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THE PROBLEM OF UNDER-IRRIGATION IN WEST PAKISTAN: RESEARCH STUDIES AND NEEDS

by Garth N. Jones
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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U.S. DEPARTMENT OF AGRICULTURE

JUNE 1971

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TECHNICAL REPORT NO. 8

THE PROBLEM OF UNDER-IRRIGATION IN WEST PAKISTAN: RESEARCH STUDIES AND NEEDS

Water Management Technical Report No. 8

by

Garth N. Jones

and

Raymond L. Anderson

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THE PROBLEM OF UNDER-IRRIGATION IN WEST PAKISTAN:

RESEARCH STUDIES AND NEEDS

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by

Garth N. Jones and Raymond L. Anderson

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THE PROBLEM OF UNDER-IRRIGATION IN WEST PAKISTAN: RESEARCH STUDIES AND NEEDS

by

Garth N. Jones and Raymond L. Anderson*

I. Introduction

In the mid-1960's, irrigation agriculture in West Pakistan was extensively studied, largely with World Bank assistance. A large number of field studies and reports were collaboratively prepared by reputable international engineering consulting firms and counterpart Pakistani Government agencies. Tremendous amounts of raw data, herebefore unavailable, were collected. Several analytical studies, largely based on this recent data, have been published.[1]

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[1]Several exhaustive bibliographies have been prepared which reference most of these studies. See Garth N. Jones and Shaukat Ali, A Comprehensive Bibliography, Pakistan Government and Administration (Lahore: Public Administration Research Centre, 1969); Garth N. Jones, A Comprehensive Bibliography, Pakistan Government and Administration, volume two (Peshawar: Academy for Rural Development, 1971), and Garth N. Jones and others, Water Management for Agricultural Production in West Pakistan: Special Reference to the Institutional and Human Factors (Peshawar: Academy for Rural Development), forthcoming.

The principal analytical study based on the field reports is by a study group headed by Pieter Lieftinck, A. Robert Sadove, and Thomas C. Creyke, Water and Power Resources, A Study in Sector Planning, three volumes (Baltimore: Published for the World Bank as Administrator of the Indus Basin Development Fund by The Johns Hopkins University Press, 1969). Much of the data for this work is drawn from the 23 volumes prepared by Sir Alexander Gibb and Partners, International Land Development Consultants, and Hunting Technical Services (London and Arnhem), Programme for the Development of Irrigation and Agriculture in West Pakistan (Washington: International Bank for Reconstruction and Development, 1966).

Few irrigation systems, and certainly in the lesser developed world none of the size and complexity of the Pakistan system, have been so thoroughly mapped out. These recent studies provide unusual insight into this nation's agricultural problems, and clearly demarcate areas demanding further research and investigation.

These studies, along with earlier ones, characterize West Pakistan's agriculture as being caught in a vicious circle of low water supply and a low level of agricultural production, and point out that to a considerable extent these two are closely related. The fundamental task is to redesign the irrigation system to break this vicious circle. Increasing reliable supplies of water to the farmer in relation to crop and soil maintenance needs is one of the means suggested for accomplishing this.

An increase in the supply of irrigation water is not sufficient in itself to break this vicious circle. In the canal irrigated areas, under-irrigation is the common practice and is the consequence of the original design of the irrigation system. Large-scale irrigation was introduced over one hundred years ago in British India as a means of providing supplemental water to crops in times of drought, and thus eliminate the scourage of famine. The practice of distributing water over as many acres as possible in order to assure a harvest began with the first irrigation projects. This practice initiated the rapid concentration of salts in the irrigated land, destroying millions of once-productive agricultural land and now threatening millions of additional acres.[2] Although the extent of under-irrigation varies

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[2]See K. N. Raj, "On Agricultural Growth in Developing Countries," World Agriculture, 20(January 1971), pp. 15-18.

considerably between and within canal commands, an average of 20 percent under-irrigation has been estimated throughout the Indus Basin.[3]

Field investigations reveal that increased water supplies and applications of other farm inputs yield the best results when used together. These complementarities result when additional water supplies are used (1) to expand the crop acreage by increased cropping intensity[4] or (2) to increase the water application to the existing acreage.[5]

The typical response of the Pakistani farmer to increased water supplies, derived from the canals, tubewells, or Persian Wheels, has been to (1) extend the acreage he crops each season by reducing his fallow land rather than (2) increase the water application rate or "delta"[6] applied to the acreage which he was already cultivating.[7] Agronomic studies reveal that as long as traditional agricultural practices are followed, production can be more greatly increased in the short run, before prolonged underwatering leads to salinization

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[3]See, particularly, Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Annexure 14, Chapters 4 and 6.

[4]Cropping the year round is possible in most of the Indus Basin. The year is divided into two cropping seasons--kharif (summer) and rabi (winter). Cropping intensity is the percentage of cultivable land cropped in both season, which could theoretically reach 200 percent.

[5]Lieftinck and others, Water and Power Resources of West Pakistan, 1966, Vol. I, p. 23.

[6]"Delta" is defined as the amount of irrigation water required to obtain optimum crop yields in the Indus Basin. Included is the amount of water needed to control soil salinity.

[7]See Lieftinck, op. cit., p. 23 et seq.

of the top soil, by bringing additional land under cultivation rather than by concentrating the water use on smaller areas. The longer range detrimental consequences of building up the salinity in the soil is obvious. To sustain agricultural production over the years requires full "delta" watering to control salt build-up and application of chemical supplements to maintain soil fertility.

Although working with rather gross data, the World Bank studies reveal that with the typically scarce and unreliable water supplies of the Indus Basin, the farmers, within limitations, can substantially increase production by using available water on a larger area than would be consistent with full "delta" watering of crops. As shown in Graph 1, yields decline as the degree of under-irrigation increases, but the rate of yield decline is disproportionately smaller than the rate of water level applications in the higher ranges. For wheat, it was estimated that twenty percent under-irrigation results in a yield reduction of only 8 percent--subject, of course, to the timely application of water.[8]

The same relationship, as shown in Figure 1, generally holds true for other crops. The field studies, however, exclude cotton because of its extreme sensitivity to water stress.[9] These studies also note that the relationship will vary somewhat depending on the type and variety of crop and the use of other inputs such as fertilizer. This matter needs special study by the agronomists to accurately

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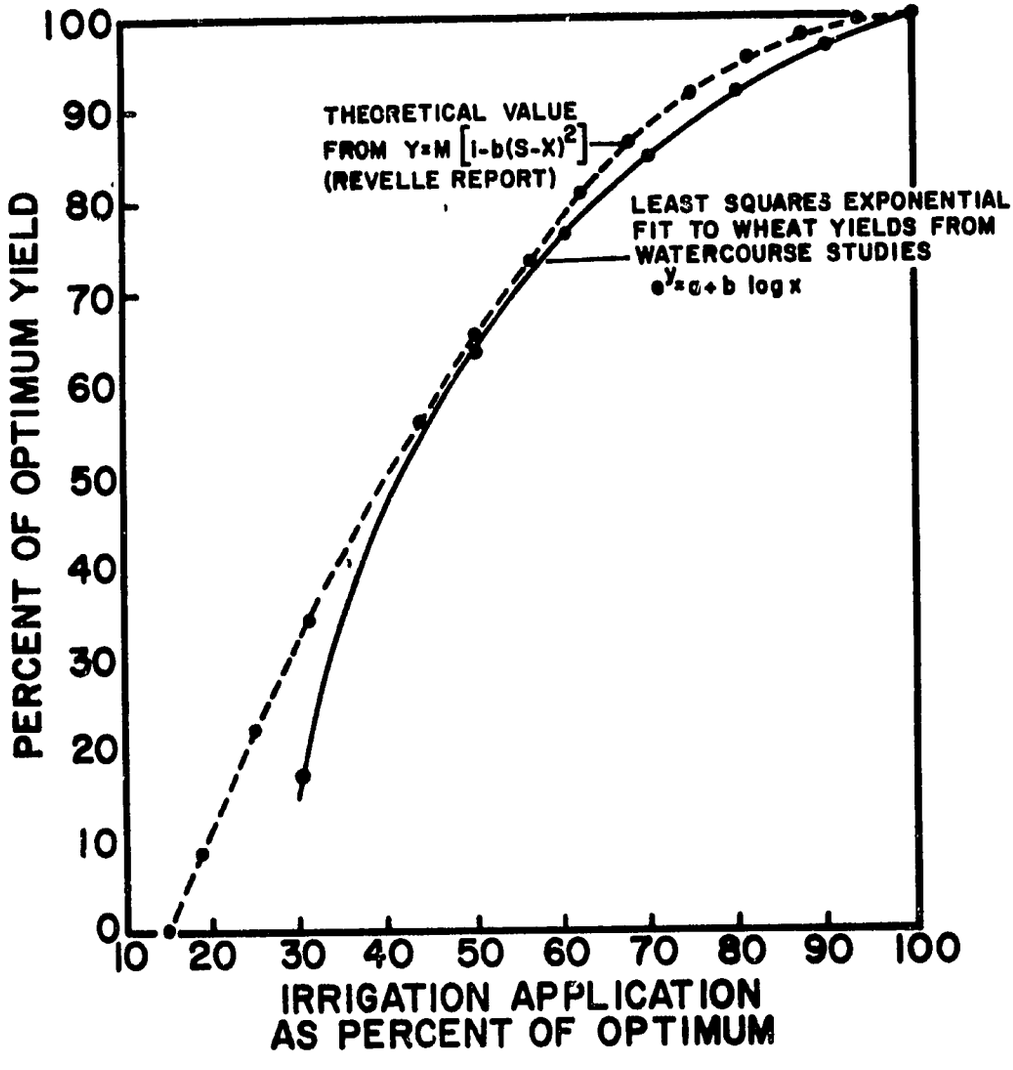
[8]See Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Annexure 9, pp. 96-97.

[9]Lieftinck and others, op. cit., Vol. II, p. 38.

