factors associated with an irrigation system affect both the costs and the production levels of the irrigated crop. The link between the hydrologic and the economic systems is the production function. Based on this linkage, a conceptual method is proposed for combining various irrigation factors into a unified procedure for optimizing the design and management of irrigation systems.

IRRIGATION DESIGN AND MANAGEMENT RELATED TO ECONOMICS

by

Jack Keller[2], J. Paul Riley[3], and R. John Hanks[4]

INTRODUCTION

Irrigated agriculture is an environmental technology with its prime focus being on the management of land, water, air, and biological resources for the production of food and fiber and for the preservation of natural resources. In this sense, the modern irrigated farm is a managed eco-system, where the renewable resources are effectively conserved. In many instances, the quality of the resources even has been substantially improved by careful use and management, as, for example, certain well-managed regions in the western part of the U.S. By contrast, the unsound use of renewable land and water resources has led to disasters of the magnitude of the "dustbowl" which occurred in the United States during the early 1930's, and to the water-logging of many irrigated lands. More than ever before it is imperative that intensive efforts be applied to develop and use technology by which agricultural practices more effectively use and conserve the vast land and water resources of this country.

Although irrigation is practiced on only about one-tenth of the world's arable land, irrigated agriculture supplies as much as one-fifth of the total food and fiber. It is the mainstay of the agricultural

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economy of many semi-arid and sub-humid regions. A considerable part of the world's future food needs will be met through the efficient use of available land and water resources. As resource utilization becomes more intense, interactions, or interdependency effects between the various parts of the total system become more pronounced, and it becomes increasingly necessary to consider not only the specific components of this system, but to include also the economic, political, and sociological dimensions.

This paper will consider the problems of designing and managing an on-farm irrigation system within the constraints imposed by the physical and economic processes. There is an increasing need to formulate management decisions on the basis of a fundamental understanding of these processes as they interact in the system as a whole. It is realized that there are other sociological constraints, such as local customs, but the paper emphasizes only the influence of economics on the design and management of irrigation systems.

The importance of the vegetative production function as the link between the hydrologic and the economic systems has long been recognized (Packer, et al, 1969)[1]. However, much work is still needed to well define the influence of various irrigation practices upon both costs and crop production. An attempt is made here to identify and to discuss, often in speculative terms, some of those factors associated with irrigation which influence both the cost and the quantity of vegetative production.

IRRIGATION FACTORS WHICH INFLUENCE COST

Irrigation costs originate from two primary sources, namely; (1) those associated with the system hardware (fixed costs); and (2) those which are related to the amount and rate of water application (variable costs). Various individual cost factors in each of these two categories are illustrated for sprinkler irrigation systems by Figure 1. Similar relationships hold for other methods of irrigation. The ordinate of each of the trend charts shown by this figure refers to irrigation costs, while in each case the abscissa represents the range of a particular irrigation factor which affects the costs. Some of the relationships suggested by Figure 1 are reported in quantified terms by Liang and Wu,1970[2] It might be noted that the six functions illustrated by this figure are essentially independent of one another.

System costs

Figure 1(a) illustrates that for a constant average water application rate, $I_{\bar{x}}$, costs decrease with a decreasing uniformity of

