

THESIS

IRRIGATION SCHEDULING IN PAKISTAN

Submitted by
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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION
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ABSTRACT OF THESIS

IRRIGATION SCHEDULING IN PAKISTAN

Water, being the "life blood" of both plants and animals is a limiting factor in the agricultural economy of most of the late developing countries. Pakistan is no exception. Where water is plentiful, it is often wasted. This wastage often results in waterlogging. Where there is a limited supply of water, wastage leads to decreased yields and salinity problems. Efficient use of limited irrigation water supplies in Pakistan has become more important since the demand for irrigation water has increased and new sources of supply are becoming harder to develop. To get the most out of each unit of water one must know how much water to apply, when to apply, where to apply and how to apply water to crops. Present on-farm water management practices are the major constraint on food production in Pakistan.

In spite of limited irrigation water supplies, over-irrigation is a common practice in Pakistan due to unlevelled fields and lack of knowledge of plants' water requirements. Tremendous delivery losses have been measured by others in badly managed earthen watercourses. Extensive measurements on farmers' fields indicated substantial field irrigation application losses.

To determine the proper amount and timing of irrigation, different methods of determining crops peak water use were compared. Water use as estimated from pan evaporation was more closely correlated to actual water use under the

conditions of the study than were estimates using the empirical equations. Consequently, estimates of water use based on pan evaporation are recommended for use in this area.

The need for an irrigation extension advisory service to provide scientific irrigation scheduling services to Pakistani farmers has been recognized. Accordingly, scientific irrigation schedules were prepared for a maize crop. Recommendations were made regarding reorganizing the existing institutional infrastructure both in public and private sectors to implement on-farm water management in Pakistan with irrigation scheduling as its basic component.

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GLOSSARY

<u>Abbreviation/Term</u>	<u>Explanation</u>
MAF	Million acre feet
WAPDA	Water and Power Development Authority, Pakistan
WASID	Water and Soil Investigation Division of WAPDA
Mogha	Ungated water outlet from the canal or distributary discharging a specific discharge for a designed head difference
Distributary	Small canal
Cusec	Cubic feet per second (cfs)
Watercourse	Lateral taking water from canal outlet to the farmer's fields
Delivery or Conveyance Efficiency (E_d)	Ratio of the water available at the farmer's fields and that at the canal outlet and is represented by a percentage
Application Efficiency (E_a)	Ratio of water needed in the crop root zone and the water applied to the crop and is represented by a percentage
Farm Irrigation Efficiency	Product of Delivery and Application Efficiency
Katcha Warabundi System	Irregular, continuously changing irrigation turn system for water allocation
Pacca Warabandi System	Permanent turn system for water allocation with a fixed weekly time for each farm
Nakka	A cut on the watercourse for diverting water to the field

Maize crop	Corn crop
USDA	United States Department of Agriculture
USBR	United States Bureau of Reclamation
Doab	Tract of land between two rivers
SCARP	Salinity Control and Reclamation Project
Kharif Crops	Crops grown between April 15 to October 15. Mostly summer crops.
Rabi Crops	Crops grown between October 15 to April 15. Mostly winter crops.
Katcha	Temporary, earthen
Pacca	Permanent, concrete
ETP	Potential Evapotranspiration Rate
ETA	Actual Evapotranspiration Rate

Units of Measurement

One Acre = 43,560 square feet

One Maund = 82.28 pounds

One Rupee = U.S. \$0.101, Pakistani currency unit

Chapter I

INTRODUCTION

A. Background

Water, which is the life blood of plants and animals, is a limiting factor in the expansion of irrigated areas and in the production of food. As the population increases, greater competition for the water supply makes conservation and efficient use of water imperative. Where water is plentiful it is often wasted. Where there is a diminishing supply of water, or it is scarce and expensive, conservation methods are most apt to be practiced. The purpose of irrigation is to provide an optimal water supply, avoiding shortage and excess of water. Limited water supply leads to growth retardation and salinization of soils as soil water is evaporated and transpired and salts remain in the soil. The removal of these salts requires extra irrigation for leaching purposes and the drainage of this water. Over-irrigation on the other hand results in excessive percolation of water to the substrata resulting in low irrigation efficiency, leaching of nitrates and a rising water table.

When adequate irrigation water supplies are readily available and irrigation water costs are small, the main purpose of irrigation water management for food and fiber production is to maintain the soil water level within a range that does not significantly limit plant growth and crop production. When water supplies are limited and maximum crop production is needed for seed crops, food, and

fiber, the main objective may shift to maximizing net income per unit of irrigation water.

To get the most out of each unit of water, one must know how much water to apply, when to apply it, where to apply it, and how to apply the water to crops. Irrigation scheduling is a decision making process by which the amount and time of irrigation is determined from current measurements (direct or indirect) and immediate future predictions of the plant use of water. Present day investigations and applications of the scientific irrigation scheduling concept have greatly broadened its scope in order to meet the scope of modern agricultural technology. At present an irrigator is primarily dependent on the judgment and experiences of his immediate associates and himself, i.e., the well informed, experienced farmers are often able to judge the need for an irrigation based on the general appearance of the crop and soil.

Scientific irrigation scheduling is based on a thorough understanding of the primary parameters affecting crop water demands, i.e., climatic, crop and soil factors. Meteorological conditions determine the atmospheric demand for water from the plant. More than 95% of the water used by the plant is used in the process of evaporation and transpiration. Crop parameters which should be considered include: tendencies to resist transpiration, stages of crop growth as they determine critical water use periods, and plant growth characteristics such as size, density of cover,

and crop rooting depths. The soil conditions include texture and structure of the soil as they influence the water infiltration rate and soil moisture storage capacity.

B. Irrigation System in Pakistan

Pakistan is a river born country. The history of its people has been closely associated with the development of irrigated agriculture on the alluvial plains. Pakistan stretches from latitudes 24° to 37°N and longitudes 62° to 75°E . It lies wholly outside the tropics and although its climate is generally classified as "tropical monsoon," it is in fact continental in character. Annual rainfall averages only 12 inches, but the ranges of precipitation and temperature are considerable. Water is the primary factor which has influenced the pattern of agricultural production, the productivity of land and the economic welfare of most Pakistani farmers.

The flat and fertile Indus Plains of Pakistan, its 35 million acres of rich alluvial soils endowed with an ideal combination of solar energy, excellent climate for year round cropping, a large groundwater aquifer and above all, its 66 million sturdy and hard working people provide one of the greatest potentials for agricultural productivity in the world. The irrigation system of Pakistan represents one of the largest modern conveyance systems in the world and is a marvel of engineering skill and technology up to the mogha outlet. However, beyond the mogha the conveyance and utilization of water are less efficient resulting in low cropping

intensities averaging less than 60 percent per season and some of the lowest yields per acre in the world.

The canal system in Pakistan was designed in the second half of the 19th century during the British regime, with the objective of extensive irrigation to bring more area under irrigation to settle more people. This system provided a water allowance of about one cusec for 350 acres of culturable commanded area which is low as compared to one cusec for 75 acres in the Imperial Valley system in California. A combination of events have resulted in intensive studies of major problems related to irrigation water management in Pakistan. According to an estimate (Early, 1975), as shown in the accompanying flow chart, 142 million acre feet (MAF) of water are available for extraction in the Indus River system annually, about 92 MAF are diverted to the canal system, leaving 50 MAF to go to the sea. From the 92 MAF at the canal headworks, 29 MAF are lost in the main canal system and 63 MAF are available at the watercourse head. An estimated 30 MAF of water are added through 1,200,000 tubewells working both in the public and private sectors and this makes 93 MAF available at the watercourse head. It is further estimated that 44%, or 37 MAF of this available water, is lost between the mogha and field nakkas due to faulty design and poor maintenance of watercourses resulting in overtopping and spillage losses. It has further been noted that on the average, 25% of the application to the fields is lost due to over-irrigation in

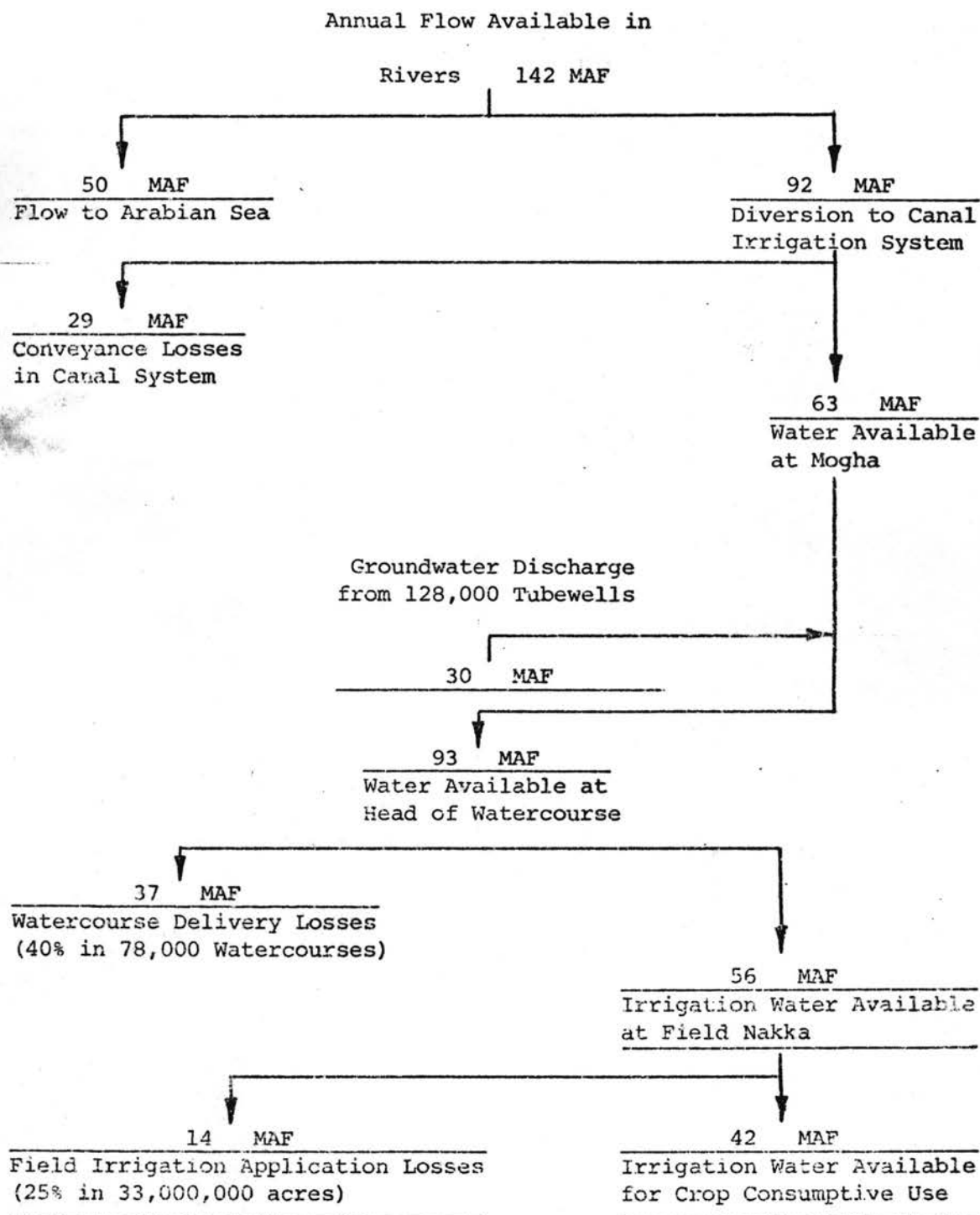


Figure 1. Flowchart of Indus Basin Water Supply System
(after Early, 1975)

quantity applied and frequency of application on unlevelled fields using inefficient irrigation methods. Thus, out of 93 MAF available at the canal outlet only 42 MAF are used for crop production. Saving 14 MAF of water lost largely through over-application and application at the wrong time is the main target of scientific irrigation scheduling in Pakistan.

In Pakistan, the strategy used for water resources development for the last two decades has been to replace water lost to India in the Indus Basin Agreement, to increase water availability for irrigated agriculture, and tackle the immense problem of waterlogging and salinity. This strategy laid major emphasis on development and improvement of the existing surface and groundwater resources of the Indus Basin through the construction of marvelous engineering structures at Mangle and Tarbela, and utilization of groundwater resources through installation of tubewells. It was assumed in the development of the strategy that efficient water management exists in the watercourse command area and that irrigated agriculture becomes more efficient as more water is made available.

Recent studies (e.g., Corey and Clyma (1974), Lowdermilk et al. (1975)) from a large sample of villages in Pakistan indicate less than 50% irrigation efficiency within the watercourse command. These data indicate a greater potential for improving water supplies to crops by improving watercourses and application efficiencies than by increasing diversions from the river system.