Figure 1.--Relationship between Wheat Yield and the Percent of Optimum Irrigation Water Application, West Pakistan. (Pieter Lieftinck and others, Water and Power Resources of West Pakistan, A Study in Sector Planning, Baltimore: Johns Hopkins University Press, 1969, Vol. II, p. 37.)



determine the relationship between under-watering and yield reduction, but substantial evidence indicates that the farmer discovers this by trial and error.[10]

The basic formula used in making this analysis is that application of a given quantity of water will result in a given quantity of crop product (yield), or that crop quantity (product) is a function of water quantity.

Twenty watercourses located in 10 regions in the upper Indus Basin were investigated for a period of at least one year to measure the extent of over- and under-irrigation.[11] These analyses were made largely within the terms of gross factors. Water consumption requirements or standards needed to achieve optimum yield for each major crop grown in the Upper Indus Basin were developed.[12] Data for a 1-year period were obtained on each of the watercourses for the following factors: (1) the total available irrigation water supplies, (2) planted crop acreage and the cropping intensity, and (3) crop yields.

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[10] Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Annexure 14, p. 59.

[11] This comprises the irrigator's channel, taking its supply from a Government canal, from which farmer's fields are irrigated directly. The typical watercourse is supplied water at only one canal outlet point which has a continuous flow ranging at each outlet from 1 to 4 cubic feet per second. The area usually falls in the neighborhood of 250-400 acres, which are cultivated by 10 to 35 farmers.

[12] These standards were based largely on the following studies by A. G. Asghar and Nur-ud-Din Ahmad, "Irrigation Requirements and Consumptive Use of Water by Crops in West Pakistan - 1," Pakistan Journal of Science, 14(July 1962), pp. 166-80 and "Consumptive Use of Water by Crops," Pakistan Journal of Scientific Research, 14(October 1962), pp. 157-61.

The data assembled within this concept are impressive, and certainly bear out the premise that the farmer pursues a rational course of action in the short run in maximizing his output. In areas where water is in short supply and amounts are unreliable but land is plentiful, as is generally true throughout the Indus Basin, the practice of under-irrigation has high economic "pay-off." Up to a certain point, it pays to under-irrigate, as production from the extra acreage planted more than exceeds the loss in yield which occurs because of under-watering.

The shortage of water supplies for supporting improved agriculture may be the most critical aspect of irrigation development in West Pakistan. The unreliability of water supplies at critical growth periods during each cropping season imposes a major constraint on the farmer in modernizing his agricultural practices. Watercourse studies show a close correlation between the unreliability of water supplies and the farmer's acceptance of other inputs and innovations.[13]

More attention must be given to redesigning Pakistan's irrigation system so that it provides sufficient amounts of water to the farmers when needed. Equally important is research concerning the relationship of water application and crop yield (crop consumptive water use).

The World Bank studies stress that the timely distribution and regularity of application are just as important as the amount of water used. The severest constraint on the farmers is the irregularity of water supplies. This accounts in part for the farmer's willingness

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[13] See especially Lieftinck and others, op. cit., Vol. I, pp. 24-25.

to pay considerably more for tubewell water than canal water. In other words, he is willing to pay substantially more because tubewell supplies are more reliable. The World Bank studies revealed that nearly all of the farmers in the upper Indus Basin felt that canal water supplies were insufficient, and preferred to see the supplies doubled per cultivated acre.[14]

[14] See Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Annexure 13, particularly p. 95.

II. Crop Response to Water Deficiencies: Research Studies

The data amassed by the World Bank studies were impressive as to the behavior of Pakistan's irrigation system, which irrefutably constitutes the major factor for the widespread practice of under-irrigation throughout the Indus Basin. However, they contribute little toward a solution to the problem. Under-irrigation cannot be rectified simply by increasing the supplies of water to the farmer on a more regular basis--a fundamental premise upon which much of the World Bank's sector planning on agriculture growth in West Pakistan is based.[15]

Pakistan's irrigation system is presently not designed to provide water to the farmer on a regular basis. Water availability is highly erratic, and the farmer can operate only within wide projections of water availability and amounts. Yet the proper timing and regularity of application is at least as important as the total amount of water delivered to the farmer. While nearly every irrigation system in the world is subject to fluctuations in providing irrigation water, some provide wider extremes than others. Few have as wide a range as Pakistan's. More attention must be directed toward correcting this situation. However, this aspect of the problem falls largely outside the scope of this essay.

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[15] See Lieftinck and others, op. cit., Vol. II, particularly annex 2.

Factors Influencing Plant Water Stress

Lacking in Pakistan's research on irrigation is the response of crops to particular irrigation sequences or regimes.[16] Whenever irrigations are irregular or erratic, plant-soil moisture stress is likely to develop. Crop response to moisture stress is crucially important to the farmer who is operating with scarce water supplies. The difficulty in not being able to irrigate at the proper time is closely related to the water rights of the canal serving the farm (whether a perennial or a non-perennial supplier), water availability, and the particular distribution rules and/or systems used in the watercourses (warabandi). The type of crop, stage of growth, plant coverage of the soil surface, root depth of the plants, and effect of internal plant water stress on yields--all are factors affecting the length of time in crop development before declining soil moisture becomes critical. The soil and its structure, profile characteristics, infiltration and internal drainage rates, and water retention capacities are also important in determining irrigation sequences. Climatic factors, such as solar radiation, humidity, and advection from winds, affect rates of evapotranspiration which in turn affects irrigation requirements.

Irrigation should take place before soil moisture becomes so depleted that the plants come under stress conditions severe enough to reduce yields or quality of crops harvested. Experiments have been conducted in Pakistan to determine the permissible water deficit,

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[16]This section builds heavily upon the research and writings of Professors Raymond L. Anderson and Arthur Maass. See particularly their recent publication, A Simulation of Irrigation Systems: The Effect of Water Supply and Operating Rules on Production and Income on Irrigated Farms, Technical Bulletin No. 1431 (Washington: Economic Research Service, Department of Agriculture in cooperation with the John Fitzgerald Kennedy School of Government, Harvard University, 1971).

in the sense of not adversely affecting yield and quality of harvestable product.[17] Virtually no studies have been made on the effect of limited irrigation water on crop yields, beyond the gross computations already noted in the World Bank surveys.

Need for Irrigation Schedules. Irrigation schedules need to be developed for the major regions in the Indus Basin to give normal crop yields with relatively efficient water use.[18] These schedules should reflect the irrigations a prudent farmer would apply on a crop under normal weather conditions. If a crop requirement has been established as 6 inches for a 2-week period, the farmer might apply 3 inches of water each week instead. For some crops a single 6-inch application may be just as effective as two 3-inch applications. Crops such as potatoes may need to be irrigated weekly in order to avoid moisture stress. A crop's need for water is reflected in both frequency and quantity requirements.

Experiments have been held in the United States to determine permissible water deficits in relation to the yield and quality of

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[17] See the following, for illustration: Nazir Ahmad, "Water Conservation Studies for West Pakistan," Reprinted from Symposium, Role of Engineering in The Developing Economy in Pakistan, Lahore: West Pakistan Engineering Congress, 9(October 1966), pp. 119-40; Nazir Ahmad and Mohammad Akram, "An Estimate of Water Consumption, By Sugar Cane and Wheat Crops under High Water-Table Condition and Its Effect on Their Yield," Reprinted from "Engineering News," Quarterly Journal of the West Pakistan Engineering Congress (Lahore), 9(September-December 1966), pp. 32-53; Howard N. Watenpaugh and Muhammad Hassain, "Crop and Irrigation Guide, Pakistan Punjab Area," Karachi: Agency for International Development, 1966 (processed), and two studies by Asghar and Ahmad, "Consumptive Use of Water by Crops," 1962 and "Irrigation Requirements and Consumptive Use of Water by Crops in West Pakistan," 1962.

[18] Along this line of thinking, see particularly Watenpaugh and Hussain, ibid.

harvestable product. Common criteria allow depletion of various fractions of available soil moisture (water) in crop-root depth prior to irrigation. Water depletion levels are frequently set at 25 percent, 50 percent, or 75 percent of available soil water. In selecting the level of soil water depletion to be permitted prior to irrigating, consideration must be given to the effects of other soil factors, plant root and shoot characteristics, climatic conditions, and management decisions involving cultural and harvesting operations. The expanding root system of annual crops complicates the problem. Thus, for some crops and some stages of development, 25 percent of available soil moisture is all that should be depleted before irrigation. For some other crops and stages of development 75 percent of the soil moisture can be depleted before irrigation is necessary.

Plant growth is directly related to the water balance in plant tissues. As water deficits develop, physiological processes are disturbed, and growth and yield are subsequently reduced. The relative rates of water absorption and loss by plants determine their internal water balance, which represents the plant's interaction with its environment. The farmer tries to keep this water balance in a favorable condition in order to obtain the optimum yield from the crop.

Plants normally do not exhibit visible signs of water stress nor can visible growth retardation be detected until most crops are damaged with the result that subsequent irrigations can seldom overcome the loss in yield. Plant wilting is the most obvious sign of plant water stress, but the growth of most plants is retarded before visible

wilting occurs. Nevertheless, wilting is the principal indicator the farmer uses in determining whether or not it is time to irrigate.

Effect of Limited Irrigation Water Supply on Crop Yields

Whenever the water supply is insufficient for all crop needs during a given period, a decision has to be made on the allocation of the water. In economic terms, the ideal practice is to distribute the water in such a manner that the marginal value product (M.V.P.) from the use of the last unit of water is the same for all crops.

This is the traditional way of allocating limited labor and capital inputs in a production process. This rule is extremely difficult to apply when dealing with limited supplies of water in the midst of an irrigation season. First, decisions on the use of a limited water supply may have to be made during several time periods of a season. Irrigation is not a once-a-production-period decision. Multiple time-period decisions impinge upon one another. The marginal value of an acre-inch of water has different values for a crop during its various periods of development, and if the crop cannot be brought to successful completion because of water shortages, all previous decisions will have been invalid.