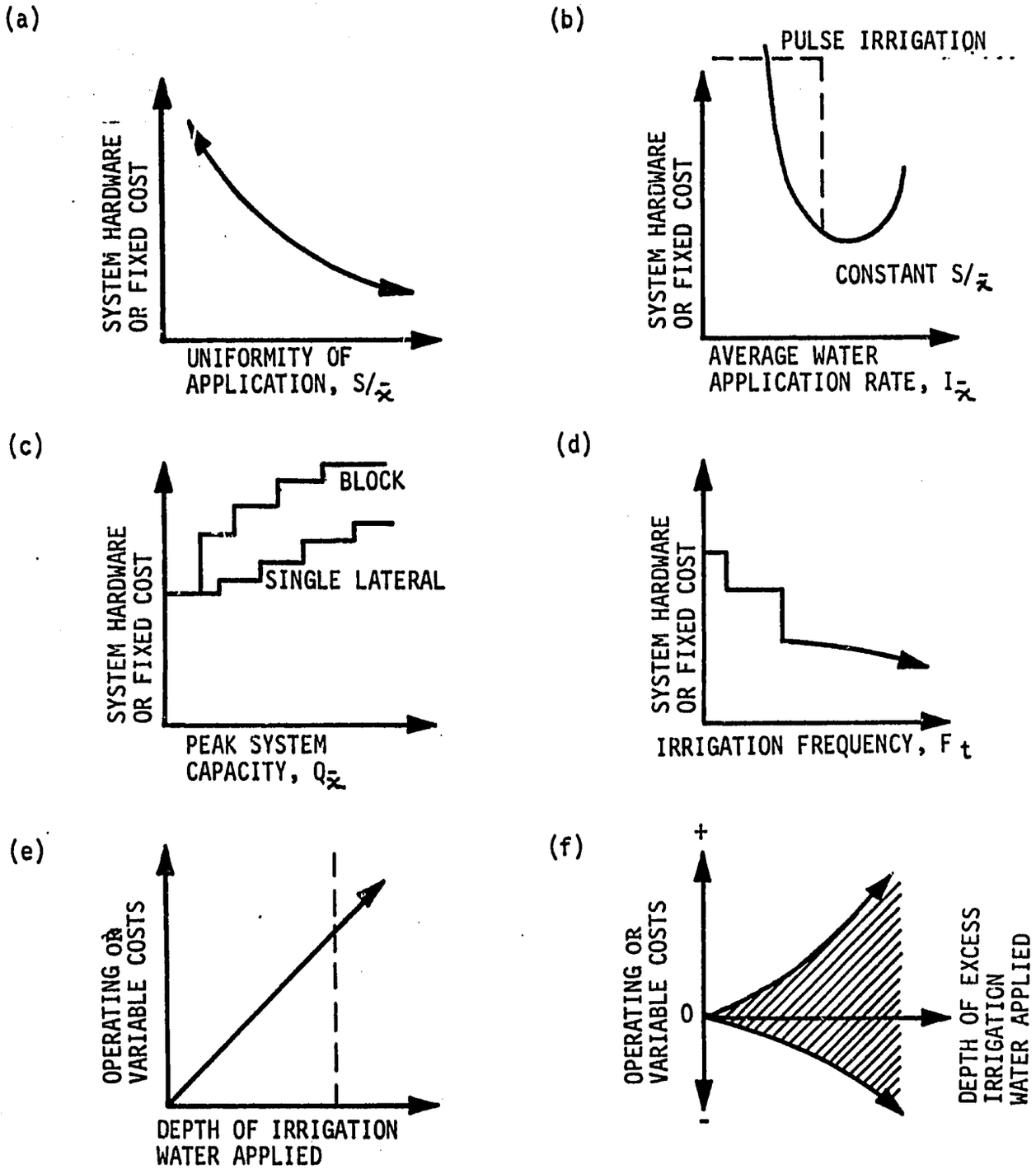

Figure 1 - Cost factors associated with irrigation.

application as expressed by the parameter $S/\bar{x}$. In this notation S represents the standard deviation and $\bar{x}$ the mean.

Figure 1(b) illustrates that for a given uniformity of application, costs decrease with increasing application rates. This decrease is associated primarily with the shortened operating time as application rates increase, and thus reflects reduced operating costs. A point is reached, however, when costs associated with system capacities (fixed costs) begin to offset the lowered operating costs, and the cost curve is reversed.

The effect of system capacity, $Q_{\bar{x}}$, on costs is illustrated for both a single lateral and a block of laterals by Figure 1(c). These costs, which are usually associated with pumping plant and mainline costs, are incremental in nature and are thus shown by a form of a step function. Figure 1(d) suggests that as the interval between irrigations, F_t, is increased, costs, as reflected by labor and/or automation costs, decrease. The zero point on the abscissa of this chart represents, of course, continuous irrigation.

Water costs

Figure 1(e) illustrates the relationship between depth of water applied during any given time increment and costs. The costs in this case are, of course, operating costs and include power and water costs, and perhaps some additional costs for fertilizer as the depth of water applied increases. The maximum depth obtainable is constrained by limitations in the supply of water and/or system capacity.

Figure 1(f) suggests that the depth of excess water applied, $d_{\bar{x}}$, may provide either a cost or a benefit to the system. On the one hand, excess water can produce drainage and polution problems which would be associated with costs. On the other hand, the deep percolating waters could have a beneficial effect on land reclamation needs and also contribute to a recharge of underground aquifers. Both of these effects would be beneficial in nature.