C. Nature of Problem

The irrigation system in Pakistan, with its operating procedures, has limitations which must be considered when planning for improvement. A basic feature of the canal system is that it was designed to operate on a constant discharge basis which makes it difficult to respond to irrigation demand. This was done because all canals are alluvial channels which can only operate within a limited discharge range if they are to remain in "regime," which prevents the silt from depositing in the canals and creating a maintenance liability.

The moghas are open concrete structures with no control gate and in a de jure sense every watercourse on the canal receives water on an equal basis in proportion to the acreage served. On the watercourse, farmers utilize the flow on a turn by turn (warabundi) basis with each farmer taking the flow during his particular weekly time allotment, which is in proportion to his area cultivated on the watercourse. The irrigation water is supplied on a rigid schedule with each farmer receiving water on a regular basis for a fixed time interval. Even if a particular farmer, at a particular time, has no crop planted, he (according to the rules) is required to use the water during his turn. This type of scheduling appears to be a water disposal system rather than an irrigation supply system. Some trading of water occurs between farmers, which is not according to the rule. This rule is not enforced by the Irrigation

Department, but farmers who trade and thus take water out of turn normally have to fill a longer section of watercourse and lose an appreciable portion of the water to wetting of dry banks and dead storage. The irrigation system is in place and the farmer can utilize this resource most effectively if he learns the water requirements of his crops and how to apply the water appropriately.

The water records of the Irrigation Department show the flow rate of water legally allocated to the mogha and the irrigation time assigned to a farmer. What he actually receives may be different because of illegal changes in structures and submerged moghas. The lack of water flow measurement facilities in the watercourse command area has been a primary factor in the lack of knowledge concerning delivery and application efficiencies.

The on-farm water management aspects of irrigated agriculture are completely neglected in the institutional infrastructure of the existing Irrigation and Agriculture Departments in Pakistan. Farmers present practices for determining the timing and amount of irrigation water are a logical consequence of their present knowledge and the constraints that the present irrigation system places on them. Therefore, they are not entirely responsible for the mismanagement, but this mismanagement emphasizes the need for research on the most practicable method of scientific irrigation scheduling in Pakistan.

D. Objectives

The objectives of this study are:

- a) To determine the most practical method for predicting potential evapotranspiration for scientific irrigation scheduling using climatic, crop, and/or soil data.
- b) To determine the best irrigation schedules for maize fodder.
- c) To determine the potential for improving the efficiency of water use by the farmers through comparison of irrigation application efficiencies in normal farmers' fields, compared to fields where the timing and amount of water is optimized.

E. Scope of Study

The scope of the study is limited to conducting field studies, including collection of climatic, crop and soil data on a selected watercourse command area at Kanjra in the Shadab Pilot Project of the Integrated Rural Development Program. The study involved the following:

1. Determination of potential evapotranspiration from pan evaporation, the Penman equation and the Jensen-Haise method of estimation and comparison of these estimates with the field data for soil moisture depletion measured by frequent soil samplings (these experiments were conducted on wheat and continued for maize fodder).

2. Precisely leveled fields were planted to maize fodder and a selected method for irrigation scheduling was applied to demonstrate the methodology under Pakistan's farm conditions.
3. Comparison of application efficiencies was made through extensive discharge measurements at field nakkas during each irrigation for a series of improved and unimproved fields during the growing season of both wheat and maize fodder crops and comparisons of the amounts of water applied with the amounts of water used by the crops.

Chapter II

LITERATURE REVIEW

A. Soil-Plant-Water Relationship

To understand the necessity of continual application of science and technology to improve crop production, one must recognize the role that water plays in the complex crop-soil-climate system. Slatyer (1967) indicates that water is essential for the structural integrity of biological molecules, cells, tissues, and for the transport of mineral nutrients and the translocation of materials in solution throughout the plant body. In plants, there is a liquid phase continuity from the water in the soil through the plant to the liquid gas interface at the evaporation sites in the leaves. The root system provides an extensive absorbing surface across which pass virtually all of the water and mineral nutrients utilized by the plant. The plant leaves provide a complex evaporating surface through which most of the water used by the plant passes as transpiration.

The key factors controlling the plant water needs are meteorological, crop, and soil factors. Meteorological factors determine the atmospheric demand for water from the plant. More than 95% of the water used by the plant is utilized in transpiration, evaporative cooling, and less than 5 percent is used in photosynthesis which develops the organic building blocks used in the cellular structure of the plant. Atmospheric demand is dependent on radiant energy,

relative humidity and wind intensity. Important crop factors include the type of crop, stage of growth, density of cover, and the crop rooting depth with respect to time. The important soil factors include the texture and structure of the soil as these properties influence the infiltration rate, soil moisture storage rate, and the size of the root zone-soil moisture reservoir.

Once the pattern of plant water needs is known, a daily water balance equation can be maintained for the root zone using irrigation and precipitation as inputs while evaporation, transpiration, deep percolation and surface runoffs are withdrawals. This water-balance equation which is an application of the continuity equation can then be used as the basis for scientific irrigation scheduling.

B. Water Balance Equation

The water-balance equation can be defined as follows

(Fig. 2):

$$W_s = W_i + W_r - W_{et} - W_l$$

where W_s = change in soil water stored in the root zone of the plant.

W_i = Water added by irrigation.

W_r = Water added by rainfall.

W_{et} = Water consumptively used in evapotranspiration.

W_l = Water lost in the soil profile due to deep percolation, surface runoff or wind drift of the humidified atmospheric strata above the wetted soil during irrigation.

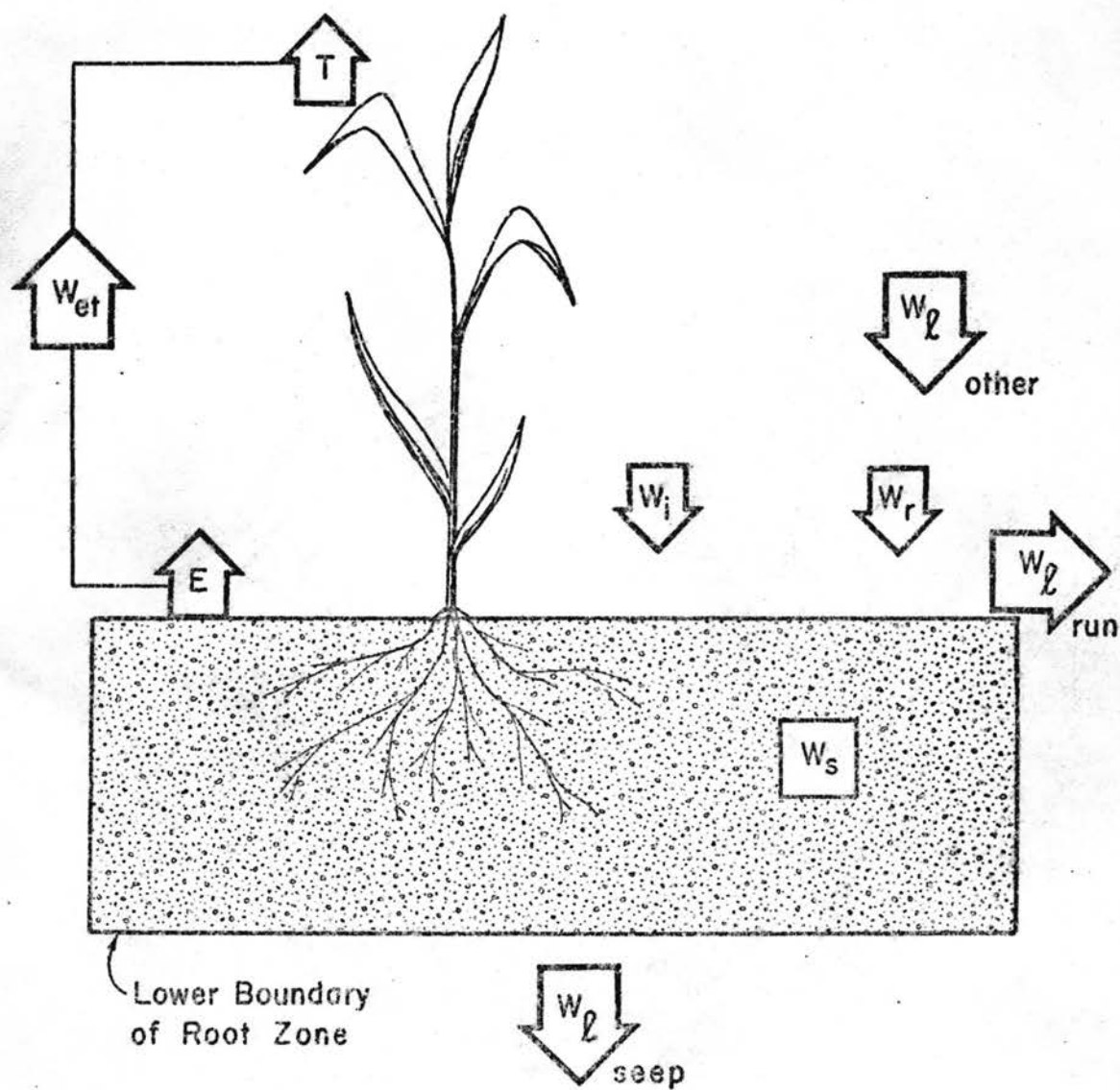


Fig. 2. Sketch for Water Balance Equation.

C. Consumptive Use

Consumptive use of water is combined evaporation from all soil and plant surfaces, transpiration of plants and the amount of water used by the plant for metabolic activities. Except for the negligible amount of water used in the metabolic activities, evapotranspiration is the same as the consumptive use.

Although evaporation and transpiration have been studied for more than 200 years, the term "consumptive use" probably was not applied to water consumption prior to 1900 (Chang, 1968).

D. Methods of Irrigation Quantity and Timing Determination

Studies of consumptive use and irrigation water requirements were started since irrigation water supplies were generally inadequate to irrigate all of the available lands in areas where civilization first began to rely on agriculture as a way of life. Numerous procedures have been proposed and advocated for decades to determine when and how much to irrigate crops.

1. Probably the earliest and most common procedure proposed is to note the appearance of the soil in the root zone using a probe or a shovel. Farmers were reluctant to expend this effort to assess irrigation needs by this method.

2. Plant appearance was also used to determine crop water needs, but generally by the time the plant shows the symptoms of water shortage, crop yield or quality have already been irreversibly and deleteriously effected.

3. Using tensiometers to determine when to irrigate has been advocated for many years. Tensiometers have not been routinely accepted by many for practical use since they require much time for installation and recording observations several times each week. Tensiometers may interfere with cultivation and may give erroneous readings caused by poor contact with the soil. Tensiometers are also practically limited to the soil moisture range of less than 0.8 bars tension.

4. Electrical resistance or soil moisture blocks have also been used for many decades to determine crop water needs. Soil moisture blocks can be used effectively by trained irrigation technicians in research.

E. Methods of Consumptive Use Determination

1. Tank and Lysimeter Experiments: Lysimeters are tanks buried in the ground which collect percolation of water out of the soils and thus simplify the water-balance equation. Generally, they are weighed or refilled to constant water content, allowing direct measurement of water use. Lysimeters can be a dependable means of directly measuring the consumptive use of water. Reliability of consumptive use determinations by means of lysimeters is dependent on nearness of reproduction of natural growing conditions and physical surroundings. Deviations from natural conditions are caused by limitations of soil, size of tank, regulation of water supply and sometimes environment (Chang, 1968).

2. Gravimetric Soil Moisture Determinations: Changes in soil moisture which show the water consumptively used by the crop are determined from periodic soil moisture samplings in the soil profile. Soil moisture samples are taken by using soil augers and king tubes for a range of depths of the soil profile. Moisture content is determined at different depths by gravimetric analysis. Wet soil samples are weighed and then oven dried for about 24 hours at 105°F temperature until there is no change in the sample weight by further drying. Moisture content on a dry weight basis is determined from the ratio of the weight of water and the dry weight of the soil sample. The moisture content on a volume basis is determined from multiplying the dry bulk density of the soil sample by the moisture content on a dry weight basis. This method is less accurate than the tank and lysimeter experiment since it does not precisely take into account the upward and downward movement of the water from the soil profile due to rising water table and deep percolation from the soil profile during the period between samplings, respectively. The method also involves much labor and, therefore, results in errors in determinations. This is the more commonly used method for consumptive use determinations.

F. Prediction of Potential Evapotranspiration

Penman (1956) defined potential evapotranspiration as the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never

short of water. Several methods of predicting potential evapotranspiration are in common usage in various parts of the world.

1. Thornthwaite's Method: Thornthwaite (1948)

presented a formula for estimating potential evapotranspiration based on lysimeter and watershed observations of water loss in the central and eastern United States. The formula developed is:

$$E = 1.6(10T/I)^a$$

where E = unadjusted (30 day - each a 12 hour day)
potential evapotranspiration in centimeters

T = mean monthly temperature in $^{\circ}\text{C}$

a = constant, based on location, latitude

I = annual heat index. The annual heat index, or I , is the sum of 12 monthly heat indices i , where

$$i = (T/5)^{1.514}$$

To evaluate " a ," Thornthwaite used the following equation:

$$a = 0.000000675i^3 - 0.0000771i^2 + 0.01792i + 0.49239$$

He corrected the unadjusted potential evapotranspiration by actual day length of hours and days in a month to give the adjusted potential evapotranspiration.