Second, if a crop is skipped in one irrigation period, it will not have the same water requirement during the subsequent period that it would have had if it had been previously watered. It will have the normal requirement plus some additional requirement because of continued extraction of soil moisture by evapotranspiration during the intervening period. The aim in irrigating is to bring available soil moisture in the root zone back to field capacity whenever it

falls to a certain level. If soil moisture is not replaced, the plants continue to extract moisture as best they can from the soil down to their wilting point. A number of studies indi ate that as soil moisture decreases to the lower half of the range of available soil moisture, growth and yield of crops are decreased before the permanent wilting point is reached.[19] The emphasis here is on returning the soil moisture to field capacity rather than to 80 percent or some other level. This is necessary because of the nature of the soil. It is impossible to wet a given volume of soil to less than field capacity. If only a small amount of water is applied, only the surface layers will become wetted. Water will not move downward in soil until field capacity is reached in a layer. As more water is applied, the soil at progressively lower depths will become wetted to field capacity.[20]

If less than the rooting depth is wetted, the plants are deprived of soil volume from which to draw moisture and plant nutrients. Irrigation water inadequate to fill the root zone of crops advances the time at which a succeeding irrigation will be required. Under-irrigation will result in the onset of moisture stress sooner and more suddenly when the subsoil layers are very dry than when deep reserves are available. When subsoil layers are dry, root penetration will be limited. Thus, the risk of yield-depressing stress periods are greatly enhanced by too light a water application at any given irrigation.

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[19] Paul J. Kramer, "Soil Moisture in Relation to Plant Growth," Botanical Review, 10(November 1944), p. 550.

[20] Ibid.

A number of studies have been made on the effects of controlled soil moisture deficiencies on crop yields. A common plan for testing the effect of moisture deficiency on irrigated crops has been to allow the soil to dry out to a predetermined level, as indicated by a tensiometer or some other device, and then to add sufficient irrigation water to bring all the soil in the root zone to field capacity. This type of experiment subjects the plants to a definite water regime and has been carried out in the United States with notable results on dwarf kidney beans,[21] apple trees,[22] alfalfa, sugar beets, and potatoes.[23]

General observations on the effects of moisture stress on various crops have been made by a number of researchers. For example, it has been found that winter and spring wheat exhibit tolerance to moderate moisture stress throughout the growth cycle. Periods of high stress at any time prior to, during, or for a few days after heading of the grain result in reduced vegetative growth. High stress at any stage of growth will reduce grain yield appreciably if it is severe enough to desiccate the lower leaves. Late-season stress causes yield reduction through shriveling of grain. Hot, dry winds occurring during periods of moisture stress greatly intensify shriveling. A particularly critical period for wheat is about two

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[21] C. Wadleigh and Alvin D. Ayers, "Growth of Bean Plants as Conditioned by Soil Moisture Tension," Plant Physiology, 29(1945), p. 29.

[22] A. L. Kenworthy, "Soil Moisture and Growth of Apple Trees," Proceedings of American Society of Horticulture Science, 54(1949), p. 217.

[23] S. A. Taylor, "Use of Mean Soil Moisture Tension to Evaluate the Effect of Soil Moisture on Crop Yields," Soil Science, 74(1952), p. 217.

weeks before pollination when moderate moisture stress is sufficient to reduce grain yields.[24]

Corn generally displays tolerance to moisture stress during early periods of the growing season. Significant reductions in grain yields apparently occur in early seasons only when stress is prolonged and severe enough to cause wilting. Plant height and vegetative yields are reduced by leaf desiccation. However, even moderate stress during tasseling, silking, and pollination periods reduces yields greatly.

Robins and Domingo, in studies of moisture deficiencies on corn yields in the Columbia Basin in Washington State, show that depletion of soil moisture to the wilting percentage for 1-2 days during tasseling or pollination periods can reduce yields about 50 percent.[25]

The reaction of grain sorghum to moisture stress is similar to that of corn. Moisture stress sufficient to cause leaf desiccation results in significant reduction in forage and grain yield. Severe stress during the boot-to-flowering stage results in pollination failure (head blast).[26]

Jensen and Sletten, in studying the response of grain sorghum to soil moisture deficiency, concluded that yields were greatly reduced

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[24] P. A. Henkle, "Physiology of Plants Under Drought," Annual Review of Plant Physiology, 15(1964), pp. 363-86.

[25] J. S. Robins and C. E. Domingo, "Some Effects of Severe Soil Moisture Deficits on Specific Growth Stages of Corn," Agronomy Journal, 45(December 1963), p. 621.

[26] J. T. Musick and D. W. Grimes, Water Management and Consumptive Use By Irrigated Grain Sorghum in Western Kansas, Kansas Agricultural Experiment Station Technical Bulletin 113, 1961.

when the average available soil moisture level was allowed to decline to less than 25 percent before each irrigation.[27] Figure 2 shows the yield response of grain sorghum to various levels of moisture deficiency before each irrigation. This type of curve is useful only if the soil moisture declines to the same level before each irrigation. Decline of soil moisture to several different levels during the season will give results deviating from the relation shown in Figure 2.

Laing, in a study of change in yields of soybeans due to soil moisture stress applied at selected periods of growth, derived the data shown in Figure 3. This graph shows the differential effect on yield when moisture stress is allowed to develop at different periods during the growing season. In this study, soil moisture was adequate at all other periods during the season.[28]

For on-the-farm watering decision purposes, it would be helpful to have data showing the yield of crops for various levels of water shortage during a season. This would allow development of a "loss function" showing the decline in yields as a result of varying percentages of water shortage. Unfortunately, crop response to soil moisture deficit does not assume this relational form. For instance,

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[27] W. E. Jensen and W. H. Sletten, Evapotranspiration and Soil Moisture-Fertilizer Interrelations with Irrigated Grain Sorghum in the Southern Great Plains, Conservation Research Report No. 5, Agricultural Research Service, United States Department of Agriculture and Texas Agricultural Experiment Station, August 1965.

[28] R. H. Shaw and D. R. Laing, "Moisture Stress and Plant Response," in W. H. Pierre and others, Plant Environment and Efficient Water Use (Madison, Wisconsin: American Society of Agronomy and Soil Science of America, 1966), chapter 5, p. 9.

Figure 2.--Yield response of grain sorghum to decline in available soil moisture in the 0-to-4-foot depth prior to irrigations (adapted from Jensen & Sletten, 1965).

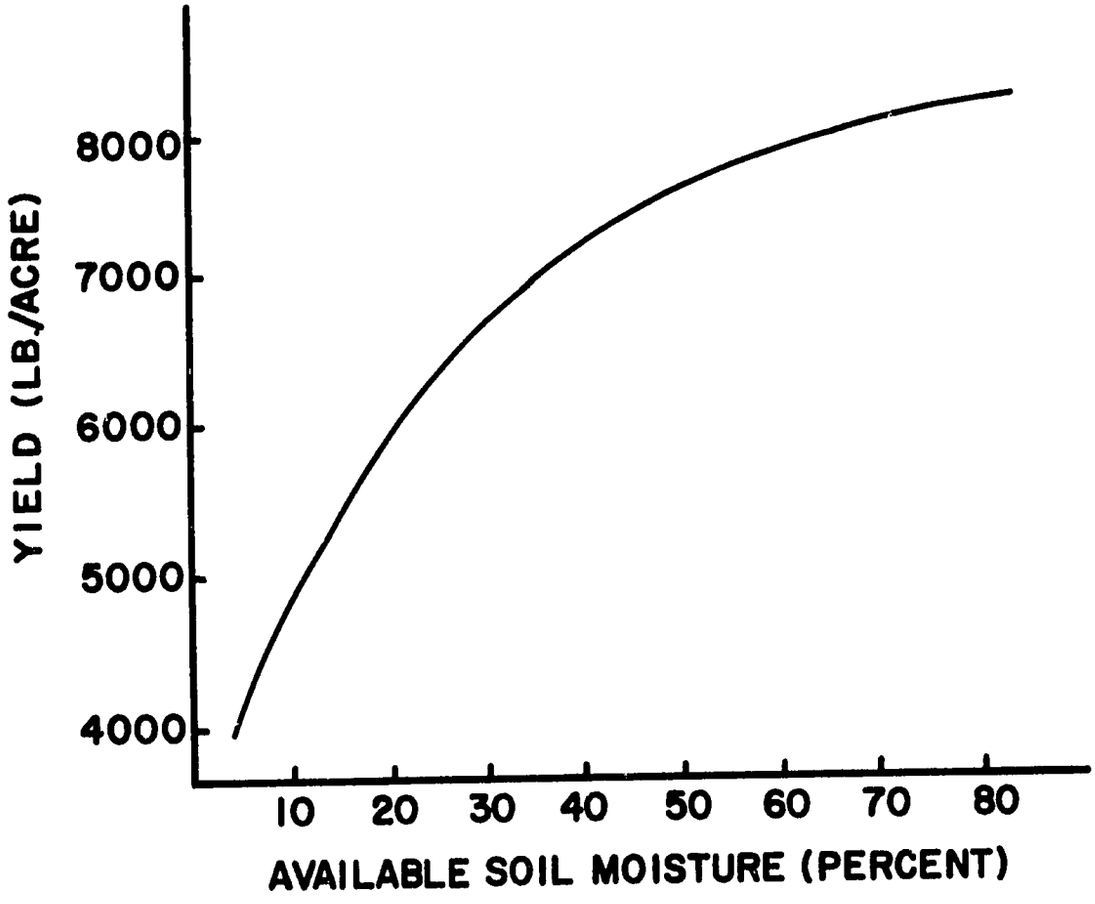
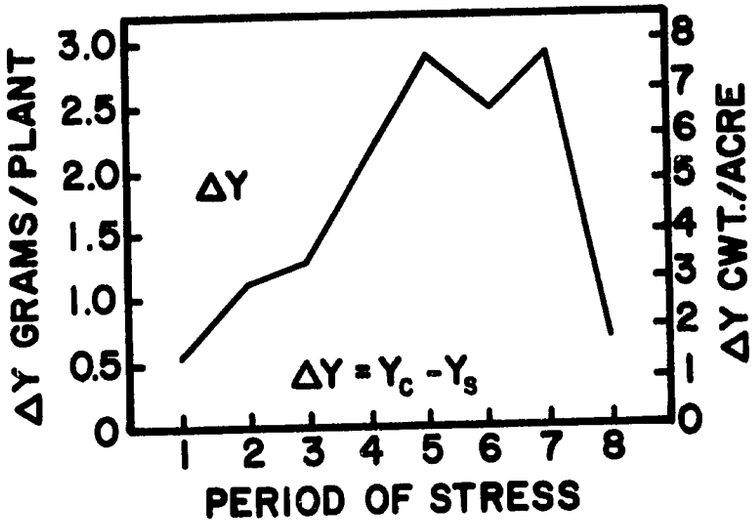


Figure 3.--Change in soybean yields due to moisture stress applied at selected periods of growth. (Laing, 1965. Unpublished Ph.D. thesis, Iowa State University Library.)



a 10 percent water shortage during a growing season will induce several different levels of yield on a particular crop, depending on when the shortages occur during the growing cycle, as indicated in Figure 3.