IRRIGATION FACTORS WHICH INFLUENCE VEGETATIVE PRODUCTION

Plant growth as influenced by the irrigation of a specific crop in a given physical and biological environment is a function of (1) the energy required to extract water from the soil, E; and (2) the level of soil aeration, A, throughout the growing season. These relationships are shown qualitatively by Figures 2(a) and 2(b) respectively, in which the ordinate P represents the yield or productivity of the crop in terms of vegetative growth. The two curves, X and Y, represent relationships for two different crop varieties, with curve X

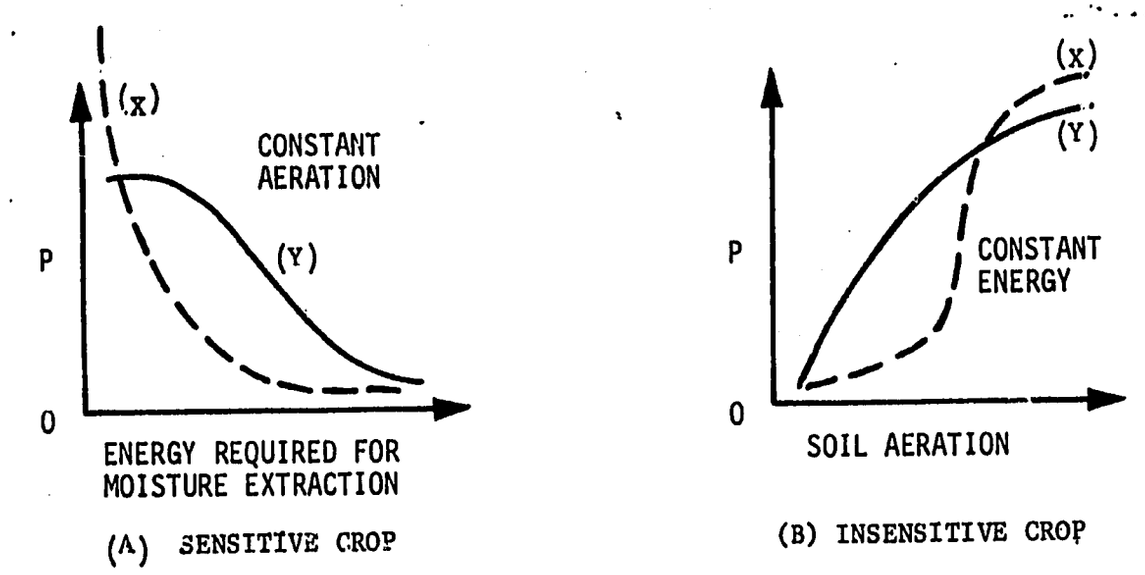

Figure 2 - Vegetive production as a function of soil moisture tension and aeration.