Thornthwaite's method worked well in the temperate continental climate of eastern North America where the formula was derived and where temperature and radiation are strongly correlated. In other parts of the world, the Thornthwaite approach has been less successful. The most serious shortcoming is that temperature is not a good

indicator of the energy available for evapotranspiration. Secondly, according to the Thornthwaite formula, evapotranspiration will cease when the mean temperature is below 0°C . This is by no means true, although the amount of evaporation may be small. Furthermore, the maximum temperature of various days during a cold winter month may rise well above freezing. The formula thus underestimates winter evapotranspiration in middle and high latitudes except in areas of strong advection of warm air (Chang, 1968).

2. Blaney-Criddle Formula: Blaney and Criddle (1950) simplified the Blaney and Morin (1942) formula by dropping the humidity term from the equation for actual crop evapotranspiration and multiplying the result times a crop coefficient to predict actual evapotranspiration. The original formula proposed by Blaney and Morin (1942) was:

$$U = KTP (114-b)$$

where U = monthly consumptive use in inches

K = crop coefficient

T = mean monthly temperature in $^{\circ}\text{F}$

P = monthly percentage of day time hours in the year

b = mean monthly relative humidity.

Later, Blaney and Criddle (1950) simplified the earlier equation by dropping the humidity term, thereby yielding the commonly employed Blaney-Criddle equation:

$$U = KTP$$

This formula has shortcomings similar to those of the Thornthwaite method. Stanhill (1961) noted that outside

the semiarid climate of the western United States, the performance of the Blaney-Criddle method was usually very poor.

3. Penman Equation: Solar energy in conjunction with the aerodynamic effect of air movement has been shown by many to be largely responsible for the consumptive use of water by plants. Briggs and Shantz (1913) stated that the water requirement measurements must be considered relative rather than absolute. They also recognized while recording meteorological data that solar radiation was the primary cause for the cyclic changes of environmental factors.

Penman and Budyko (1930) applied the energy balance concept developed by Briggs and Shantz (1913) to crops. Penman (1948) combined an energy balance and aerodynamic equation to form a so-called combination equation which is now being used in modified forms extensively throughout the world to predict potential evapotranspiration. The equation as per Israelson and Hansen (1962) is:

$$ETP = \frac{\Delta H + 0.27 E_a}{\Delta + 0.27}$$

with values of H and E_a as

$$H = RA(1-r)(0.18+0.55n/N) - \sigma T_a^4(0.56-0.092\sqrt{ed})(0.10+0.90n/N)$$

$$E_a = 0.35(e_a - e_d)(1 + 0.0098U_2)$$

where H = daily heat budget at surface in mm of H_2O /day

RA = mean monthly extraterrestrial radiation in
mm H_2O /day

r = reflection coefficient of surface

- n = actual duration of bright sunshine
 N = maximum possible duration of bright sunshine
 σ = Stefan Boltzman constant = 2.01×10^{-9} mm/day
 σT_a^4 = mm H_2O /day computed for absolute temperatures,
 T_a , degrees Kelvin
 e_a = saturation vapor pressure at mean air
temperature in mm Hg
 U_2 = mean wind run at 2 meters above the ground
(miles/day)
 E_a = evaporation in mm H_2O /day contribution due to
vapor diffusion
 e_d = saturation vapor pressure at dew point
temperature
ETP = potential evapotranspiration in mm H_2O /day
 U_h = measured wind speed in miles per day at height
 h in feet. Where wind run at other heights
is converted to 2 meters equivalent assuming
logarithmic wind profile and using the
equation $U_z = U_h \frac{(\log 6.6)}{\log h}$
 Δ = slope of saturated vapor pressure versus
temperature curve at absolute air temperature
 T_a in degrees Fahrenheit (mm Hg/F°).

Penman's definition of potential evapotranspiration does not specify the size of the field or the condition of the surrounding areas. In other words, no provision is made for the effect of advected energy, i.e., exchange of energy or moisture as a result of horizontal heterogeneity (wind movement). If an area upwind of an irrigated field is hot and dry, then sensible heat will be transferred to the irrigated field and its evapotranspiration rate will be increased. On the other hand, if the advected air is colder than the vegetation, then the evapotranspiration rate will be relatively low. Advection is a serious problem in arid

and semiarid climates (Chang, 1968). Pruitt (1960) designated the term "potential maximum evapotranspiration" to describe the situation when advected energy is present.

Thus, one should not expect the empirical coefficients utilized in the Penman potential evapotranspiration equation derived in a humid climate to be adequate for estimating the potential maximum evapotranspiration in an arid or semiarid climate like Pakistan.

Penman and Schofield (1951) gave two reasons why the potential evapotranspiration of a short crop is less than open water evaporation; (1) the higher albedo of the vegetation, and (2) closure of the stomata at night. Neumann (1953) argued from the standpoint of turbulent theory that the potential evapotranspiration of a short crop is approximately 75% of the open water surface evaporation.

Application of the Penman equation requires observations of radiation, temperature, humidity and wind which are usually available only in first order weather stations. The computation of the equation is quite complicated. In order to expedite the computation, Macculloch (1965) presented tables for the various components in the equation, whereas Rijkoort (1954) and Kohler et al. (1955) have prepared nomograms that enable the computations to be completed in a few minutes.

The coefficients used in the Penman equation were determined for a rather humid area not far from the ocean and essentially covered with growing vegetation; thus, the

Penman equation has given better results in humid areas like England than in arid, low humidity areas where temperature and radiant energy may be excessive.

4. Jensen-Haise Equation: Jensen and Haise (1963) introduced the potential evapotranspiration equation based upon radiation and average temperature data. They re-evaluated 30,000 published and unpublished short period measurements of evapotranspiration by their equation which is as follows:

$$ETP = C_T (T - T_x) R_s$$

where ETP = the potential evapotranspiration for reference crop in inches/day

C_T = the air temperature coefficient which is constant for a given area and is derived from long-term mean, maximum and minimum temperatures for the month of highest mean air temperature

T = mean daily air temperature

T_x = a constant for a given area and is merely the linear equation intercept on the temperature axis in the solar radiation-air temperature relationship

R_s = the daily solar radiation expressed as the equivalent depth of evaporation (inches/day).

Jensen (1972) stated that the accuracy of consumptive use measurements by the potential evapotranspiration concept be within 10 to 15%. It is significant to note that Jensen, a co-developer of this concept has stated a preference to use the Penman equation when the required climatic data are available (Hart, 1975).

5. Pan Evaporation: Evaporation from open basins of water called pans have been used throughout the world to

estimate evapotranspiration for different crops and have given very reliable results. Fuchs and Stanhill (1963) make reference to some experimental work where a high correlation was found between the actual evapotranspiration from a number of crops receiving an optimum irrigation treatment and the amount of evaporation from adjacent Class A, U.S. Weather Bureau Pans.

Blaney and Morin (1942) concluded that the meteorological factors affecting evaporation from free water surfaces also affect evapotranspiration from vegetation, which indicates that evaporation from a free water surface under given conditions can be used to estimate evapotranspiration in areas where there is no limitation in water supply during the growing season. They also considered the main factors effecting evapotranspiration as wind movement, temperature and humidity.

Many studies over several decades have suggested the use of pan evaporation data to estimate potential evapotranspiration using the equation

$$ETP = K_e E_{pan}$$

where K_e is dependent on the reference crop and type of pan involved. Such studies have led to the use of evaporation pans in scheduling irrigations.

G. Irrigation Scheduling Research

1. Historical Perspective: Before the development of the present scientific irrigation scheduling technology, a farmer was primarily dependent on his judgment and his experience and that of his immediate associates. The

farmers who produced the greatest yields were able to judge the need for an irrigation based on the appearance of the crops. Since the days in the Tigris and Euphrates Valleys centuries ago, farmers engaged in irrigated agriculture have had to face the critical decision of how and when to irrigate their lands. Irrigation scheduling, therefore, in its primitive form emerged long before the introduction of digital computers, climatological monitors and instantaneous communication systems.

2. Soil Moisture Approaches: Improvements in irrigation scheduling, utilizing advancements in irrigation science and technology resulted when numerous devices like atmometers, evaporation pans, tensiometers and soil moisture blocks were introduced. The lack of change in irrigation scheduling practices by the farmers after 20 to 30 years of advocating using these instruments implies that these participatory procedures for providing irrigation scheduling information have not been very effective.

3. Climatological Approaches: Irrigation scheduling using climatic data seems to be the most attractive and promising technique where the farmer's control the irrigation system.

Das (1930) suggested the use of climatic data to control irrigations. Penman (1948) and Thornthwaite (1948) developed equations to determine irrigation needs. The others who discussed the climatic approach for scheduling irrigations were Pruitt and Jensen (1955), Rickard (1957) and Van Bavel (1960).

Several procedures were developed to schedule irrigations after 1965 in the U.S.A. that utilize computer technology and current climatic data. Jensen, et al. (1969-70) introduced computerized irrigation scheduling using the Jensen-Haise (1963) equation based on solar radiation and average temperature data.

4. Irrigation Scheduling Services in the United States:

The components of current irrigation scheduling services in the United States were developed and evaluated in 1966 and 1967 in southern Idaho by personnel of the Agricultural Research Service of the U.S. Department of Agriculture (USDA). Beginning in 1968 and 1969 the program was accepted on a larger scale in Arizona, Nebraska, Kansas, Colorado, New Mexico, Washington and California. Professional irrigation scheduling services are rapidly expanding and many of the companies are using the computer program developed by the USDA. This program used meteorological, soil and crop data to predict irrigation dates and amounts.

5. Computerized Irrigation Scheduling Technology: The USDA computer program was developed in 1968 cooperatively with farm managers and service groups to incorporate their reactions during the formulation of the program. Several service groups and companies gained experience using this concept of providing irrigation management services in 1970.

The U.S. Bureau of Reclamation (USBR) modified the computer program to provide either general irrigation forecasts for several major crops, soil types and dates of

planting within an irrigated area, or field-by-field scheduling. The present USBR general program predicts irrigation dates for major crops and soils, but the printout to each farm is selected from a combination of six crops, four soils and three planting dates.

The field-by-field method, involving field inspections by trained professional or technical staff members was evaluated on 5,000 acres by the USBR in 1971.

A commercial irrigation management service corporation was formed by potato growers in southern Idaho in 1971 to provide irrigation scheduling services on a commercial basis. Another company began providing irrigation scheduling services in cooperation with a sugar company in southern Idaho in 1971.

On the Salt River Project near Phoenix, Arizona, the problem of irrigation scheduling was approached via two methods which determine soil moisture levels and the evapotranspiration rates for different crops and soils. These methods included repetitive field checks by trained specialists and a computer program described by Jensen which uses either the Jensen-Haise or the modified Penman equations for potential evapotranspiration. Jensen's computer program was rewritten by Tankersley (1968) and was tested on 2100 acres located on 19 farms in the Salt River Valley.

Scientific irrigation scheduling as currently defined is based on gravimetric soil sampling by instruments that

measure soil water directly, or instruments that indirectly indicate soil water content, evaporation devices and predictors of potential evapotranspiration based on climatological data. The extent to which trained personnel provide irrigation scheduling services with these instruments and methodologies is very limited.

Chapter III

WATERCOURSES IN PAKISTAN

A. Introduction

Agriculture in Pakistan is dependent on irrigation. Dams, barrages, canals, watercourses and wells are not only the backbone of her economy, but are so intimately related to the life of the people that irrigation is very much a human problem. The lack of irrigation would result in starvation and misery for large parts of the population.

Water has bestowed both blessings and destruction upon mankind. Civilizations have always developed where water was available. Man's responses have been filled with both deed and myth. His attempts to utilize and control water have progressed from simple ditches and flood control devices of primitive man in the remote civilization (2500-1500 B.C.) of the Indus plain to the modern complex irrigation system. Evidence from Mohenjodaro and other archaeological sites in Pakistan shows that, as early as 1000 B.C., land near the rivers of the Indus Plains was being cultivated under flood irrigation.

The first canals in the Indus Valley which comprises a major part of Pakistan, were constructed some five or six centuries ago and were extended under the great Moghul emperors. These canals were inundation channels which delivered water to the fields when rivers were high in summer. But they were rather unpredictable in operation and were subject to both frequent breaches and serious siltation problems.

The canal system which is seen today commanding some 33 million acres of land in Pakistan was started about the middle of the 19th century during the British regime. The works undertaken resulted in the world's largest integrated system to provide irrigation facilities. Barrages with controllable gates to provide some upstream channel water storage and diversion and headworks with fixed position weirs for water diversion were constructed so that the supply of irrigation water was no longer so dependent on the natural variations in the river levels. The present canal system was generally designed for extensive irrigation (i.e. to command as much land as possible) so that as many persons as possible could be settled on the projects. Although water allowance was made to meet the crop water requirements, the designed cropping intensities were very low. The cropping intensities are only one-third of the intensities which the lands and climate have the potential of supporting.