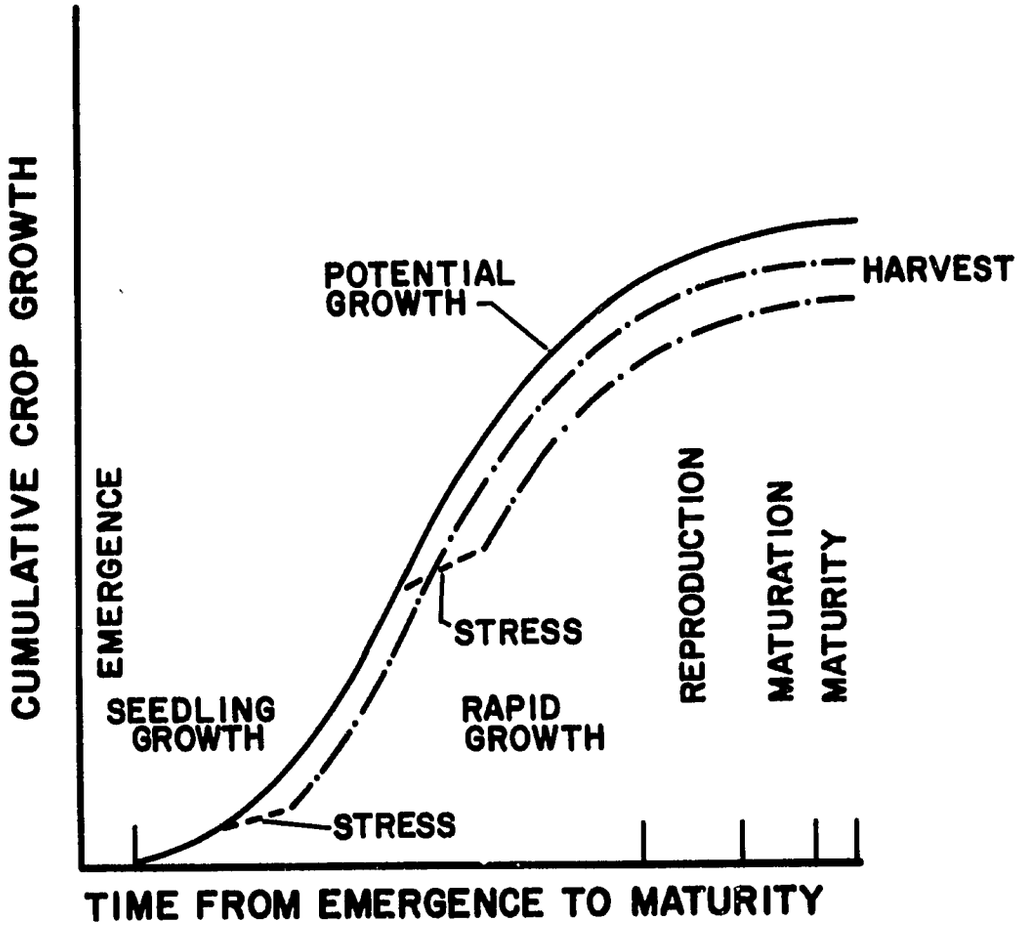
Figure 4 is a schematic drawing of potential and actual growth curves of an annual crop under irrigation. The time and cumulative growth scales of the chart can be expanded or contracted to take into account the differences in length of growth cycle and yield of various crops. This figure illustrates the potential growth and yield of a crop when soil moisture is adequate throughout the growing season and shows the reduction in potential growth whenever soil moisture stress occurs. Since potential growth and yield are associated, it follows that harvestable yield will most likely be reduced from the occurrence of moisture stress. The amount of reduction in growth and yield will depend on duration and severity of the stress period and the time of occurrence during the growth cycle. If stress occurs when plant growth is rapid, water demands are high, or reproductive processes are critical, it will cause a greater reduction than if it occurs during periods when growth and development are slow, such as near maturity. A specific water deficiency of 4 or 6 acre-inches will have varying effects on yields, depending on the time of occurence during the season and upon the crop that suffered the shortage.

Economic Effects of Inadequate Irrigation

Irrigation practices in California reported by Moore and Hedges[29] show that moisture stress caused by delayed irrigation has significant

[29] C. V. Moore and T. R. Hedges, Economics of On-Farm Irrigation Availability, Gianni Foundation Report No. 261, March 1963.

Figure 4.--Potential and actual growth curves of an annual crop under irrigation. (After Flinn and Musgrave, 1967.)



effects on crop yields, even though the total seasonal water applications are about the same. One of their studies reports crop yields under two irrigation regimes. One regime allows a depletion of 80 percent of available soil moisture, and the other a depletion of 100 percent, before irrigating. (It is not clear from this study exactly what is meant by these two moisture depletion levels.) Yields of sugar beets under these two irrigation treatments are shown in Table 1.

Table 1.--Yield and returns of sugar beets under two irrigation regimes, California, 1961

	Soil Moisture Depletion Levels before Irrigation	
	80%	100%
No. of irrigations	6	5
Total water applied	63.5 inches	62.6 inches
Yield	23.1 T	21.6 T
Sugar content	12.5%	11.7%
Sugar yield	5775 lbs.	4867 lbs.
Total value at 5.3 ¢ /lb.	$306.07	$257.95

According to these data, delayed irrigations and application of one acre-inch less of water resulted in a 908 pound decline in sugar production, and a $48.12/acre decline in returns. Total cost in savings in water and labor amounted to about $2 per acre.

Robins and Domingo reported the response of potato yields to moisture deficits (Table 2).[30] Their studies show that equal total applications of water applied in different sequences can produce

[30] J. S. Robins and C. E. Domingo, "Potato Yield and Tuber Shape as Affected by Severe Soil-Moisture Deficits and Plant Spacing," Agronomy Journal, 48(1956), pp. 488-92.

widely differing yields of high-quality potatoes. Total water application of 19 net inches per acre, at 4-7 day intervals, gave a yield of 12.7 tons of No. 1 grade potatoes, while total application of 21 net inches, applied at 16-22 day intervals, yielded 5.4 tons of No. 1 grade potatoes per acre, or a 58% reduction in yield. Total yields for all grades were 18.8 tons and 14.1 tons respectively. At a price of $1.30/cwt. for No. 1 grade, the frequently irrigated fields returned $330 per acre, and the infrequently irrigated field returned $140 per acre.

If the potatoes below No. 1 grade could be sold for 70¢ per cwt., total revenue for the frequently irrigated field would be $415 per acre and for the less frequently irrigated, $262. Potatoes cost about $300 per acre to raise. The frequently irrigated fields would return about $115 net income per acre, while the infrequently irrigated fields would give a net loss of $30 per acre, if labor is charged at $1 per irrigation (Table 2).

Table 2.--Returns from irrigated potatoes in Prosser, Washington, 1954.

	Irrigation Sequence	
	Frequent	Infrequent
No. of irrigations	13	5
Net water applied	19 inches	21 inches
Yield total	18.8 T	14.1 T
No. 1 grade	12.7 T	5.4 T
Value No. 1 grade	$330	$140
Total value all grades	$415	$262
Cost	$300	$292
Net return	$115	-$ 30

These studies show that with development of moisture stress, crop yields can quickly fall below profitable levels. Agronomists, apparently responding to knowledge of yield reductions from moisture deficiencies and the subsequent effects on profitable production, have concentrated research on the means of achieving ever-higher yields through improved varieties and increased fertilizer applications, always assuming water requirements are met.

These examples stress the importance of meeting irrigation water requirements by relatively short time periods, if the best yields are to be achieved and irrigated crop production is to be most profitable. As shown by the examples, when moisture stress is allowed to develop, yields can easily fall to such an extent that losses in income occur for crops that otherwise would have been profitable. This happens even under situations where total seasonal applications of water approximate the seasonal requirements.

III. Water Requirements for Irrigated Crops

The computing of water requirements for irrigated crops requires data on water use by specific periods throughout the growing season. In order to develop data on when crops need water, and the amount needed, it is necessary to use one of several methods that have been developed to estimate consumptive use or evapotranspiration. To rely entirely on farmer irrigation practices would reflect a number of factors other than crop needs. Frequently local customs, availability of water, farm labor, and other factors affect irrigation rates and timing as much as do crop needs.