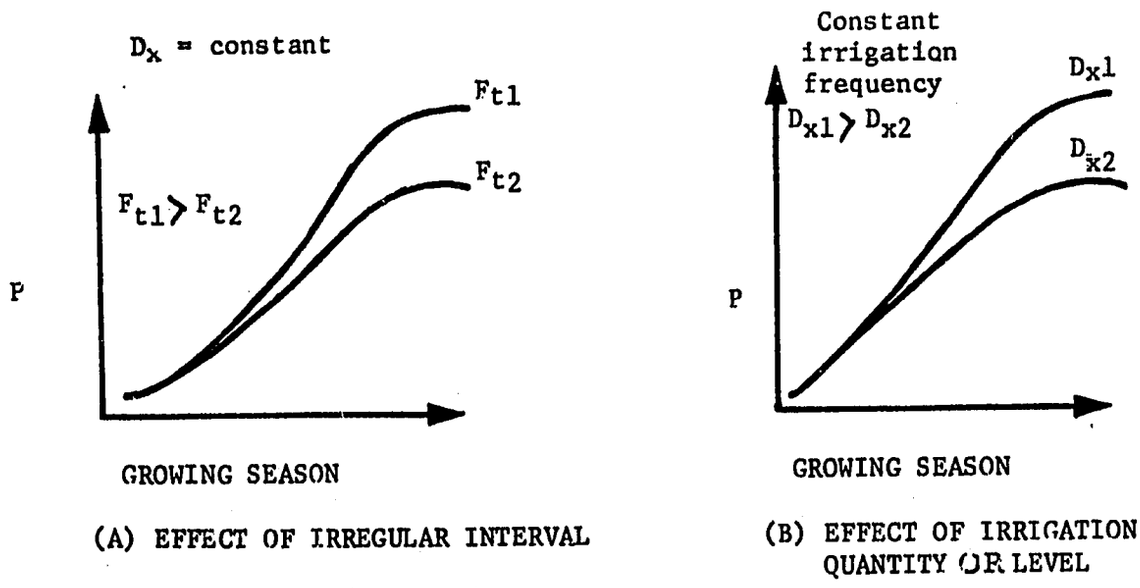

Figure 3 - Vegetive production as a function of irrigation interval and quantity.

intending to represent a crop having greater sensitivity to soil moisture and aeration than crop Y. The main irrigation factors affecting soil moisture and soil aeration at a given location are the depth of water applied, D_x , the frequency of irrigation, F_t, and the application rate, I_x. In addition, the two parameters E and A are also influenced by the total quantity of irrigation water applied, W, during the growing season.

Figure 3(a) illustrates the effect of irrigation frequency on crop productivity. It is assumed that the soil moisture holding capacity of the root zone is filled by each irrigation. Figure 3(b) demonstrates the influence upon yield of the two different irrigation quantities (or levels of irrigation) applied at the same frequency, F_t. This curve typifies the results reported by many researchers (for example, Howell, 1964)[3] who have studied the influence of available soil moisture on crop yields. If it is assumed that D_{x2} does not fill the soil moisture holding capacity within the root zone and that D_{x1} is greater than D_{x2}, yield trends will generally be as shown by this figure.

The relationship between irrigation water applied and crop production is generally regarded as being the link between the hydrologic or irrigation system, and the crop production or economic system. Thus, this relationship is vital when attempts are made to base irrigation design and management on sound economic principals.

Typical relationships for vegetative production as a function of irrigation water applied are shown by Figure 4. The development and use of curves of this nature are discussed by Yaron, 1971.[4] The relationship which is represented by the straight line beginning at the origin considers only water that is used consumptively by the crop. The other curves on this figure are intended to represent production functions at various irrigation frequencies, with F_1 being a high frequency (for example, an irrigation interval of one day) and F_{16}, a low irrigation frequency. At a given production level of, for example, 25 units, the water required to meet consumptive use needs is approximately 33 units. However, at an irrigation frequency of F_1, the water requirements are more than 67 units, which indicates that the water losses at this frequency of application and production level are in excess of 33 units.

Figure 4 also illustrates the effects of the interdependency of frequency of irrigation and total water applied during a season. Thus, at high frequencies more water is applied and maximum production is higher than in the case for low irrigation frequencies. For example, at a frequency of F_1, approximately 130 units of water are applied for a maximum production level of 75 units, while at a frequency of F_{16} about 60 units of water are needed to produce a maximum of 45 units.