More than one hundred years of irrigation development in the Indus Valley have resulted in the world's largest integrated irrigation system. There are an estimated 60,000 miles of canals which command a gross area of 33 million acres of fertile soils. About 25 million acres actually receive surface water. Today there are about 1,200,000 tubewells supplementing the Indus Basin and providing water to an additional 8 million acres. Water flows from the main channels through distributaries to minor canals and then outlets through a mogha into a watercourse, which supplies water to the command area through field ditches.

Forty thousand miles of the network of canals, distributaries and minors deliver water to more than 78,000 individual watercourses. Large link canals, installed across the Doabs, transfer water from western rivers to eastern rivers, and the system reservoirs at Mangla and Tarbela even out the seasonality of riverflows. More than four million individual farmers with an average farm size of eight acres are dependent on this system.

The canal irrigation system of Pakistan is not only large but it is unique in several other aspects. One disappointing feature, however, is the present low production in light of the apparent highly suitable soil, water and climatic resources. These factors suggest a production potential many times greater than presently achieved.

Many experts agree that the farming practice, including irrigation water management, must be modernized in order to achieve higher production. The Revelle Report (1966), which initiated the present cycle of developmental activity, states that: "In (West) Pakistan, we have the wasteful paradox of a great and modern irrigation system pouring its water on lands cultivated as they were in the middle ages."^{2/}

The irrigation system in Pakistan operates at less than 50% overall efficiency. For each 90 MAF of water diverted, plus 30 MAF pumped from the groundwater aquifer, at the most 45 MAF, and probably less than that, are effectively stored in the root zone for crop use. Most of the losses occur in

^{2/}The Revelle Report (1966).

watercourses below the mogha as delivery losses and field irrigation application losses. The 78,000 watercourses contain more than 1.5 million miles of poorly constructed and poorly maintained earthen channels. Dr. Wayne Clyma was probably the first in Pakistan to measure the real magnitude of operational losses occurring beyond the mogha in the farmers' watercourses due to seepage, spillage and leaky nakkas. He continued his studies of measuring watercourse losses at different sites at the Mona Reclamation Experimental Project at Sargodha, Shadab project in Lahore, and Lar in Multan. He also measured the field application efficiencies on levelled and unlevelled farmers' fields to determine the extent of field irrigation application losses.

Clyma (1974) and Clyma et al. (1975) provided their observations on watercourse losses and invited the attention of the Government of Pakistan and the United States Agency for International Development (USAID), which ultimately resulted in launching of different programs under the Water and Power Development Authority (WAPDA) and Punjab Government to further investigate the extent of watercourse losses. These studies resulted in watercourse improvement programs. Because the watercourse losses reported by Clyma et al. (1975) were about four times those assumed previously, they received much criticism from different agencies. The watercourse dead storage losses reported by them were particularly criticized, but these reports played a major role in awakening the planning agencies in Pakistan to start

watercourse improvement programs. The data gathered recently (i.e., Clyma et al., 1975; Early et al., 1976) on watercourse losses has shown that previous assumptions and research substantially underestimated the extent of delivery losses. Most of the early water balance studies simply assumed unrealistically high efficiencies for the watercourse system. Table 1 shows the extent of losses in the watercourse command area estimated by different agencies in Pakistan. The serious nature of the problems is realized from the fact that watercourse command efficiency does not exceed 50 percent on the average, while it is as low as 12 percent in wet seasons in SCARP areas of Pakistan. Delivery efficiency measurements of losses from the mogha to farmers' fields have ranged from 30 to 70 percent. On the average, at least 40 percent losses of water in the watercourses from the mogha to farmers' fields are attributed to badly designed earthen nakkas.

Early et al. (1975 and 1976) conducted a comprehensive study to evaluate the present irrigation system beyond the mogha by selecting watercourse command areas in different districts in the Punjab and Sind Provinces of Pakistan. Table 2 shows the extent of losses during conveyance and field application of irrigation water. They have shown that mean watercourse delivery efficiencies range from 50 to 70 percent and application efficiencies range from 40 to 100 percent at ten sites for 18 watercourses of the Punjab. The watercourse command efficiency varies from 20 to 60

TABLE 1. Present Watercourse Command Efficiency in Pakistan

Reference Source	Watercourse Conveyance Efficiency %	Field Efficiency %	Command W.C. Efficiency %	Remarks
1. Expert Committees on Water Losses in the Irrigation System (1972)	85	75	63	No measurements taken. Took certain references outside Pakistan.
2. The Importance of Farm Water Management in Pakistan, Corey and Clyma, CSU Sept. (1974)	50-80 Average 60	20	12	SCARP Command Area
3. USAID, Pakistan Economic Development Data. August (1974)	70	46	32	Based on CSU work
4. IBRD, Irrigation and Drainage Sector Report. May (1974)	75	65	49	No specific recommendations but suggests urgency for work
5. Irrigation Practices and Application Efficiencies in Pakistan, Clyma et al. CSU January (1975)		20-50 Average 30		
6. Watercourse Losses as Related to Composition and Condition of Banks, Kemper et al. CSU/WAPDA April (1975)	60	-	-	50% suggested for seasonal efficiency
7. IBRD, Agricultural Sector Survey	75	65	49	
8. Watercourse command survey in Pakistan's Punjab and Sind; System constraints and Farmer's responses. (Technical Report No. 46, Forthcoming (1977), Lowdermilk et al.	52	77	40	Results of 40 watercourse survey measurements taken over a 14 month period

TABLE 2. Overall Irrigation Efficiency by Watercourses and Districts in Pakistan*

Location (Month of Evaluation)	Mean Delivery Efficiency %	Mean Application Efficiency %	Percentage Overall Efficiency
1. Lyallpur (May)	68	76	52
2. Multan (June)	58	96	58
3. Lahore (June-July)	62	97	60
4. Gujranwala (Sept-Oct)	58	51	30
5. Sargodha (July-August)	52	41	21
6. Muzaffargarh (January)	67	93	62
7. Bahawalpur (January)	66	96	63
8. Sukkur (Feb-June)	67	97	65
9. Dadu (February)	60	79	47
10. Thar Parker (February)	56	87	49
11. Thatta (March)	30	58	17

*Early et al., 1975; Early et al., 1976

percent (Early and Lowdermilk, 1975). Mean watercourse delivery efficiencies for southern Punjab and Sind varied from 30 to 70 percent and application efficiencies range from 55 to 100 percent for the given sample of 22 watercourses (Early et al., 1976). The command efficiency varies from 15 to 65 percent.

B. Watercourse Problems in Pakistan

Many of those who develop water resources are only concerned with delivering the water to the mogha. Such developers tend to forget that the real purpose of irrigation is to produce crops.

The Irrigation Department in Pakistan has jurisdiction past the "mogha" or outlet for the watercourse, but does not exercise physical control of the water beyond that point. Thus, the watercourse is the community property of the farmers being served. It is built and maintained largely by the skills, knowledge and efforts of the community of farmers on the watercourse who are commonly unaware of the tremendous losses occurring in the watercourse command area due to faulty design, poor maintenance of the watercourse, and their mismanagement. The major problem is the lack of knowledge concerning their potential for improvement and how to carry out the improvement. As a result, most farmers are deprived of over 40 percent of their water.

Percolation (deep vertical losses) accounts for less than one-quarter of the watercourse conveyance losses in Pakistan. Water which percolates from an earthen watercourse

is not lost completely from the delivery system, but it is a loss to the individual farmer who does not have a tubewell on that watercourse, and is re-obtained only at a considerable cost to the farmer who owns a tubewell.

Spillage of different types such as overtopping, side leakage and badly managed nakkas accounts for most of the conveyance losses. These losses are the result of: poor maintenance of watercourses by the farmers; faulty designs for accommodating the given discharge of water; very steep, thin and poorly managed banks; rodent holes; and vegetation on the banks of the watercourses.

Faulty design of the watercourse, with the bed elevation of the watercourse too far above or below the ground surface, is a problem with many earthen watercourses in Pakistan. The construction of the channel is often such that it cannot be completely drained into the field since its bed is below the ground surface, resulting in dead storage in the watercourse which evaporates or seeps into the ground. An estimate of the total water loss due to dead storage by Corey and Clyma (1973) is 3.5 to 7 MAF annually for all 78,000 watercourses in Pakistan. In other cases, the bed elevation is far above the surrounding ground level and lateral seepage through the banks is excessive. The optimal bed elevation is a trade-off between dead storage losses and lateral seepage losses through the banks of the watercourse. This problem needs further investigation.

Lack of maintenance of watercourses results in silting in the watercourses and clogging with weeds and other vegetation. Thus, with decreased gradient and increased roughness coefficient, the watercourse channels are unable to carry the required discharge from the mogha, thereby leading to frequent breaches of the banks.

The figures of 3.5 MAF to 7 MAF for dead storage losses reported by Corey and Clyma (1973) seem to be excessive. The author's experience on many watercourses in districts of Lyallpur, Multan, Lahore and Sahiwal in Punjab shows that many of the farmers use a low field, or lower the elevation of one of their fields by excavation until its surface is at or below the bed elevation of the watercourse. This field is irrigated at the end of their turn and it drains most of the water from the farm watercourse, which otherwise would have been lost as dead storage. Lowering the elevation of a small field is often worth the effort for the farmer who wants to obtain all the water his warabundi turn entitles him to.

C. Strategy for Water Management Improvement

The serious nature of the problems on the watercourse command areas, and the tremendous amount of losses occurring on the watercourses resulting in wastage of more than 50 MAF of water beyond the mogha, emphasize the need for the development of a strategy to increase the agricultural productivity by increasing cropping intensity and yield per acre through improving delivery and application efficiencies in the watercourse system.

The proposed strategy for improvement of the irrigation system in Pakistan aims at development and implementation of an effective on-farm water management program which must contain the following three basic components:

- a. Watercourse improvement program
- b. Precision land leveling program
- c. Irrigation extension service including scientific irrigation scheduling services.

These three components of the water management improvement strategy are interdependent and linked with one another in such a way that one loses its significance when the other two are not applied. The potential benefits of water saved through watercourse improvement can only be achieved in terms of increased crop productivity, when it is applied efficiently on precisely leveled fields in the proper amount and at the proper time.

Research studies at Grand Valley, Colorado have shown that scientific irrigation scheduling when implemented in conjunction with other water management technologies viz, watercourse improvement, and land leveling and drainage, played a major role in controlling the salinity problem in Grand Valley and reduction of the salt load of the Colorado River (Skogerboe et al., 1974).

Chapter IV

POTENTIAL FOR IRRIGATION SCHEDULING IN PAKISTAN

"The modern farmer needs and wants a continuing service that gives the present soil water status on each of his fields, predicts irrigation dates, and specifies the amount of water to apply on each field. He could also use predictions of adverse effects, such as the effects of delaying an irrigation for several days or perhaps terminating irrigations on the yield of marketable products." (Jensen, 1972)

A. Introduction

An important fact often overlooked in irrigation water management is that irrigation scientists, engineers, and technicians do not make the required daily or weekly irrigation decisions. Irrigation management decisions are generally made by very busy people with limited technical know-how and training in the management of a complex crop-soil-climate system. In addition, the desired decision-making data seldom are available to those who make these decisions on a day-to-day basis. The decision-making data for efficient irrigation water management requires knowing: i) The current level and expected change in available soil water of the field during the next week; ii) The expected latest date of the next irrigation to avoid detrimental plant water stress, and the earliest date to predict efficient irrigation to avoid over or under irrigation; iii) The amount of water to be applied on each field if the farmer is able to determine or control the amount; and iv) Some indications of the adverse effects of irrigating too early, too late or perhaps terminating irrigations.

Scientific irrigation scheduling is an approach for predicting the plant's future need for water based upon measurements made in the immediate past, and historical data. The past measurements allow estimation of the current plant moisture status and the historical data allow extrapolation to the future. Scientific irrigation scheduling is an integral component of the on-farm water management strategy which ensures that water is applied only at the time and in the amount needed. In water deficient areas this can result in increased yields through an extension in cropped areas, while in water surplus areas it can help to alleviate waterlogging and salinity problems which may result from excessive irrigation water applications. It can also reduce the loss of nutrients through deep percolation.

To understand the potential of scientific irrigation scheduling, or on-farm water management to improve crop production, one must recognize the role that water plays in the complex crop-soil-climate system. When the vital role that water plays is recognized, it is not too difficult to comprehend the importance of efficient irrigation water management.

There are many factors which determine the agricultural production of any particular area. On-farm water management is the most important constraint to increased food production in many developing countries and Pakistan is no exception. There has been enough evidence that the so-called "Green Revolution" of the 1960's has been most successful where conditions of good on-farm water management exist.