Water requirements include consumptive use, as well as water losses occurring in canals and while irrigating fields. Consumptive use, or evapotranspiration, is the amount of water used by the vegetative growth in a given area in transpiration and building of plant tissue, plus the water evaporated from adjacent soil or the intercepted precipitation on plant foliage in any specified time.[31]

When using consumptive use estimates as a basis for developing total irrigation water requirements, it should be kept in mind that consumptive use is just one of several important factors. On lands under gravity irrigation, from one to three times the amount of water actually used to satisfy consumptive use is lost in the process of delivering water and applying it to the field. Seepage from canals,

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[31] Irrigation Water Requirements, Technical Release No. 21 (Washington: Soil Conservation Service, Department of Agriculture, 1964), p. 1.

laterals, and farm ditches, as well as evaporation, administrative losses and waste, surface runoff, and deep percolation on farm fields, all deplete the water supply initially diverted.

In Pakistan's vast irrigation system, the regional differences of system efficiency vary greatly. Only 25 percent of the mean annual river discharge is utilized. During the summer, two-thirds of the river discharge passes unused to the sea.[32] The losses in the canal system before the water reaches the watercourse head is roughly 50 percent, although this figure is extremely difficult to compute and varies greatly with each major canal command.[33] Watercourse studies place the field efficiencies between 60 to 70 percent.[34] The losses in the Lower Indus Basin are in the neighborhood of 40 percent; in the Upper Indus Basin losses are around 30 percent. In both regions, substantial savings in water could result from improved layout of the watercourse distribution system. Estimates of savings are as high as 20 percent -- placing the water efficiency in the watercourses around 80 percent.[35]

Evapotranspiration, the basic phenomenon in determining water requirements, occurs at varying rates throughout a normal cropping season. It is the rate at which water is extracted from the soil by

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[32] I. A. Carruthers, Irrigation Development Planning, Aspects of Pakistan Experience (Wye College, Ashford, Kent, U.K.: Economics Department, 1968), p. 11.

[33] See Lieftinck and others, op. cit., Vol. II, especially Chapter 3, "Development of Water Resources."

[34] See Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Volume 7, Annesure 9, especially pp. 61-66.

[35] Ibid., Volume 10, Annexure 14, "Watercourse Studies."

evaporation and plant use; the amount of water the soil can readily supply determines when crops must be watered. In order to estimate the rate of evapotranspiration occurring in an area for various crops, a number of techniques for computing consumptive use have been developed. One group of techniques measures moisture content of the soil through use of neutron probes, electrical soil-moisture resistance blocks, tensiometers, and other devices. When the soil moisture declines to a certain level as indicated by readings from the measuring devices, the crops need to be irrigated. These systems are technically advanced and work well in measuring the soil moisture status in relation to plant growth, climatic conditions, and precipitation occurring during a growing season. These measurements require an operating irrigation system, and the results obtained from such observations would apply only under similar plant, soil, and climatic conditions.

Several methods of estimating consumptive water use rely on climatological data. These methods allow for generalizations of water use over a typical season, and can also be used to estimate water requirements for areas that are to be irrigated. Climatological systems provide a basis for developing irrigation water requirements, such as used for various irrigation projects.

Hedke, Lowry-Johnson, Thornthwaite, Penman, and Monson have all developed methods for estimating irrigation water requirements for crops by use of various meteorological observations. Each of these methods could be useful if sufficient data on an area are available.[36]

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[36]For the use of these several methods, see Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Volume 7, Annexure 9, p. 60. Generally, the consumptive values using various methods were approximately the same, although significant differences did result for some crops.

Two other methods of estimating irrigation water requirements have greater flexibility and are less reliant on detailed meteorological data. These estimating procedures assume a full water supply to the crop, and use a common two-factor approach. A climatic factor is measured (pan evaporation, pond evaporation, potential evapotranspiration, or consumptive use factor). This factor is then modified by a crop coefficient reflecting the type of crop, stage of growth, and climatic factors other than those covered in the climatic factor. One estimating procedure developed by Jensen and Haise uses solar radiation and temperature as a basis for estimating consumptive use of water by crops. They use total shortwave solar radiation (R_s), expressed in inches of evaporation equivalent, as a climatic factor and then a dimensionless crop coefficient (ET/R_s), to reflect the effects of type of crop and stage of growth, as well as climatic factors not accounted for by solar radiation.[37] The crop coefficients are presented as continuous crop curves (ET/R_s vs. percent of growing season) for individual crops. Potential evaporation is defined as the evapotranspiration which can be expected to occur from an irrigated, full-coverage crop in an arid or semiarid area. It is expressed as:

$ET_p - (0.014T - 0.37)R_s$, where

ET_p is potential evapotranspiration in inches,

T is mean daily temperature in degrees Fahrenheit, and

R_s is total solar radiation in inches of evaporation equivalent.

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[37] Marvin E. Jensen and Howard R. Haise, "Estimating Evapotranspiration from Solar Radiation," Journal of the Irrigation and Drainage Division (ASCE), 89(December 1963), NIR 4.

The linear temperature correction factor was derived by plotting ET/R_s versus T for selected field crops in which evaporating and transpiring surfaces did not limit water vaporization.

Figures 5 through 12 show the crop curves for commonly irrigated field crops as developed by the Bureau of Reclamation, using the Jensen-Haise method as a base. Basic input data needed for this method are total shortwave solar radiation and mean daily air temperature.

Another commonly used procedure for estimating consumptive use requirements is that of Blaney and Criddle. Blaney and Criddle refined earlier formulas for computing consumptive use of water by crops, by basing their formula on mean monthly temperature and percentage of total annual hours of daylight during the month. The formula is $U = KF$ where U is the consumptive use over the period, K is the coefficient depending on the crop, and F is the sum of monthly consumptive use factors for the period considered.

It might be difficult to see why this formula works, since evapotranspiration does not depend on monthly temperatures and depends only indirectly on the number of daylight hours in a month. A consideration of the underlying physics shows that these factors provide a reasonable approximation of evapotranspiration. The reasoning goes something like this: Evapotranspiration depends in part on the vapor-pressure gradient from the evaporating surface to the air. The surface vapor pressure is a function of the surface temperature, whereas the vapor pressure of the atmosphere is relatively constant during the day. A simplifying approximation is to

Figure 5.--Preliminary crop curve for alfalfa. (From ASCE, Methods of Estimating Evapotranspiration, New York, 1966, pp. 188-190.

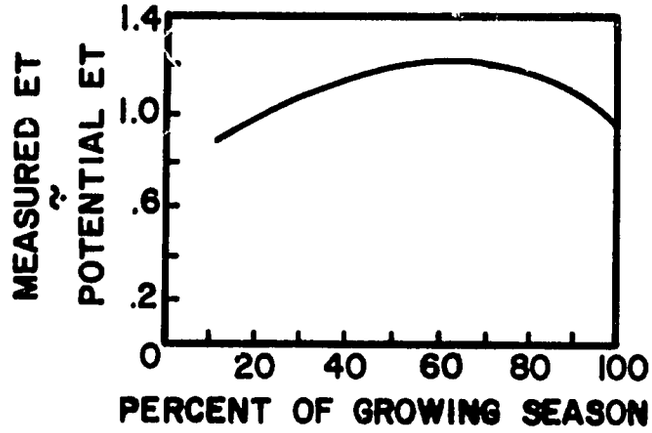


Figure 6.--Preliminary crop curve for beans.

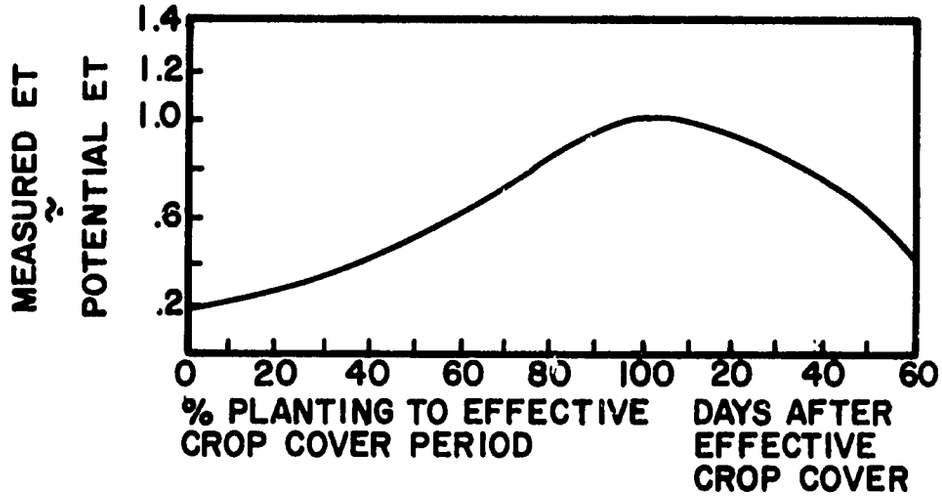


Figure 7.--Preliminary crop curve for oats.

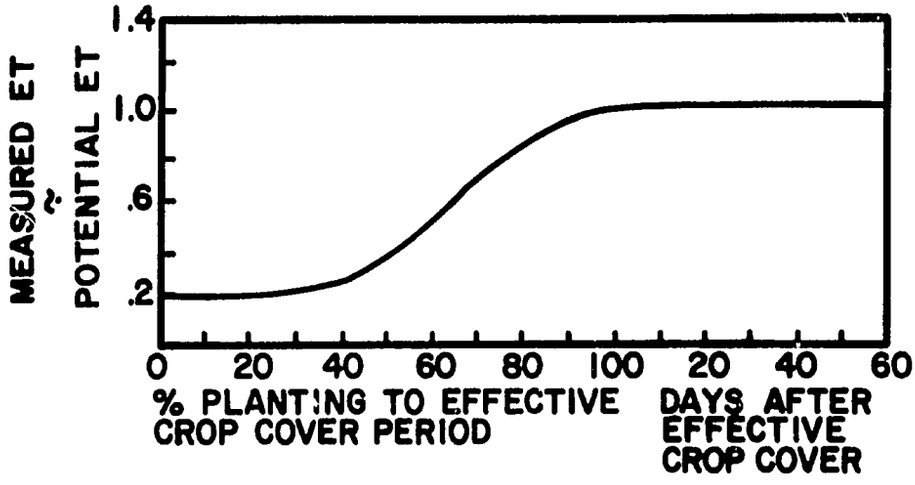


Figure 8.--Preliminary crop curve for corn.