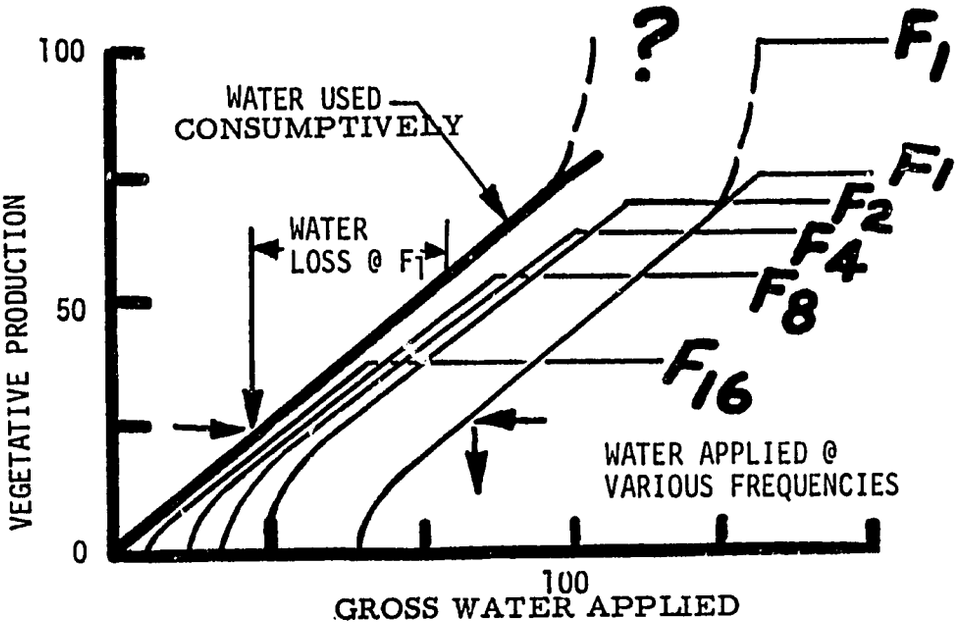

Figure 4 - Vegetive production as a function of water applied and sprinkler irrigation frequency for a given crop, soil, and climate system, and where soil aeration is not limiting.

The vegetative production curves illustrated by Figure 4 are based on the assumption that the salinity of the soil water solution (which is not considered by this paper) and duration of the irrigation water application are not limiting factors to production. For medium and heavy textured soils, aeration might be limiting, especially at the higher irrigation frequencies. The possibility of achieving the high rise in production under ultra-high frequencies of F_1 or more is subject to question at this time and is being studied. It is speculated that this high rise might be attainable in the field of low soil moisture tensions and good soil aeration are simultaneously attained. Pulse irrigation, for example, applies water at ultra-high frequencies, and might be able to achieve these conditions. To eliminate aeration problems under conditions of low soil moisture tension requires either very low application rates or application as a series of pulses at very high frequencies. When low frequency irrigation is employed, the lack of aeration during irrigation occurs only for a relatively short period of the total growth time.

Figure 5 illustrates the value of crop production under conditions where soil aeration is limiting for a crop which is sensitive to both aeration and soil moisture levels for irrigation frequencies of 0.1, 1.0, and 4 days. The solid lines represent the potential production under the various frequencies, while the dotted lines represent the actual production. Thus, in this case the differences between the dotted and solid lines represent the degree to which aeration affects production, while the difference between the solid lines represent the degree to which soil moisture affects production. Musick and Dusek, 1971[5], in a study of the response of grain sorghum to number, timing, and size of irrigations, report results which confirm the form of the relationships proposed by Figure 5.

As illustrated by Figure 6, plant moisture requirements vary throughout the growing season. Thus, a farm irrigation system might not be able to meet peak crop requirements at certain periods during the growing season. With adequate moisture storage in the root zone vegetative growth might not be adversely affected for some time after the crop requirements have increased beyond the capability of the system to meet those requirements. It is speculated that the problem of predicting the effect of inadequate system capacity on vegetive production might be approached by applying the production curves of Figures 5 and 6 on an incremental basis. Thus, the growing season is broken into parts, with the final or total production being a function of the summation of the individual quantities of water applied during the component periods. The production function which is used in this analysis must include the effects of evaporative losses associated with the method and frequency of application. This approach is possible only for the case of a linear production curve because errors would be introduced by applying the technique to non-linear curves,