With average delivery efficiencies less than 60 percent and application efficiencies similarly low, overall average irrigation efficiency appears to be down around 40 percent. There is obviously a potential for raising this efficiency and a strategy should be developed to do so. An on-farm water management strategy must contain three components of water management technology; precision land leveling, watercourse improvement and scientific irrigation scheduling. All of the three components of the strategy are important. If farmers continue their present irrigation practices, then the potential benefits from either precision land leveling or watercourse improvement are limited. Therefore, while irrigation scheduling programs may be much more difficult to implement and their benefits harder to evaluate specifically than the other components of the strategy, it is essential that a scientific irrigation scheduling service should receive just as much or more emphasis and full coordination within the overall program. In fact, the three components of on-farm water management technology are interdependent, just as much so as nitrogen, phosphorus and water inputs to wheat production.

B. Benefits of Precision Land Leveling

Precision land leveling or land forming is the technique of translocating soil to precisely level the field with certain desirable grades for even distribution of irrigation water. Precision land leveling is the basic requirement of any successful surface irrigation system and its importance

for any program for improving irrigation water management and reducing waterlogging and salinity cannot be overemphasized.

The topography of the Indus Valley is fairly flat, with a one foot per mile average slope, and is well suited for surface irrigation. However, the average difference between the lowest and highest points in irrigated fields is often as much as 0.3 feet; thus, there is a great need for precise land leveling to allow uniform application of irrigation water over the field, to prevent over-irrigation on low areas and under-irrigation on high areas. Precision land leveling in Pakistan costs less than leveling in most other parts of the world where larger natural slopes require larger cuts and fills. The deep alluvial nature of the soil in Pakistan reduces the time required to bring the soil back to full productivity.

1. Increased Cropped Area: When the field is precisely leveled with the desired slope, which is almost zero for soils of the Indus Valley, borders are designed keeping in view the discharge available, and the infiltration rate of the soil. The high discharge of watercourses and the low infiltration rate of soils of the Indus Valley suggest that border lengths up to 1000 feet length should be feasible while at present the border length is generally not more than 200.

With precision land leveling followed by utilization of the border method of irrigation, the fields can be reshaped more efficiently so that the length of the watercourses

serving the fields can be reduced, which has the double impact of eliminating sections of leaky watercourses and increasing the acreage of the cropped land. On a compact block of 9 acres at the Mona Project, 7 watercourses occupied 0.33 acres of land. After precision land leveling, 6 watercourses were removed, thus adding 0.3 acres to the cultivated area. When the area was served by 1 watercourse instead of 7, using only one-tenth the length of channel, irrigation water was supplied to the leveled field with higher delivery efficiency than before, and because of the leveling, water applications in the 1000 foot length borders as small as 2 inches were possible (Ali et al., 1975).

2. Improved Irrigation Application Efficiency:

Pakistani farmers do level their fields by means of an indigenous scraper called "Karah" without applying engineering techniques. Most of their fields remain sloping or have high and low spots. Generally, the farmers apply irrigation water until all of the field is covered, including any high spots. This results in very little water covering the high spots, while excessive amounts cover low spots. Actual intake differentials are even greater since difference in the hydraulic head results in faster infiltration in low areas and possible salt accumulation can reduce infiltration on the high areas.

At Mian Channu, 10 measurements were made during irrigations of leveled, partially leveled, and traditional fields as shown in Table 3. Two leveled fields had an average application efficiency of 85 percent. In four other

TABLE 3. Comparison of Irrigation Application Efficiencies for Precisely Leveled and Traditionally Leveled Fields in Mian Channu, Pakistan (Ali, Arshid et al., 1975)

Date	Field Description	Date of Last Irrigation	Soil Moisture Deficiency (inches)	Application Acre-Inches Acre	Application Efficiency (percent)	Irrigation Percentage Completion
June 20, 1973	Leveled, Furrow	June 13, 1973	1.0	1.2	80	100
June 20, 1973	Traditional	Rauni	1.2	2.9	60	100
Sept 10, 1973	Leveled, Furrow	Before rains	3.3	1.9	100**	58***
Sept 11, 1973	Traditional	Before rains	1.5	2.8	55	100
Sept 12, 1973	Partially Leveled	Before rains	5.6	2.5	100**	45***
Sept 13, 1973	Leveled	Aug. 13, 1973	3.0	2.9	100**	97
Sept 13, 1973	Leveled	Aug. 13, 1973	2.9	3.3	90*	100
Sept 13, 1973	Leveled	Before rains	3.0	2.6	100**	87
Sept 13, 1973	Leveled	Before rains	3.0	1.6	100**	53***
Sept 13, 1973	Traditional	Before rains	2.4	3.5	70	100

*Irrigation applications such as this example are optimal for maintenance of low salt balance. Ninety percent efficiency means that a surcharge of approximately 10 percent of extra water has been used to flush soluble salts through the soil profile.

**Under irrigation, when a field received insufficient water, the amount of water stored, is the amount of water applied.

***Uncompleted irrigations to this small percentage of completion cannot be a sustained management practice in Pakistan without significant soluble salt accumulations at the soil surface and in the root zone.

leveled fields application efficiency was 100 percent, showing under-irrigations since the water applied was not sufficient to fill the root zone with water that had been consumptively used by the crop. On leveled fields, only an average of 5 percent of the water was wasted by over-irrigation. On unleveled fields, the average application efficiency was 55 percent; 45 percent of the water was wasted.

At the Mona Project, precision land leveling followed by the border method of irrigation showed an increase of 60 percent in application efficiency (Ali et al., 1975).

3. Better Use of Fertilizer: Fertilizer use efficiency is directly related to irrigation application efficiency. Over-irrigation on unleveled fields would leach the applied fertilizer below the root zone, thereby resulting in lower recovery or plant uptake rates. Very low fertilization efficiency in Pakistan, where 80 percent of the energy needs are imported, emphasizes the need for improved application efficiencies through precision land leveling.

4. Better Seed Germination: Unleveled fields cause non-uniformity in wattar condition (i.e., proper soil moisture condition for germination), which ultimately results in poor and uneven crop stands. Production losses worth Rs. 80 to 160 per acre have been estimated due to poor germination on account of variations in elevations of the field and subsequent variations in water content.

5. Higher Yields: Precision land forming followed by reshaping the existing field sizes to the border method of irrigation can increase per acre yields by 50 percent in

Pakistan as noted by Clark (1975). A comparison of crop yields on fertilized, leveled, and unleveled fields at Lyallpur in 1973 resulted in 50 mds. and 30 mds. of wheat per acre, respectively (Clark, 1975).

C. Watercourse Improvement

Over eighty thousand watercourses with an average culturable commanded area of 400 acres each are the main source of losses in the irrigation system of Pakistan. The average length of watercourse per unit area is more than 0.05 mile per acre, or approximately 1 mile per 20 acres. Thus 32,000,000 acres have more than 1,600,000 million miles of watercourses (Lowdermilk et al., 1975). The problems pertaining to the water delivery system beyond the mogha are mainly attributed by many planners in Pakistan as due to the inability of the farmers to efficiently utilize the water supplies delivered at the mogha. The watercourse losses from the mogha to farmers' fields, which are the results of faulty design of watercourses, non-alignment of channels, leaky nakkas due to frequent cuts in the watercourses, seepage, and spillage losses amount to over 30 MAF of water, and are a major contributor to waterlogging and salinity in the Indus Basin. These losses merit the immediate attention of the planners, engineers and people associated with the irrigation system of Pakistan. It is essential that some agency of the government begin to help the farmers to understand and reduce these water losses.

There are several alternatives for reducing the delivery losses in watercourses such as:

1. Renovation and maintenance of existing watercourses.
2. Katcha watercourse improvements through better engineering design with improved check structures, with proper compaction and with frequent maintenance.
3. Concrete lining of part or all of the watercourse, with improved check structures and with frequent maintenance.

1. Renovation and Maintenance: About 80 percent of the watercourse losses are attributable to spillage losses due to leaky nakkas, and the zigzag shape of watercourses with wide variations in cross-sectional area, frequent turns, and overtopping of banks due to silt accumulation and vegetation in the watercourse. These losses can be minimized to a greater extent by joint efforts of the shareholders of the watercourse through organizing themselves into so-called "water users' associations" as advocated by Radosevich and Kirkwood (1975). This aspect of watercourse improvement neither involves government participation nor engineering assistance. All the beneficiaries of the watercourse can work jointly for the watercourse improvements. This would involve realigning the watercourse to avoid zigzag plan section and frequent undesired turns in the watercourse, strengthening of the existing watercourse banks with fresh soil to close the leaks, and frequent cleaning of the watercourse by the farmers. This type of watercourse improvement does not need any capital, except for that to

train personnel who will help the farmers recognize the potential for improvement, and organize to do the job and demonstrate the most efficient methods of renovation and maintenance.

2. Katcha Watercourse Improvement through Engineering Design: A watercourse improvement program requires that the watercourse command area be surveyed and that a topographical map be prepared for the area. An earthen water channel is designed taking into account the discharge available at the outlet, full supply levels of the canal and watercourse, minimum head to provide for the highest field in the command area, and soil characteristics, etc. Check structures are designed for maintaining the required velocity of flow and damming water for application to branch watercourses. After the design is in hand, farmers of the watercourse can be involved to provide labor for excavation, filling and construction of banks with proper compaction and side slopes as required in the design. When the section is complete, pacca structures should be installed, including culverts and field nakkas. Farmers can be organized in one group or three sub-groups each at head, middle or tail for operation and maintenance of the watercourse. This approach of Katcha watercourse improvement with pacca structures has proved to be more efficient and workable at the Mona Project and Kanjra.

3. Lining of Watercourses: Lining of watercourses can practically eliminate seepage and spillage losses when it is accompanied by leak-proof nakkas. In practice,

delivery efficiency is often about 90% since small leaks usually persist through the masonry and imperfectly closed nakkas.

Different materials have been tried in Pakistan for lining of watercourses such as polyethelene lining, bentonite lining, clay soil-cement blocks lining, brick lining and concrete lining.

At the Mona project, different types of channel lining were tried to find the most economical method for lining of watercourses in Pakistan. Lining the entire watercourse and branches by bricks and mortar at Mona gave a benefit/cost ratio of 0.1 to 0.4: 1 showing this level of investment to be completely infeasible with respect to the losses encountered.

Lining only the main channel with concrete or bricks gave benefit cost ratios greater than unity when the discharge range was from 2 to 3 cusecs. The trapezoidal section with concrete lining gave the highest efficiency and benefit/cost ratio of 3:1. (Eckert et al., 1975). It would be financially impossible to do trapezoidal concrete lining in all of the 80,000 watercourses in Pakistan which would involve billions of Rupees and other resources. It would, therefore, be in the best interest of Pakistan to implement katcha watercourse improvement with pacca structures as part of the on-farm water management program in Pakistan, and use pacca channel improvements only in cases of extremely high expected losses.

D. Farm Water Management Extension Advisory Service
Including Scientific Irrigation Scheduling

1. Farm Water Management: The farmers are not able to attain maximum crop production with existing water supplies for several reasons. Neither the Agriculture nor the Irrigation Department assumes responsibility for Irrigation Extension activities to advise farmers on optimum use of their limited water. The delivery system is rigidly controlled by the Irrigation Department to deliver water on a rotation basis that is often not related to the consumptive use and available soil water capacities.

Reduction of water losses occurring beyond the mogha in the irrigation system of the Indus Basin will require comprehensive planning for the organization of institutions to improve "On-Farm Water Management." In order to implement the strategy for "On-Farm Water Management" in order to overcome irrigation water losses beyond the mogha which amount to more than 50 MAF annually lost in watercourses and during field irrigation applications, there is a dire necessity for development of an "Irrigation Extension Advisory Service" in the public sector, as well as the organization of farmers' institutions like "Water Users' Associations" in the private sector. The irrigation extension advisory service can help farmers to optimize their return from their labor, capital, credit and water resources. These institutions can help and guide the farmers to improve their watercourses and schedule their crops to maximize

cropping intensity and water utilization to obtain maximum use of the water saved.

There is a need to determine the levelness of farmers' fields and demonstrate the benefits of precision land leveling and also to advise farmers regarding the best design and layout of watercourses, irrigation methods and layout of furrows, borders and basins. Agro-meteorological observatories are needed to obtain estimates of evaporation and rainfall which can enable extension agents to help farmers over whole areas to properly schedule irrigations. Structures and other aids to allow measurement of the rate of flow in watercourses will enable extension agents to help farmers evaluate their water use and recommend watercourse renovation procedures.

Projects such as on-farm water management programs often fail to produce the required results when implemented by the public sector without farmer involvement. It is, therefore, essential to help organize farmers' "Water Users' Associations" to work cooperatively with the On-Farm Water Management Extension Advisory Service. These associations should be actively involved in watercourse improvement programs and the maintenance programs that are necessary to sustain the high delivery efficiencies. Irrigation scheduling programs definitely need the participation and involvement of these institutions to help farmers help each other because there are so few extension agents compared to the number of farmers.