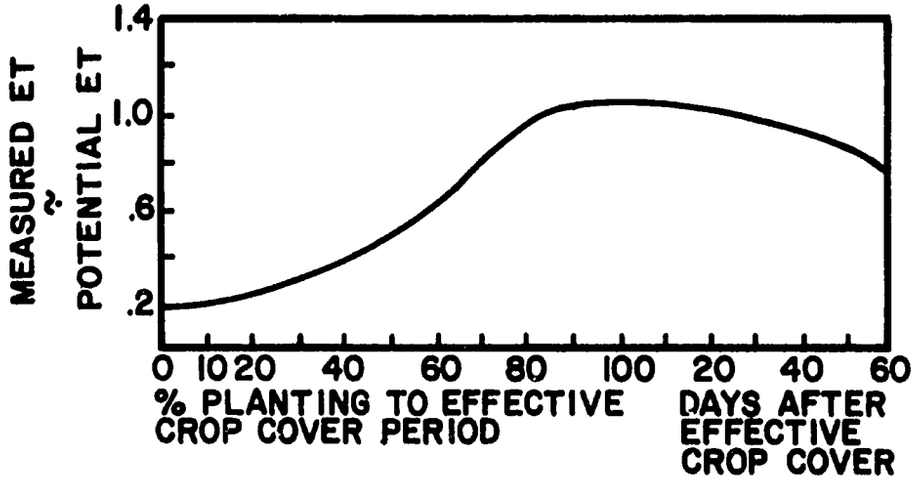


Figure 9.--Preliminary crop curve for sugar beets.

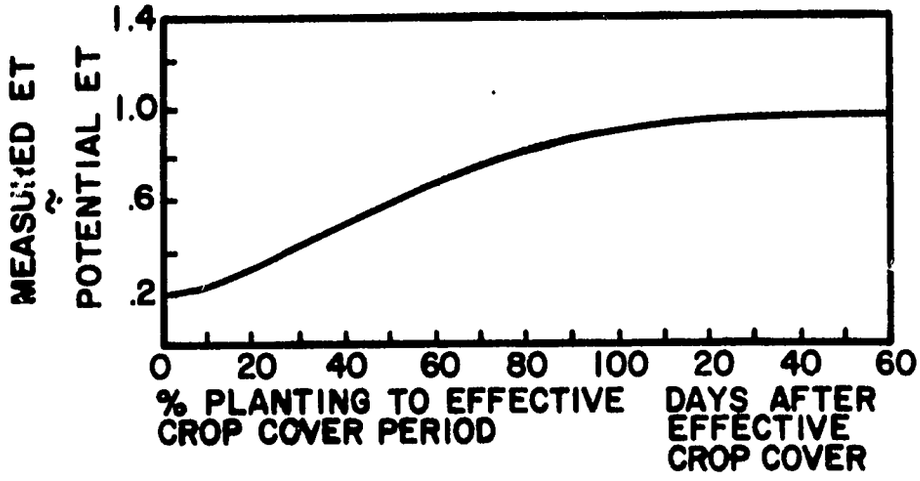


Figure 10.--Preliminary crop curve for cotton.

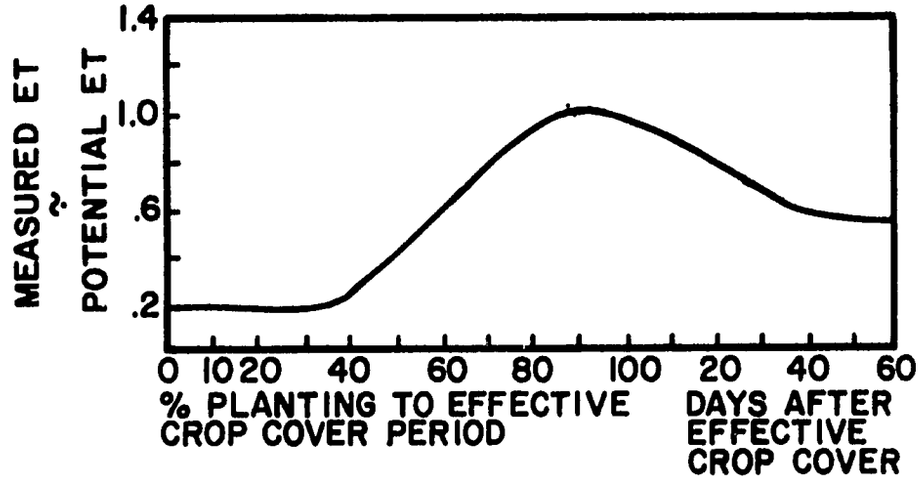


Figure 11.--Preliminary crop curve for sorghum.

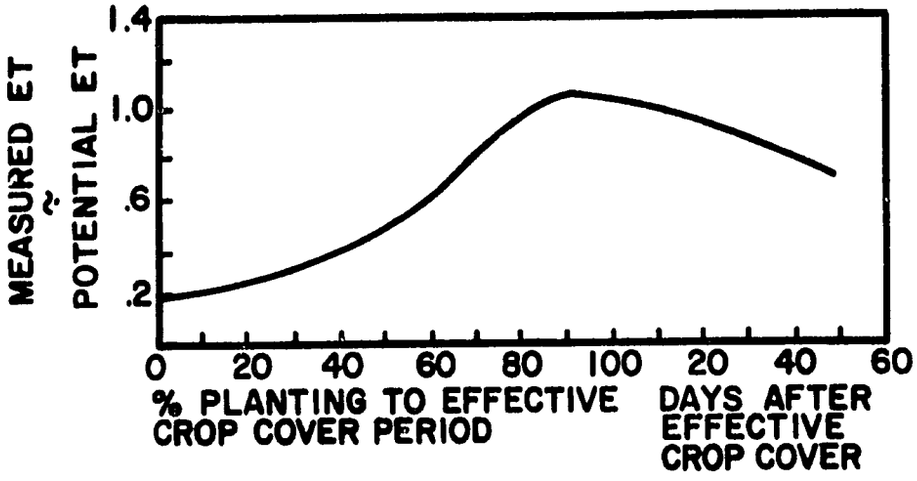
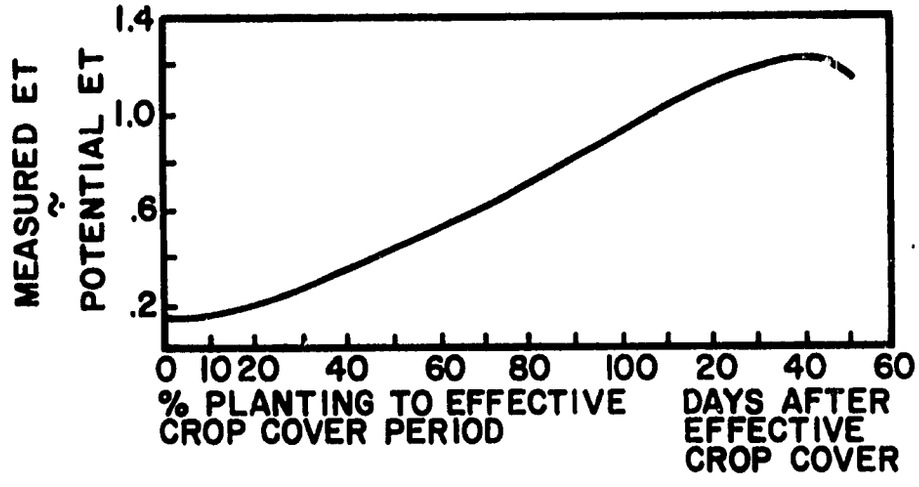


Figure 12.--Preliminary crop curve for potatoes.



relate evaporation to surface temperature. A further approximation is to replace surface temperature with air temperature, thus giving the basis for the Blaney-Criddle formula.[38]

In a study comparing methods of estimating potential evapotranspiration from climatological data in arid and subhumid environments, Cruff and Thompson concluded that of six methods compared (Thornthwaite, Weather Bureau -- a modification of the Penman method, Lowry-Johnson, Hamon, Blaney-Criddle, and Lane) the Blaney-Criddle method, which uses climatological data that can be readily obtained or deduced, is the most practical method for estimating potential evapotranspiration.[39]

In spite of some obvious shortcomings, the Blaney-Criddle formula has been used extensively in estimating irrigation requirements. Probably, the empirical determination of the K factor in different regions makes up for much of the deficiency in measuring other factors in the rest of the formula. In most cases, it seems to work well enough to give reasonable water use estimates for many irrigated crops.

Blaney, Criddle, and others associated with them have published an extensive list of bulletins and papers in which they have developed and applied their formula to various irrigated areas.[40] These

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[38] M. B. Russell (ed.), Water and Its Relation to Soil and Crops (London and New York: Academic Press, 1959), p. 28.

[39] R. W. Cruff and T. H. Thompson, "A Comparison of Methods of Estimating Potential Evapotranspiration from Climatological Data in Arid and Sub-humid Environments," Geological Survey Water Supply Paper, 1839 M., Washington: Department of the Interior, 1967, M1.

[40] Harry F. Blaney and Wayne D. Criddle, "Determining Consumptive Use for Planning Water Developments," Methods for Estimating Evaporation (New York: American Society of Civil Engineers, 1966), pp. 1-34.

publications contain tables that give suggested monthly consumptive use coefficients (k) representing empirical consumptive use coefficients for crops grown in the Western U.S. Another set of tables contains normal monthly consumptive use factors (f) which are essentially the monthly percentage of daytime hours (p) times mean monthly temperature (t) divided by 100, $f = \frac{t \times p}{100}$. Consumptive water use of a crop for the month is $u = f \times k$. Irrigation water requirements are computed by dividing (u) by farm headgate efficiency, which includes irrigation efficiency and losses in laterals to the field. Irrigation specialists seem to favor 55 to 60 percent as being the usual water use efficiency on irrigated farms.