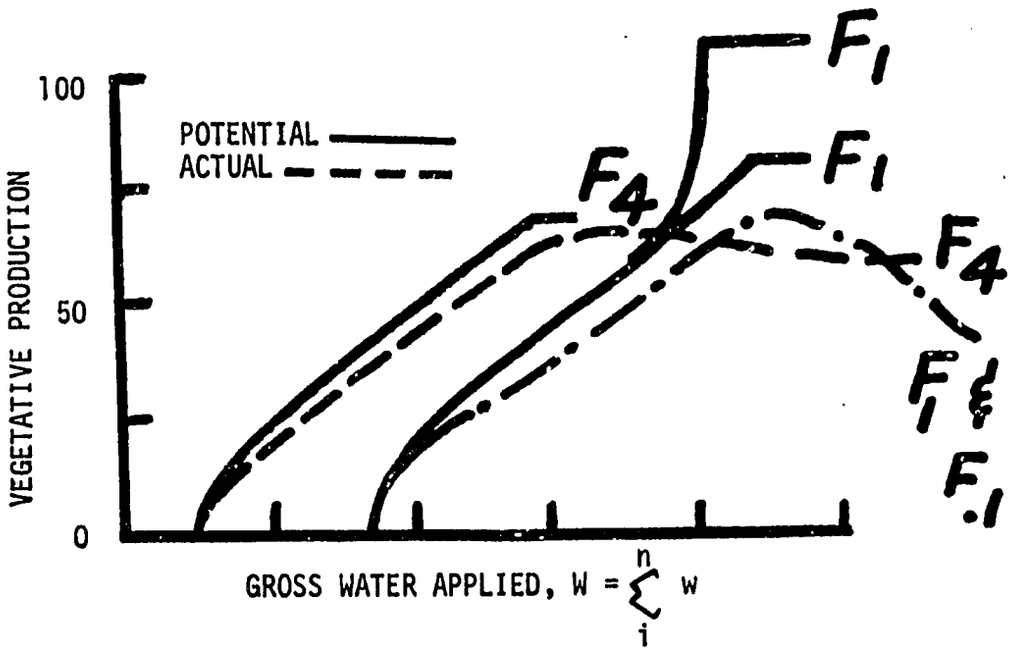

Figure 5 - Potential and actual vegetative production as a function of water applied and where soil aeration is a limiting factor.

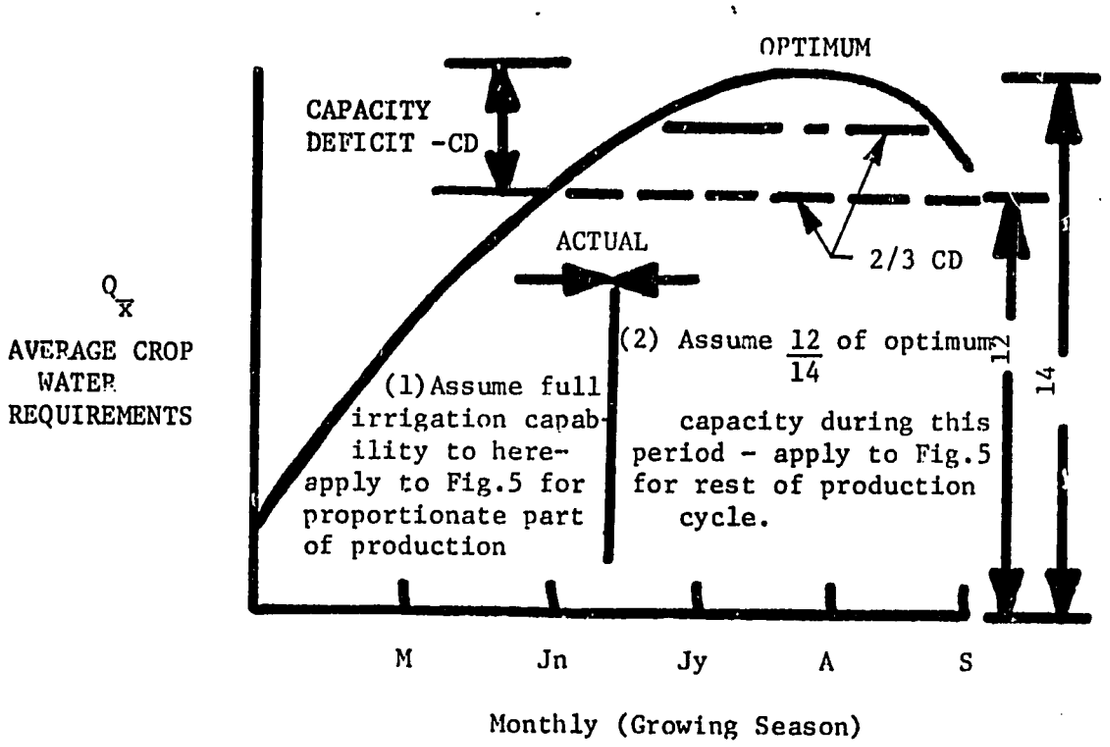

Figure 6 - Typical irrigation system capacity requirements as a function of time during the growing season.

as, for example, the high levels of production speculated at a frequency of 0.1 days shown by Figure 5.

The problem of applying a given water supply in the most economic manner is even more complicated. From Figure 4 it would appear that for a given land area the maximum production per unit of water would be obtained by low frequency irrigations. However, if ultra-high frequency (UHF) irrigation would produce the results as speculated for F.1 (Figure 4), the highest production per unit of water might be achieved by irrigating only a portion of the available land area at a frequency of 0.1 days. It is emphasized, however, that maximizing production does not necessarily maximize profit because production costs are closely associated with the area of land under cultivation and irrigation. For example, with reference again to Figure 4, if it is assumed that a productivity level of 50 is the "breakeven" point, a frequency of F_{16} would produce a loss. As in all economic systems, the maximum profit is achieved by producing at the point where incremental benefits are equal to incremental costs.