2. Water Allocation: In Pakistan, a rotation system is followed, generally on a weekly basis, and the time for which a farmer is allocated use of the water supply is proportional to the acreage he owns (and/or leases) irrespective of the cropped area and the type of crops grown. However, he pays for his water on the basis of the type and acreage of crops grown. At any particular allotted time, all the water coming from the mogha belongs to one farmer and nobody else is legally allowed to use that water or part of that water.

3. Pacca Warabundi System: In this system of water allocation or irrigation scheduling in Pakistan, the time of the turn for every individual farmer is fixed by the Irrigation Department. This is accomplished by dividing the total commanded area by the hours in the week. The supply of water goes substantially from square* to square and farmers with fragmented holdings spread over several squares get their irrigation turns fragmented because legally they cannot take the water turn of one square to another. Problems and frustrations arise among farmers at canal closure time, since a farmer who has his turn at canal closure time loses his turn. The fixed warabundi restarts with the farmer whose turn happens to fall at the time when the water comes back into the watercourse.

*A square is a block of land about 1,100 feet x 1,000 feet which is divided into 25 units or killas, each of which is slightly larger than an acre.

4. Katcha Warabundi System: In this system turns are fixed by the farmers themselves through mutual consultations and rotation is not necessarily on a weekly basis. A specific time is allotted for each acre owned by the farmers. The Irrigation Department is not involved in this system and farmers decide their problems and disputes at their own level. This system can work well when all the farmers are cooperative, but can be difficult for the small farmer if one landlord dominates on the watercourse and selects the best times and amounts of irrigation for himself, while the small farmers often suffer. When the canal reopens after closure the farmer whose turn it was at the time of closure starts getting his turn after the reopening of the canal, and the other farmers would follow him. This system of water warabundi leads to friction and disputes among farmers especially during peak water requirement periods.

Neither of the systems of water allocation in Pakistan discussed above are able to adjust canal water supply to changing crop needs. Such an adjustment would require construction of large amounts of holding capacity in the supply system, which would be expensive and require large areas of land. Such construction is not anticipated in the foreseeable future and, consequently, the farmers need to learn the consumptive use requirements of their crops, so they can adjust their crop schedules to most optimally utilize their water and land resource to gain an economic return.

Chapter V

PROCEDURE

A. General Background for Data Collection

In order to develop scientific irrigation scheduling for implementation under Pakistani conditions, a typical watercourse with its entire command area was selected as a case study site. Kanjra watercourse command area in the Shadab Project of the Integrated Rural Development Program at Niazbag distributary of Lahore Canal, was selected as a case study on the grounds that the watercourse area is owned by small and subsistence landholders, there is considerable fragmentation of holdings, with both self and tenant cultivation, and there is potential for farm water management improvement. These factors are common to many other watercourses in Pakistan. A soil survey map and topographic map of the watercourse command area had already been prepared by the Punjab Water Management Project and were available as preliminary data.

1. Benchmark Survey: A socio-economic benchmark survey of the watercourse command area was conducted on the commanded area of one of the three main branches of the watercourse which had to be improved under a related research program for watercourse improvement. The benchmark survey was based on a socio-economic and agronomic crop survey, cropping patterns, and average yields of different crops grown in the area. Physical data of the watercourse area were collected in the form of a topographic map, layout

map, soil survey map, and data on mogha and nakka discharges. Farmers' understanding of irrigation practices and extent of seepage losses in the watercourse and deep percolation losses during field irrigation applications was also evaluated.

2. Selection of Farms for Irrigation Scheduling:

Four production plots were selected on branch "A" of the watercourse, two each at the head and tail of the watercourse, for comparison of different methods for predicting potential evapotranspiration for the wheat crop. Five plots were selected for irrigation scheduling implementation for maize fodder. Delivery efficiencies were determined by comparing the mogha and field nakka discharges. Application efficiencies were determined by measuring the flow rate and time for which water was applied, as well as using soil moisture sampling to determine the soil moisture deficit at the time of irrigation. Out of the four selected fields for wheat, two each at the head and the tail of the watercourse, there were two experimental plots where improvements such as land leveling and border irrigation were in place and improved agronomic practices were followed. The other two fields, one each at the head and the tail of the watercourse, had no special improvements, were managed by the farmers and were treated as control plots. A topographic survey for both of these fields was conducted to determine the extent of levelness in these plots. The control plots were selected near the experimental plots to facilitate

field application irrigation evaluations including nakka discharge measurements, measurement of amounts of irrigation water applied, measurement of soil moisture deficiency and irrigation application efficiencies.

At the head of the watercourse, near the mogha, a cutthroat flume, with recorder, was installed to continuously record the discharge of the mogha.

A meteorological station was established at the head of the watercourse to obtain daily records of climatic factors. The station included a hygrothermograph to record air temperature and relative humidity, maximum remote recording tipping bucket and weighing type rain gauges to record amount and intensity of rainfall, sola-meter to record daily solar radiation and U.S. Weather Bureau Class A Pan to record pan evaporation. The data obtained was used as a basis for calculation and comparison of different methods or predicting potential evapotranspiration from: pan evaporation, the Penman equation and the Jensen-Haise equation.

Soil samples from successive strata of the soil profile were sent to the Water and Soil Investigation Division (WASID) soil testing laboratory to obtain moisture retention curves for both the experimental and control fields. Cutthroat flumes were installed at field nakkas to determine the nakka discharge from the head and tail sections of the watercourse into the experimental and control fields.

B. Comparison of Methods for Predicting Potential Evapotranspiration

Three methods of predicting potential evapotranspiration (including pan evaporation, the Penman equation, and the Jensen-Haise equation) were compared during the 1975-76 wheat season at Kanjra. Soil moisture depletion was measured through gravimetric sampling and used as the basis for evaluation of the predictive methods. Sowing of the wheat crop was completed by the first week of December on both of the experimental and control plots at the head and tail of the watercourse.

1. Gravimetric Soil Moisture Sampling: The first soil sampling for moisture estimation was done at the time of sowing of the wheat crop and the subsequent soil moisture samplings were carried out just before irrigation and as close as possible after irrigation. Final moisture sampling was done at the time of harvest of the crop in order to calculate the total soil moisture depleted or consumptively used by the crop. Soil samples for moisture estimation were taken with king tubes at depths of 0 to 6", 6" to 12", 12" to 24", 24" to 36", 36" to 48", 48" to 60" and 60" to 72". The replication of soil moisture sampling varied from 3 to 6 random sites from each production plot depending on the size of the plot which varied from half an acre to two acres in size. The samples were oven dried at 105°C from 16 to 24 hours until a constant weight was achieved. Dry bulk densities were calculated in each case and then the

moisture content for each layer on a volumetric basis was determined.

The average rate of evapotranspiration (E_t) between any two sampling dates was calculated using the following equation:

$$E_t = \frac{\text{Wet}}{t} = \frac{\sum_{i=1}^{N_r} \left(\frac{(O_1 - O_2)}{100} P_i \right) + R_e - W_d}{t}$$

- where
- E_t = average evapotranspiration rate between the sampling dates 1 and 2 in inches per day
 - Wet = total soil moisture depletion in the sampling period in inches
 - t = numbers of days between the sampling dates
 - i = numbers of successive strata of root zone encountered in sampling
 - N_r = total number of layers to the depth of the effective root zone
 - O_1, O_2 = volumetric moisture content in the soil on the first and second date of sampling respectively, in percent
 - P_i = thickness of each layer in inches
 - R_e = effective rainfall (that which does not run off the area) in inches between dates 1 and 2
 - W_d = drainage from the zone sampled (in inches). It is negative when there is upward flow to the sampling zone.

It is assumed that all rainfall during the growing season was effective and there was no runoff from the cropped area. All of the precipitation events during the season were of low intensity and did not exceed one inch at any time. Both upward or downward drainage was assumed to be zero since the water table was far below the effective root zone

of the crop and examination of soil moisture contents of the 5 to 6' layer indicate negligible depletion from the lower strata by the root zone. Seasonal values of evapotranspiration, or the total water consumptively used by the wheat crop during the growing season, were calculated by adding the water loss between the soil samplings (i.e., after and before irrigations), plus rainfall during this period, plus pan evaporation for three days (as an estimate of actual evapotranspiration for the period from 3 days after irrigation to the date of first sampling and from the time of second sampling to the time of irrigation).

2. Pan Evaporation: A U.S. Weather Bureau Class A Evaporation Pan was installed in the weather observatory four days after the planting of wheat. The Pan was installed in the middle of an alfalfa field, which was cut back when it reached 9 inches or more. Levels of water in the evaporation pan were recorded at 0800 hours daily and pan evaporation during the preceding twenty-four hours was calculated from these differences in water surface levels. Daily pan evaporation data was accumulated for the entire growing season and then used for comparison with other methods of predicting potential evapotranspiration.

3. Penman Equation: In another approach for predicting potential evapotranspiration, the Penman equation was applied using the meteorological data for mean daily temperature, mean relative humidity, daily wind run, and the total daily hours of bright sunshine, while predicted

daily sunrise and sunset timings were obtained from the Lahore Pilot Balloon Observatory located 10 miles from the study area.

The methodology used for solving the equation of Penman (1948) was that used by Israelson and Hansen (1963). A computer program was developed for the Penman equation and program was run at the WAPDA computer center at Lahore by coding the required meteorological data for Kanjra observatory collected during the wheat season of 1975-76. The listing of the program is attached as Appendix C, Table 1.

4. Jensen-Haise Method: The Jensen-Haise equation for predicting potential evapotranspiration was also used as a means of comparison. Daily mean temperatures and daily solar radiation were recorded at the observatory throughout the season for use in the equation:

$$ETP = C_T (T - T_X) \cdot R_s$$

where ETP = potential evapotranspiration rate

C_T = air temperature coefficient constant in inches/day for a given area

T = mean daily temperature

T_X = a constant for a given area which is (merely) the linear equation intercept on the temperature axis in the solar radiation air temperature relationship

R_s = daily solar radiation expressed as the equivalent depth of evaporation (inches/day).

The equation was calibrated to determine the constraints C_T and T_X for the study area in terms of both dry and monsoon seasons as follows:

$$C_T = \frac{1}{C_1 + C_2 \cdot C_H}$$

where $C_1 = 68 - 3.6 E/1000$ for T in degree F
 E = elevation of the area in feet above mean sea level

$$C_2 = 13^\circ F$$

$$C_H = \text{humidity index} = \frac{37.5 \text{ mm Hg}}{e_{s_2} - e_{s_1}} = \frac{50 \text{ millibars}}{e_{s_2} - e_{s_1}}$$

where e_{s_1} = saturation vapor pressure in millibars at the mean minimum air temperature during the warmest month

e_{s_2} = saturation vapor pressure in millibars at the mean air temperature during the same month

$$T_x = 27.5 - 0.25(e_{s_2} - e_{s_1}) - \frac{E}{1000}$$

The equation was calibrated for both seasons using the 12 year monthly mean temperatures of Chuharkana observatory situated 25 miles from the study area. This was assumed adequate for the study area since Jensen suggests that the calibrated equation will be reasonably valid over a 60 mile radius. Daily values of the actual evapotranspiration were calculated using the values of crop coefficients K_c after Jensen (1963).

C. Implementation of Irrigation Scheduling

On the basis of the comparison of methods for predicting potential evapotranspiration rate during the wheat season, the Jensen-Haise method was found suitable for practical use since it needs just solar radiation and mean temperature data. Accordingly, the same layout of the experimental and control plots was followed by Kharif maize fodder as for

Rabi wheat at the head and tail, except one more experimental field was included in the middle of the watercourse for implementation of scientific irrigation scheduling using the Jensen-Haise method. The experimental field at the head of the watercourse was the same as for Rabi wheat, while the control plot at the head and both experimental and control plots at the tail were changed since the concerned farmers were not willing to grow maize fodder on those plots. The newly selected fields were adjoining to the fields selected before, so moisture retention curves of these fields were assumed the same as for the previous plots. There was no change in soil type from plot to plot by visual inspection and as checked from the soil survey maps of the area.

Moisture samples were taken from the fields at the time of sowing, between the irrigations, and just before irrigation to allow both irrigation evaluations and scheduling irrigations. Flows in the watercourse were measured to find the nakka discharge at the head, middle, and tail of the watercourse and also to apply a measured quantity of irrigation to each experimental plot and to find the application efficiencies for comparison with control plots. After one week of irrigation, gravimetric soil moisture sampling was conducted to find the soil moisture depletion up to that date. Then the average evapotranspiration rate was calculated using calculated and predicted values of potential evapotranspiration for the last three

days and the three coming days. Irrigations were scheduled at 50 percent depletion of the available soil moisture for the assumed depth of crop rooting. The irrigation interval was calculated from the following relationship:

$$N = (M_o - M_d) / E_T$$

where

$$N = 0 \text{ when } M_d \geq M_o$$

N = the number of days until the next irrigation

M_o = maximum allowable depletion of soil moisture

M_d = depletion of soil moisture as occurred to date

E_T = the average daily rate of evapotranspiration by the crop.