Three tables (3 to 5), taken from Consumptive Use and Water Requirements in New Mexico by Blaney and Hansen, are presented to illustrate how consumptive use and total water requirements for crops are computed using the Blaney-Criddle method.[41] Table 3 shows the computation of seasonal consumptive use of crops near Deming, New Mexico. Table 4 shows a method for determining farm consumptive use. Table 5 shows the procedure for computing monthly consumptive use for individual crops. The (f) and (k) factors vary among locations. As a consequence, data should be reasonably representative of the area being studied in order to develop realistic consumptive use estimates. Effective rainfall figures, such as those shown in Table 5, vary from area to area and from year to year. In highly erratic rainfall areas, it would be hazardous to plan on more than a small fraction of total water coming from rainfall.

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[41] Harry F. Blaney and Eldon G. Hansen, Consumptive Use of Water Requirements in New Mexico, Technical Report 32 (Santa Fe, New Mexico: New Mexico State Engineer, 1965).

Table 3.--Example of Computation of Seasonal Consumptive Use, Effective Rainfall, and Irrigation Requirement for Crops near Deming, New Mexico.[a]

Land use and crops	Length of growing season or period	Consumptive use: Factor (F)	Consumptive use: Coefficient (K)[b]	Consumptive use: Amount (U)	Effective rainfall (R_e)	Consumptive use minus effective rainfall ($U-R_e$)	Field irrigation efficiency (E)	Field irrigation requirement (I)
				Inches	Inches	Inches	Percent	Inches
Alfalfa	April 15 to Oct. 29	42.37	0.85	36.01	6.02	29.99	70	42.8
Beans (dry)	June 15 to Sept. 15	21.92	0.60	13.15	4.01	9.14	65	14.1
Corn	June 1 to Oct. 15	30.81	0.75	23.11	5.28	17.83	65	27.4
Cotton	April 15 to Oct. 29	42.37	0.62	26.27	6.02	20.25	65	31.2
Grain (spring)	March 10 to July 1	22.25	0.70	15.58	1.25	14.33	65	22.0
Sorghums	June 1 to Oct. 15	30.81	0.70	21.57	5.28	16.29	65	25.1

a. Average frost-free period, April 15 to October 29. Irrigation prior to frost-free period may be necessary for some crops.

b. Based on U.S. Department of Agriculture measurement in Arizona and New Mexico.

(Adapted from Blaney et al., Consumptive Use and Water Requirements in New Mexico, New Mexico State Engineer, Technical Report 32, 1965, p. 37.)

Table 4.--Example of Method Used to Compute the Amount of Irrigation Water Required at Farm Headgate for 100 Acres of Irrigated Farmland near Deming, New Mexico.[a]

Land use and crops	Irrigation water required for consumptive use[b]			Farm irrigation efficiency[c]	Water required at farm headgate[d]	
	Land area	Per acre	Total		Per acre	Total
	Acres	Acre-feet	Acre-feet	Percent	Acre-feet	Acre-feet
Alfalfa	4	2.50	10.0	60	4.2	16.8
Beans (dry)	5	0.76	3.8	55	1.4	7.0
Corn	10	1.49	14.9	55	2.7	27.0
Cotton	45	1.69	76.1	55	3.1	139.5
Spring grain	16	1.19	19.0	55	2.2	35.2
Sorghums	20	1.36	27.2	55	2.5	50.0
Total or weighted average	100	1.51	151.0		2.76	275.5

a. In years of low precipitation, winter irrigation or irrigation prior to the frost-free period may be necessary.

b. Consumptive use (U) minus effective rainfall (R_e).

c. Assumed efficiencies.

d. In computing the total water requirement for a farm or project such items as farmsteads, fallow land must be considered.

(Adapted from Blaney et al., Consumptive Use and Water Requirements in New Mexico, New Mexico State Engineer, Technical Report 32, 1965, p. 38.

Table 5.--Computed Normal Monthly Consumptive Use and Irrigation Requirements for Grass - Alfalfa near Caldwell, Idaho.

Month	Consumptive use		Consumptive use	Rainfall		Consumptive use minus effective rainfall	Irrigation requirement[a]
	Factor (f)	Coefficient (k)	(u)	Total (r)	Effective (r_e)	($u-r_e$)	(i)
			Inches	Inches	Inches	Inches	Inches
May 7-31	4.30	0.83	3.57	1.08	1.02	2.55	4.25
June	6.68	0.89	5.95	0.92	0.87	5.08	8.47
July	7.58	0.90	6.82	0.24	0.23	6.59	10.98
August	6.87	0.83	5.70	0.19	0.18	5.52	9.20
Sept.	5.15	0.69	3.55	0.53	0.50	3.05	5.08
Oct. 1-3	0.38	0.35	0.13	0.12	0.11	0.02	----
Total			25.72	3.08	2.91	22.81	38.01

a. Based on 60-percent farm irrigation efficiency.

IV. Crop Water Requirements and Well-Designed Irrigation Schedules

For a particular irrigated area, each crop will have definite water requirements for the season. The moisture-holding capacity of the soil, the rate of evapotranspiration, and the level of soil moisture depletion to be allowed will determine the frequency and amounts of irrigation water to be applied. Generally, frequent light irrigations will be more wasteful of water than heavier, less frequent irrigations. The type of crop and the type of soil will be major determinants in the overall frequency of irrigations. However, high consumptive water use or particularly moisture-sensitive periods during some parts of the growing season will require greater frequency of irrigation.

A schematic irrigation schedule is presented in Table 6. Data in this table were derived from a variety of sources, and are not intended to be representative of any single irrigated region. This table is designed to indicate, by periods throughout the irrigation season, the amount of water in acre-inches that the irrigation system must provide in order to meet the water requirements of the various crops. The timing and amount of the irrigation requirements specified are the ideal water deliveries under normal climatic conditions to attain the yields specified for each crop. Irrigation periods are set at 2-week (14 days) intervals, which approximates the general situation in Pakistan.[42]

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[42]For a detailed description see Programme for the Development of Irrigation and Agriculture in West Pakistan, 1966, Volume 5, Annexure 7, "Water Supply and Distribution."

Table 6.--Typical irrigation sequences on selected crops, based on 2-week intervals during the crop growing season, Western United States.

	Irrigation periods														
	April		May		June		July-August					Sept.		Oct.	Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
	Inches of water allocated to farm1/														
Alfalfa	-	-	12	-	11	-	-	13	-	-	19				55
Beans (dry)	-	-	6	-	7	-	5	5	4	4					31
Corn	-	-	6	-	8	-	5	6	8	-	6				39
Small grain	10	-	5	-	8	-	6								29
Cotton	10	-	-	4	-	7	6	6	-	12	-	9			54
Sorghum	-	-	5	-	6	-	6	6	6	6	6	-			41
Sugar beets	-	6	-	7.5	-	5	6.5	-	5	5	8	-	4		47
Grass (Hay)	8	-	-	7	-	10	-	10	-	10	-	12			57
Potatoes	-		-	5	4	4	4	4	4	4					29
Orchard (apples)	-	-	11	-	-	-	12	-	-	12	-	-	4		39

1/ A 50 percent efficiency is assumed from the source of supply to the soil root zone.

The irrigation requirements shown in Table 6 were developed by using the consumptive use methods described earlier. These irrigation watering periods are typical of those used in many parts of the Western United States except the southern areas of Arizona and California. The same kind of requirements need to be developed for the principal regional areas of West Pakistan, beyond the gross factors already computed.

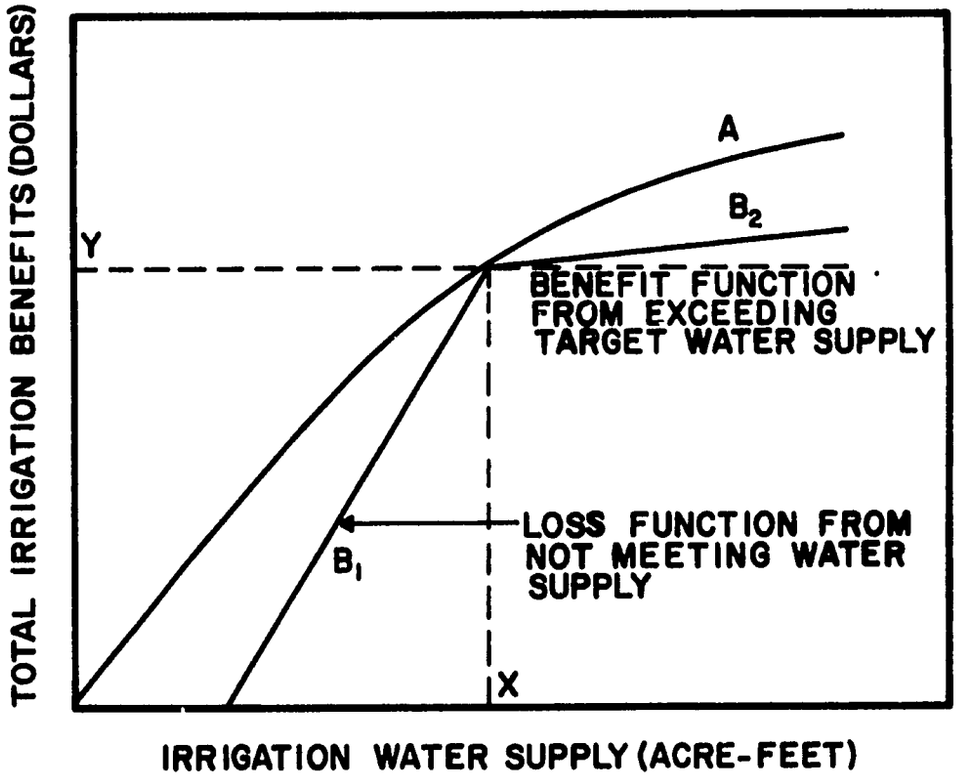
Benefits from irrigation can be thought of as having a configuration that is related to the characteristics of the production function for irrigation agriculture, as shown in Figure 13. This function has three parts:

1) Benefits from meeting a target output. These are benefits that are realized when the actual water supply over the season equals that which was forecast at the beginning of the season, and in terms of which the farm's crop pattern and operations were planned. Curve A on Figure 13 shows the relation between planned or target outputs and benefits. For a target output of X, benefits are Y.