OPTIMIZING IRRIGATION SYSTEM DESIGN DECISIONS

Optimization of irrigation system design decisions is a complex task. Fortunately, as indicated when referring to Figure 1, the irrigation cost functions are essentially independent, and because they are mechanical in nature, they can be analyzed in a relatively simple manner. The crop production functions provide a more difficult problem because for many crops these functions are not yet well established. However, it is possible to estimate vegetive production functions in accordance with the following procedure.

1. Assume that the starting point is the origin of the plot.

2. Estimate the peak production value by adding 10 to 20 percent to the highest known yields in a similar crop-soil-climate situation.

3. Estimate the quantity of irrigation water required by adjusting the potential evapotranspiration by an appropriate integrated crop coverage factor. It might be noted that this procedure does not take into account the possibility of a sharp rise in production under conditions of ultra high frequency irrigation.

4. Offset distances for curves of various irrigation frequencies are estimated by first establishing a potential production curve and then assuming that irrigation at a frequency of one day, F_1, would require about

one-third more water than that indicated for the potential curve. All remaining curves are positioned in accordance with estimated losses. For example, losses for the F_2 curve are assumed to be half those of the F_1 curve.

The upper limits of the curves are estimated by assuming that maximum yields are obtained under the high frequency irrigation portions, such as F_1, and that low frequency irrigations, such as F_{16}, produce approximately half this yield. These points are fixed from available field data. Maximum production levels for intermediate frequencies are assumed to be proportioned to the irrigation frequency. For example, the maximum production at a frequency of F_8 is assumed to fall mid-way between peak levels for F_1 and F_{16}.

Hanks and Keller in an unpublished study (1972) suggested that the potential production function for vegetation growth can be estimated from the following relationship:

$$P = \left[\frac{nm}{E_w} \quad (W - E_e) \right] v$$

in which

P - gross value of vegetative production in dollars

n - number of growing days during the season

m - a factor for a given crop and general soil-climate system expressed as kilograms per hectare-day

E_w - seasonal evaporation losses from a large water body in mm.

W - water applied to the crops during the growing season in mm.

E_e - seasonal evaporation losses from the irrigated area in mm. (does not include transpiration losses).

v - crop value expressed as dollars per kilogram

Design optimization from an economic viewpoint is the process of combining the production and cost functions under various design alternatives and of identifying that system for which the net returns (benefits less costs) are the greatest. Thus, the cost factors expressed in Figure 1 must be considered. Benefits are, of course, based

on the economic value of vegetative yields or production.

Figure 7 demonstrates a procedure for considering various factors which influence production in an estimate of gross production income. The potential production function in the upper portion of this figure was established from the preceding equation by assuming the crop to be alfalfa. Values of the variables in the equation were assumed as follows:

$$m = 63 \text{ kg./hectare-day}$$

$$n = 240 \text{ days}$$

$$\frac{W-E_e}{E_w} = 0.9$$

An irrigation frequency of F_4 was assumed and the production function at this frequency was established in accordance with the procedure described in steps 1 to 4 previously outlined and by considering aeration effects (Figure 5).

The lower part of Figure 7 provides a procedure for taking into account the uniformity of water distribution. For example, in this case a uniformity coefficient, $S/\bar{x}$, of 0.3 is assumed. Gross production is then computed on an incremental area basis in accordance with the quantity of water applied, including precipitation, to each incremental area. In this case, a precipitation quantity of 200 mm is assumed to occur during the growing season. Thus, the example shown by Figure 7 indicates that the average gross water available over the irrigated area during the season is 1200 mm, or an irrigation quantity of 1000 mm. The average gross production income is estimated at $439 per hectare.

As previously suggested, net income is computed by subtracting cost amounts from the gross income estimate. For the same crop and irrigated area, additional values of the net income are estimated by assuming other values for the irrigation frequency, the quantity of water applied during the season, and the uniformity coefficient. System and water costs change, of course, for each estimate. The system design which provides the maximum computed net return thus is identified.