The irrigation schedules were communicated to the farmers beforehand and irrigations were applied under supervision to ensure proper timing and amount of irrigation water.

D. Documentation of Water Use Efficiency and Yield Improvement

1. Application Efficiency: Continuous measurements of irrigation water applied were made both on control and experimental production plots during the wheat and maize growing seasons. Cutthroat flumes were installed at the farmers' fields to find the available nakka discharge and irrigation applications. Soil moisture deficiencies were recorded at the time of irrigation both by the feel method and gravimetric soil moisture sampling. Accordingly, irrigation application efficiencies were calculated to

determine the impact of precision land leveling and also of scientific irrigation scheduling.

2. Yield Data: Collection of random yield samples were taken from both experimental and control plots to note the impact of irrigation scheduling with respect to water savings and yields. Six samples each 10' x 10' were taken from 6 places per acre randomly selected.

Chapter VI

DATA PRESENTATION

A. Meteorological Data

Daily observations of rainfall, temperature, relative humidity, wind run, solar radiation, and pan evaporation recorded at Kanjra Observatory during the wheat season and the maize fodder season were used to determine evapotranspiration and to compare methods of ETP estimation. The data were also used to schedule irrigations for maize fodder. The data regarding hours of daily sunshine were obtained from the Lahore Weather Observatory.

Average values were calculated from seven day means for the meteorological data. The daily record of meteorological data and variations in average values on a weekly basis for the wheat growing season for solar radiation, mean relative humidity and mean daily temperature are shown at Appendix A, Table 1.

B. Comparison of Methods for ETP Determination

1. Actual Evapotranspiration (ETA): ETA was determined by observing the moisture changes in the soil profile. Soil moisture was determined gravimetrically on samples taken when the soil was approximately at field capacity and just before irrigations. Average daily evapotranspiration was calculated from the changes in soil moisture in the top 72 inches of the soil profile during the sampling interval. The daily actual evapotranspiration values were accordingly converted into average daily values

on a weekly basis for the entire wheat season as shown in Table 4.

2. Potential Evapotranspiration (ETP): The following methods were used for computing potential evapotranspiration during the wheat growing season at Kanjra.

a. Pan Evaporation: USBR Class A pan evaporation data was collected on a daily basis at the Kanjra Observatory as shown at Table 1 in Appendix A. Pan evaporation data collected on a daily basis were converted to average daily values on a weekly basis for the wheat season as listed in Table 5. Figure 3 shows the changes in the daily average values of ETA and pan evaporation during the wheat season at the study site, as well as the relationship between pan evaporation and ETA.

b. Jensen-Haise Equation: The Jensen-Haise equation (1963) was calibrated both for dry and monsoon seasons using long term meteorological data for Chuharkana Meteorological Observatory located about 20 miles from the study site. During the study, data collected at the site was used. The calibrated equations were used for determination of ETP at the study area. The procedure for calibration of the Jensen-Haise equation, actual calibration of the equation for Chuharkana, and meteorological data needed for calibration of the equation are given in Appendix B.

On the basis of the daily solar radiation and mean temperature data recorded at the study site, ETP was computed

TABLE 4. Weekly Average Values of Daily Actual Evapotranspiration (ETA) during Wheat Season 1975-76 at Kanjra by Gravimetric Method

<u>Period</u>		<u>Weekly Averages of Daily ETA</u>	
		<u>inches/day</u>	<u>mm/day</u>
December	15-21	0.013	0.33
	22-28	0.030	0.76
	29- 4	0.034	0.86
January	5-11	0.040	1.02
	12-18	0.045	1.14
	19-25	0.056	1.42
	26- 1	0.062	1.57
February	2- 8	0.068	1.73
	9-15	0.070	1.78
	16-22	0.085	2.16
	23-29	0.100	2.54
March	1- 7	0.110	2.79
	8-14	0.130	3.30
	15-21	0.150	3.81
	22-28	0.170	4.32
	29- 4	0.172	4.37
April	5-11	0.175	4.45
	12-18	0.178	4.52
	19-25	0.185	4.70
	26-30	0.192	4.88

TABLE 5. Weekly Average Values of Daily Potential Evapotranspiration (ETP) during Wheat Season 1975-76 at Kanjra by Pan Evaporation

<u>Period</u>	<u>Weekly Averages of Daily ETP</u>	
	<u>inches/day</u>	<u>mm/day</u>
December 15-21	0.07	1.78
22-28	0.05	1.27
29- 4	0.06	1.52
January 5-11	0.06	1.52
12-18	0.05	1.27
19-25	0.06	1.52
26- 1	0.08	2.03
February 2- 8	0.05	1.27
9-15	0.08	2.03
16-22	0.08	2.03
23-29	0.13	3.30
March 1- 7	0.14	3.56
8-14	0.11	2.79
15-21	0.12	3.05
22-28	0.16	4.06
29- 4	0.14	3.56
April 5-11	0.22	5.59
12-18	0.23	5.84
19-25	0.25	6.35
26-30	0.24	6.01

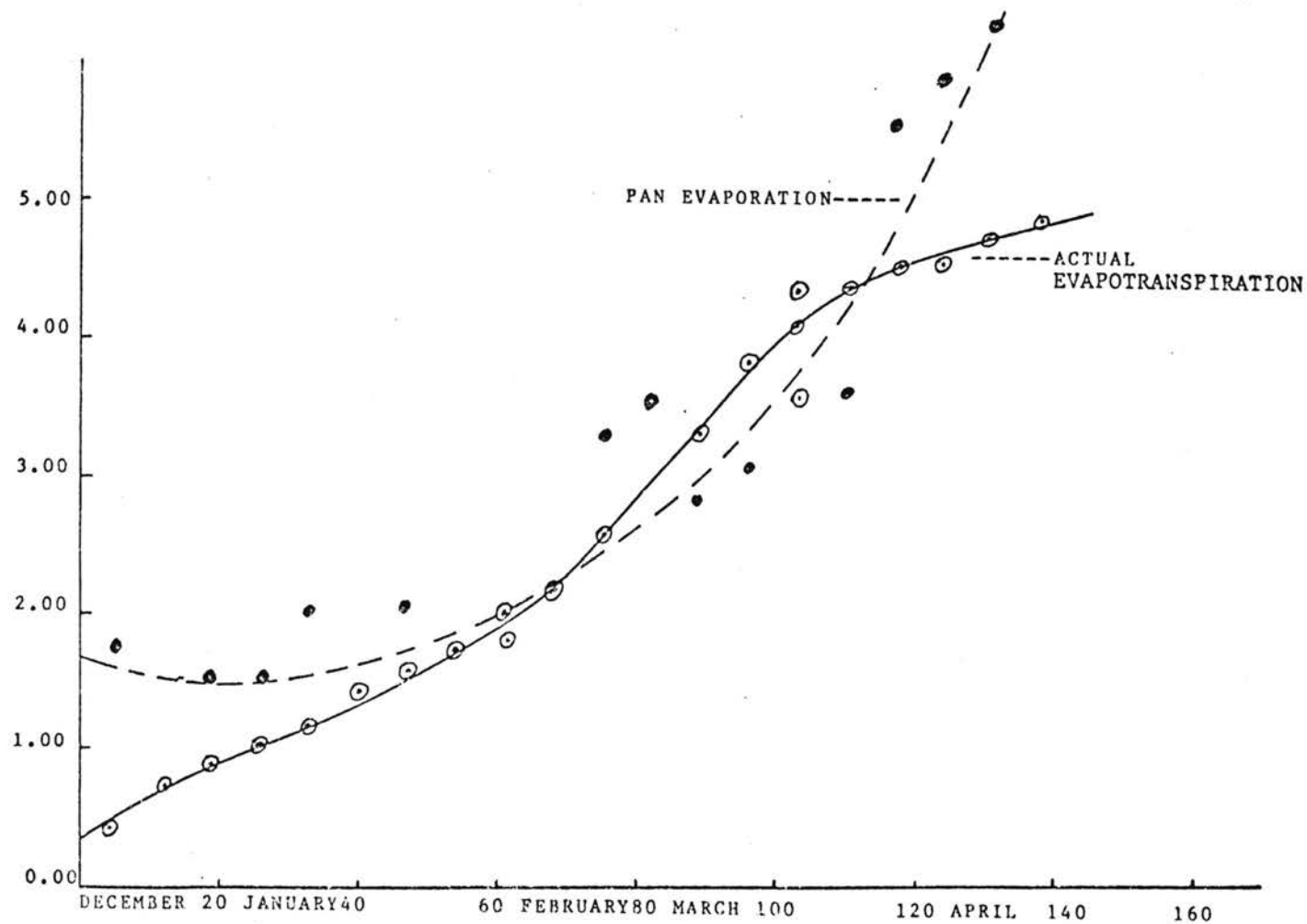


Figure 3. Relationship between Daily Pan Evaporation and Actual Evapotranspiration for Wheat 1975-76 at Kanjra

on a daily basis using the calibrated Jensen-Haise equation for the wheat season. The daily values were accordingly converted into average daily values on a weekly basis for the season as shown in Table 6. Figure 4 represents the variation and relationship of daily ETP (Jensen-Haise) and ETA during the wheat growing season.

c. Penman Equation: The meteorological data as shown in Table 1 of Appendix A was used to compute ETP employing the Penman Equation (1948) and Adapted Penman Equation (after Mateers, 1969). The meteorological data was computerized for both of the Penman equations. The listing of the computer programs for the equations is given in Table 1 and Table 2 in Appendix C.

Daily values of ETP computed from the Penman equations (1948) and the "Adapted Penman Equation" were converted to average daily values on a weekly basis as shown in Tables 7-A and 7-B, respectively.

A comparison of actual evapotranspiration (ETA) with estimates of the evapotranspiration obtained using the Penman equation (1948) and the "Adapted Penman Equation" during the wheat season (1975-76) for Kanjra is presented in Figure 5.

Figure 6 shows the comparison of Potential Evapotranspiration (ETP) estimated using all the four methods with Actual Evapotranspiration (ETA) using the daily ETP and ETA values obtained at Kanjra during the wheat season. Accumulated values of ETP by four different methods as

TABLE 6. Weekly Average Values of Daily Potential Evapotranspiration (ETP) during Wheat Season 1975-76 at Kanjra by Jensen-Haise Equation

<u>Period</u>		<u>Weekly Averages of Daily ETP</u>	
		<u>inches/day</u>	<u>mm/day</u>
December	15-21	0.080	2.03
	22-28	0.051	1.30
	29- 4	0.064	1.63
January	5-11	0.054	1.37
	12-18	0.070	1.78
	19-25	0.066	1.68
	26- 1	0.070	1.78
February	2- 8	0.081	2.06
	9-15	0.080	2.03
	16-22	0.089	2.26
	23-29	0.099	2.51
March	1- 7	0.126	3.20
	8-14	0.130	3.30
	15-21	0.087	2.21
	22-28	0.160	4.06
	29- 4	0.178	4.52
April	5-11	0.265	6.73
	12-18	0.298	7.57
	19-25	0.303	7.70
	26-30	0.343	8.71