2) Benefits from exceeding target outputs. As shown in Figure 13, the rate of gain for these benefits (the slope of curve B_2) is less than the rate of change of the long-run function A. Water surpluses during a season, that is, more water than was planned on when the crops were planted and more than these crops require, will have considerably less value than a planned increase in level of output.

3) Losses from failing to achieve target outputs. As shown in Figure 13, the rate of loss (the slope curve B_1) is greater than the rate of change of the long-run function A, because water deficits

Figure 13.--Theoretical three-element benefit function. A shows benefits as a function of target outputs. B_1 and B_2 show benefits (losses) as a function of attained outputs when target output is X.



during a season, causing losses to crops that have been planted, are more costly than a planned reduction in output at the beginning of the season.

Crop Yield Losses from Missed Irrigations

Whenever an irrigation organization cannot supply adequate irrigation water to farms during a period that crops need water, the yield of the crops not irrigated will decline from the target or potential yield. The loss function in Figure 13 is associated with the estimated yield reductions shown in Table 7. Yield reductions, and consequently the loss function, are related not only to the quantity of water shortage but also to its time of occurrence. Because of differences in crop response to moisture stress at various stages of the growth cycle, water shortages of the same nagnitude during different periods can have different yield losses associated with them. Also, the percentage yield reductions apply to the yield estimates expected at the time the shortage occurs. An example is the water requirement and yield loss for dry beans in periods 7 and 8 (see Tables 6 and 7).

The loss schedules were developed from research findings on the effects of moisture stress on yields of various crops. The irrigation season in this example is divided into 14 two-week periods with water requirements for crops specified whenever a particular crop would need water under normal conditions. The loss schedule indicates for each crop the reduction in yield if it were not possible to water the crop during the period.

An assumption used for this schedule is that if an annual crop is missed during a single period, the assigned percentage is deducted

Table 7.--Estimated reduction in crop yield when a required irrigation is not applied to particular crops during specified irrigation periods, Western United States. (Irrigation periods are 14 days.)

	Irrigation periods													
	April		May		June		July-August					Sept.		Oct.
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Percent reduction in yield													
Alfalfa	-	-	35	-	30	-	-	30	-	-	20			
Beans (dry)	-	-	10	-	35	-	35	48	40	48	-			
Corn	-	-	20	-	20	-	40	25	20	-	10			
Small grain	25	-	25	-	25	-	15							
Cotton	30	-	-	15	-	25	25	25	-	30	-	20		
Sorghum	-	-	20	-	15	-	20	20	20	20	15			
Sugar beets	-	20	-	20	-	15	20	-	15	15	25	-	10	
Potatoes	-		-	15	15	15	20	20	20	20				
Orchard (apples)	-	-	25	-	-	-	25	-	-	25	-	-	5	

Assumptions

1. Each acre receives either (a) full requirement of water or (b) none. Figures represent losses resulting from no irrigation during a 2-week period.
2. Two successive "misses" result in total loss of crop, except for alfalfa and orchards.
3. Percentage reduction is applied to expected yield of moment--except for the two successive losses, which means total loss of crop.
4. Direct relation of physical yield and value of crops, i.e., assuming water reduction affects yield and not quality (except potatoes). Ideally, would like data on other crops, but quality loss might not be as severe for other crops as for potatoes.

from the current yield; for two consecutive missed and needed irrigations, most annual crops would be destroyed by drought. Two consecutive irrigation misses means that a crop would be in a moisture stress condition for 4 weeks at a minimum and possible 6 weeks under some irrigation sequences. Some irrigated crops might survive under some soil and climatic conditions; but in most cases, reductions in yield would be so severe that further irrigation and harvest would not be profitable. For perennial crops, such as alfalfa and tree crops, two successive irrigation misses would result in reduction of the crop yield as specified in each period, but would not result in a complete loss due to moisture deficiency.

Although a number of studies, as already noted, have been made concerning yield losses resulting from soil moisture deficiencies, findings are not sufficiently complete to give a comprehensive analysis of the effects of the various timing and intensities of water shortages on yields of crops grown under irrigation. Typically, the studies give specific reductions in yield from soil moisture stress conditions for selected stages of growth. Therefore, the loss figures given in Table 7 are at best approximations of what occurs when a crop is not watered during a period in which soil moisture needs to be replenished. All of the factors that affect the water-holding capacity of the soil, the specific crop, and climatic factors affecting the moisture extraction rate from the soil would play a part in the on-set and extent of crop yield reduction resulting from soil moisture deficiencies.

V. General Conclusions

Widespread under-irrigation is a major constraint on West Pakistan's agricultural development. Studies reveal that the practice is not only profitable in the short run, but is also very much a part of the traditional agriculture pattern -- representing rational behavior in dealing with the scarce resource of water.

Substantial redesign of Pakistan's irrigation system, which would require large capital investments, will be necessary to provide the farmer with sufficient and timely supplies of water. Although not previously mentioned in this report, it is not likely that such capital will soon be available. Consequently, any future agricultural improvement must take place within the operating constraints of the present irrigation system. For most farmers, water reliabilities will be built into their farming programs by expanding the exploitation of underground water resources through the development of private tubewells. This avenue is not possible for much of the Lower Indus Basin because of the high salinity of the underground water. For this region, the Government must re-examine the flow networks of the canal system and try to build into the system a more reliable delivery capacity. With increased storage capacity at Mangla and Tarbela dams, this should be a possibility.

Regardless of the future development of the Indus Basin irrigation system, more attention must be given to better utilization of water by the farmers in the watercourses. There is a direct correlation between reliability in the amounts and the times of water and

the implementation of improved agricultural practices. Farmers with a high water reliability factor are invariably high adopters of new seeds, fertilizers, and technologies. The opposite is the case for farmers confronted with low water reliability.

Building more reliable supplies of water into the system will not guarantee that Pakistani farmers will adopt improved agricultural practices. Past studies reveal, where there is an oversupply of land in relation to water, farmers are more prone to increase total production by expanding the land area cultivated through under-irrigating, rather than following more desirable soil-conserving watering practices.

The reason is quite obvious. Under conditions of high uncertainty the farmer tends to spread his risk factor. It has not been adequately demonstrated to him that the concentrating of water on a smaller land area will necessarily improve his position.

In redesigning the Pakistani irrigation system, as well as convincing the farmer to accept improved agricultural practices, it is imperative that empirical data be secured as to the response of crops to various levels of water deficiencies over time. The recent studies making such computations in gross terms are useful for long-range planning purposes. For a given watercourse, because it is usually divided into a number of farms, there exists a production function between the total amount of water delivered and the total amount of crop produced. This does not necessarily follow, and is not usually the case, for each individual farmer. As already explained, missing one or two irrigation turns for him may result in a total loss or at least a substantial decline in agricultural

product. For the larger agricultural system, with the capacity to spread out this loss factor, a given quantity of water usually gives a given quantity of product. However, the typical farmer with his small plot of land, is not prepared to work within this risk situation, even if he has some kind of "insurance" or protection.

Tubewell water appears to be the principal means of smoothing out the irregularities and erratic tendencies of water supply in the irrigation system. However, this supply is several times more costly than canal water, and knowledge of crop response to given amounts of water over time is essential for determining economic cropping patterns. At some periods of the growth pattern, a small addition of tubewell water may give high returns and at other times it may not. The farmer needs to know more about this relationship in order to make sensible decisions as to when to irrigate with expensive water and when to not.

Going to a higher level of analysis, the Pakistani irrigation system is designed to deliver an almost fixed flow into the watercourses from canal distributaries that flow in hydraulic equilibrium without intermediate regulators. The amount of water delivered at the head of each watercourse varies from 1 to 4 cubic feet per second. The system has little tolerance for variable flows. Flows falling below three/fourths full supply cannot usually be delivered except by the rotation of supplies in the distributary canals. In economic terms it is important to know which rotations would give the highest "pay-offs," especially because land and water revenues are important to the Government's financial structure. Such a decision cannot be reasonably determined under the present state of knowledge.

As stressed in the body of this report, under-irrigation is a major factor in building up soil salinity. The World Bank studies assume that the usual water losses in the watercourses are sufficient to flush out the salts, providing the practice of under-irrigation is not followed. However, this is not a solution to the problem. The critical question is the amount of water required to flush out the soil at a particular time. Generally, it takes 6-8 inches applied at one time, rather than small amounts over a period or series of irrigations. For example, if an additional inch of water is added each time over a series of six irrigations, it is probable that no significant flushing will occur. Also, not all of the water loss occurs in the fields. Much of the loss is found in the ditches and laterals, which contributes little to flushing out the salts from the irrigated fields.

To preserve the irrigated lands under the canal commands, it is imperative that full delta watering be practiced. This would include flushing out the salinity at the end or the beginning of each crop planting. To avoid waste of scarce water, realistic irrigation schedules must be developed.

In final note, some may ask the reason for pursuing in Pakistan a line of research which has not been followed extensively in the United States. This is not sufficient grounds to dismiss our suggestions. West Pakistan constitutes one of the largest irrigation systems in the world, and its future is inextricably linked to the country's continued progress. The research needs suggested here are

believed to be very important for the future renovation of the irrigation system, in order to incorporate improved agricultural practices leading toward increased productivity.