SUMMARY AND CONCLUSIONS

Because of the importance of irrigation to the production of the world's supply of food and fiber, the design and management of irrigation systems need to be based on sound economic principles. Various factors associated with an irrigation system affect both the

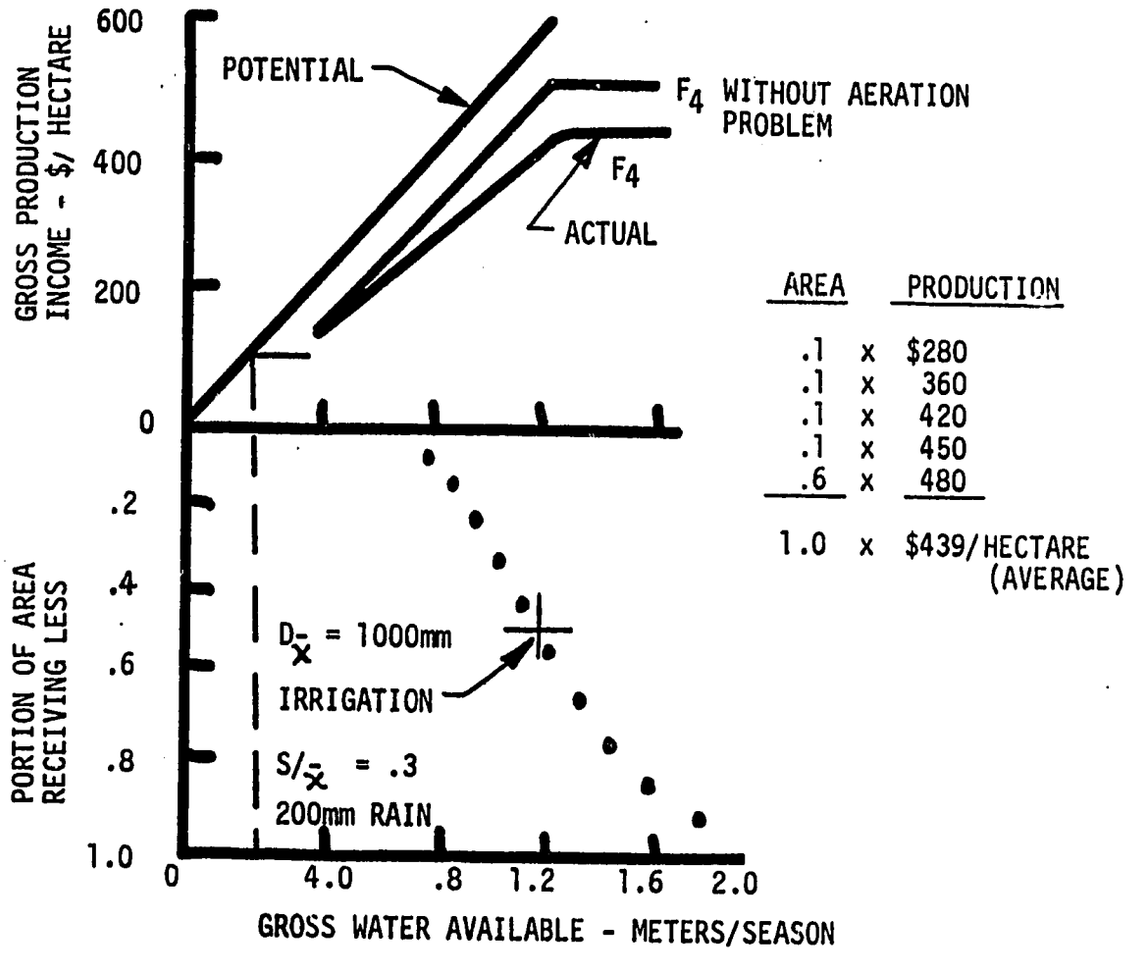

Figure 7 - Gross vegetative production as a function of various irrigation factors.

fixed and the variable costs involved. Further, many of these same factors also influence crop production levels.

The paper considers several of these irrigation factors, and attempts to develop a logical method for combining them into a unified procedure for optimizing the design and management of irrigation systems. Because of a lack of basic information, some of the relationships are discussed in an admittedly speculative manner. However, a design procedure is proposed which has been successfully applied in certain practical situations, and which hopefully merits further development and testing.

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