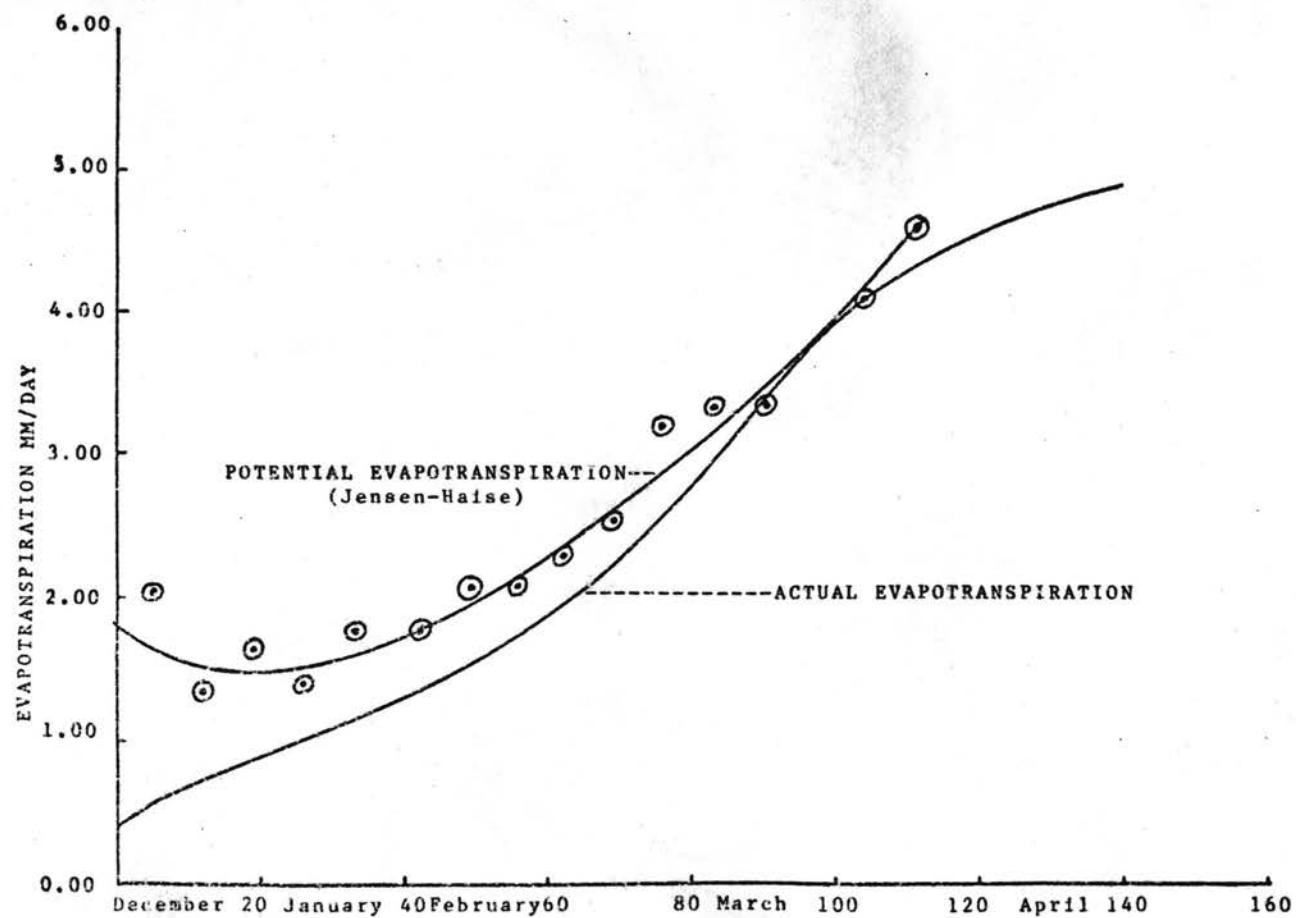


Figure 4. Daily Potential (Jensen-Haise) and Actual Evapotranspiration for Wheat 1975-76

TABLE 7-A. Weekly Average Values of Daily Potential Evapotranspiration (ETP) during Wheat Season 1975-76 at Kanjra by Penman Equation (1948)

<u>Period</u>		<u>Weekly Averages of Daily ETP</u>	
		<u>inches/day</u>	<u>mm/day</u>
December	15-21	0.03	0.76
	22-28	0.03	0.76
	29- 4	0.03	0.76
January	5-11	0.03	0.76
	12-18	0.03	0.76
	19-25	0.032	0.81
	26- 1	0.032	0.81
February	2- 8	0.060	1.52
	9-15	0.056	1.42
	16-22	0.057	1.45
	23-29	0.065	1.65
March	1- 7	0.106	2.69
	8-14	0.086	2.18
	15-21	0.073	1.85
	22-28	0.105	2.67
	29- 4	0.116	2.95
April	5-11	0.156	3.96
	12-18	0.155	3.94
	19-25	0.175	4.45
	26-30	0.178	4.52

TABLE 7-B. Weekly Average Values of Daily Potential Evapotranspiration (ETP) during Wheat Season 1975-76 at Kanjra by Penman Equation (Adapted)

<u>Period</u>		<u>Weekly Averages of Daily ETP</u>	
		<u>inches/day</u>	<u>mm/day</u>
December	15-21	0.049	1.25
	22-28	0.048	1.21
	29- 4	0.050	1.28
January	5-11	0.051	1.30
	12-18	0.051	1.30
	19-25	0.053	1.35
	26- 1	0.055	1.40
February	2- 8	0.091	2.30
	9-15	0.083	2.10
	16-22	0.085	2.15
	23-29	0.093	2.35
March	1- 7	0.148	3.75
	8-14	0.130	3.29
	15-21	0.100	2.53
	22-28	0.140	3.56
	29- 4	0.154	3.92
April	5-11	0.207	5.25
	12-18	0.205	5.21
	19-25	0.226	5.75
	26-30	0.235	5.98

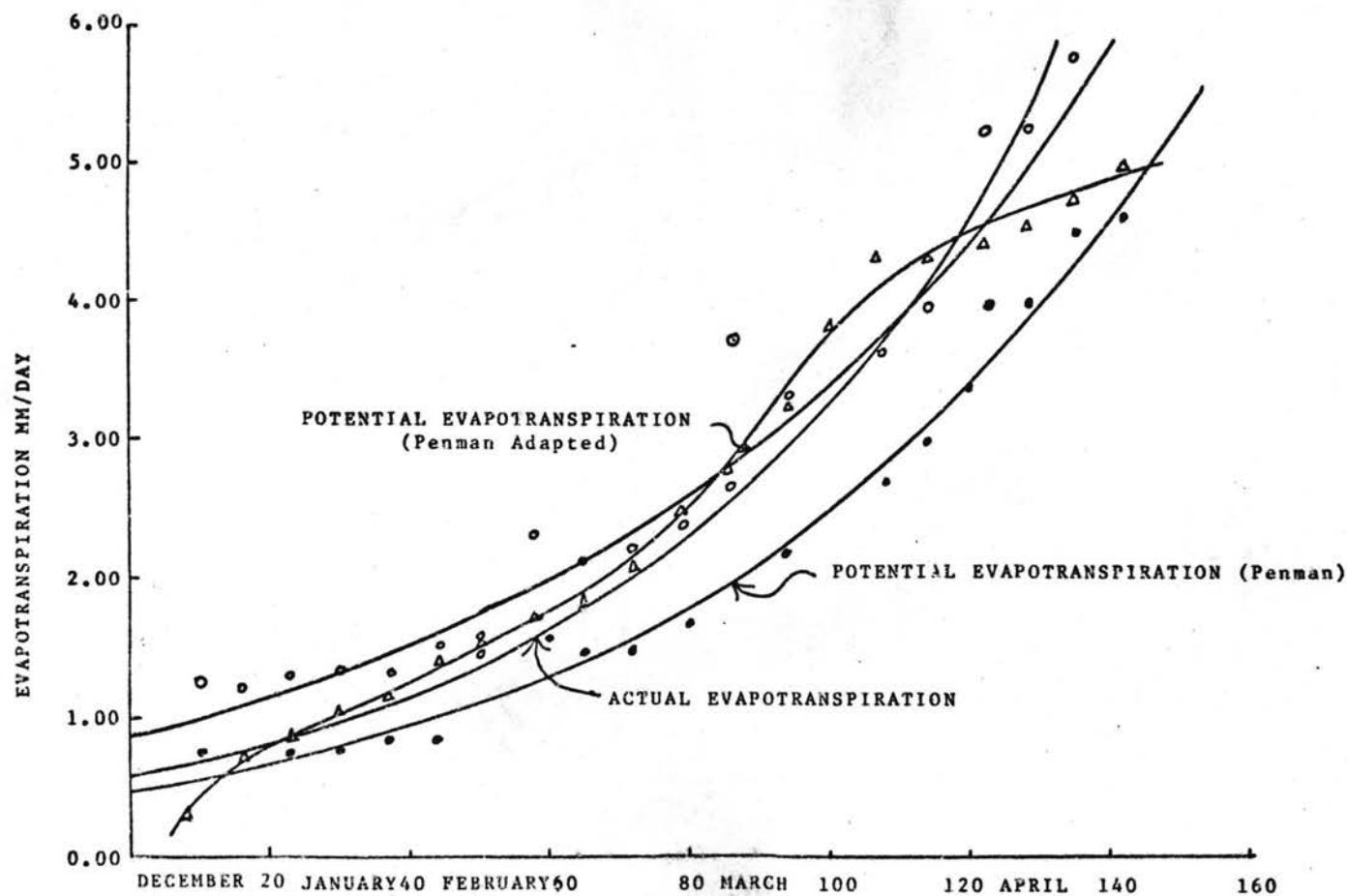


Figure 5. Daily Potential (Penman Adapted), (Penman 1948) and Actual Evapotranspiration for Wheat 1975-76

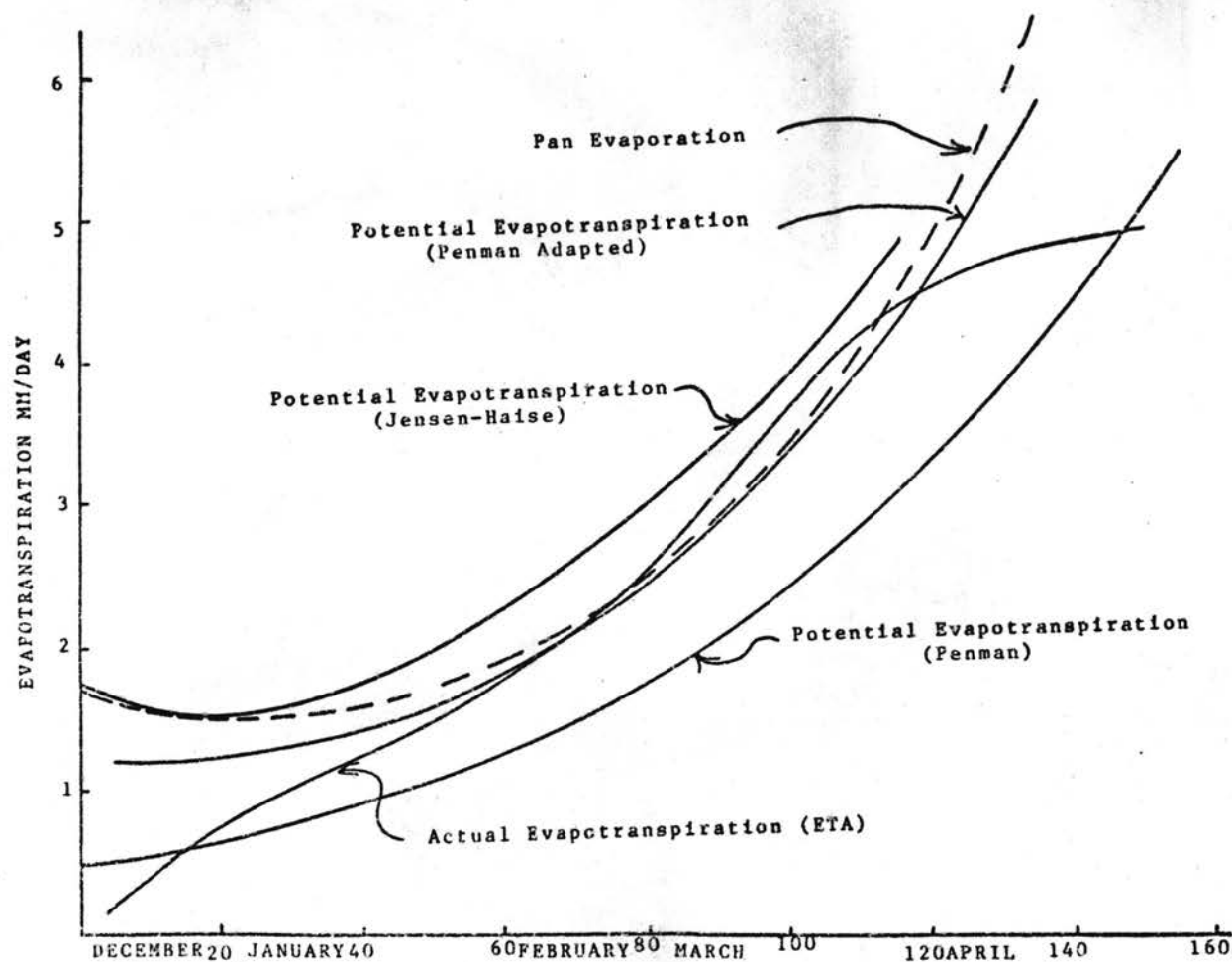


Figure 6. Comparison of Methods of Evapotranspiration Determination during Wheat Growing Season 1975-76 at Kanjra

compared to ETA for the wheat season at Kanjra have been shown in Figure 7 to provide another criteria for comparing the methods of ETP.

3. Crop Coefficients: Using the daily values of ETP as computed from four different methods and ETA, daily crop coefficients were determined on a weekly and monthly average basis for the entire wheat season for "Tanuri" variety of wheat at Kanjra as shown in Tables 8-A, 8-B, 8-C and 8-D. These crop coefficients can be used for scheduling irrigations using the concerned method. Figure 8 shows the variation in crop coefficients experimentally determined using Jensen-Haise equations for "Tanuri" (late growing Mexican variety) wheat crop for Kanjra.

C. Irrigation Scheduling for Maize Fodder, 1976

Average daily values of actual evapotranspiration were determined for maize fodder using the potential evapotranspiration values determined by the Jensen-Haise equation. The values of crop coefficients for maize were taken from Jensen (1963) as given in Figure 1 of Appendix E. The values of ETA thus determined for maize fodder are shown in Table 9.

The irrigation scheduling status report was prepared for every experimental plot at the time of sampling and irrigations were scheduled accordingly. Extent of the root zone as related to time during the growing season was estimated from Kincaid and Heerman (1974) as shown in

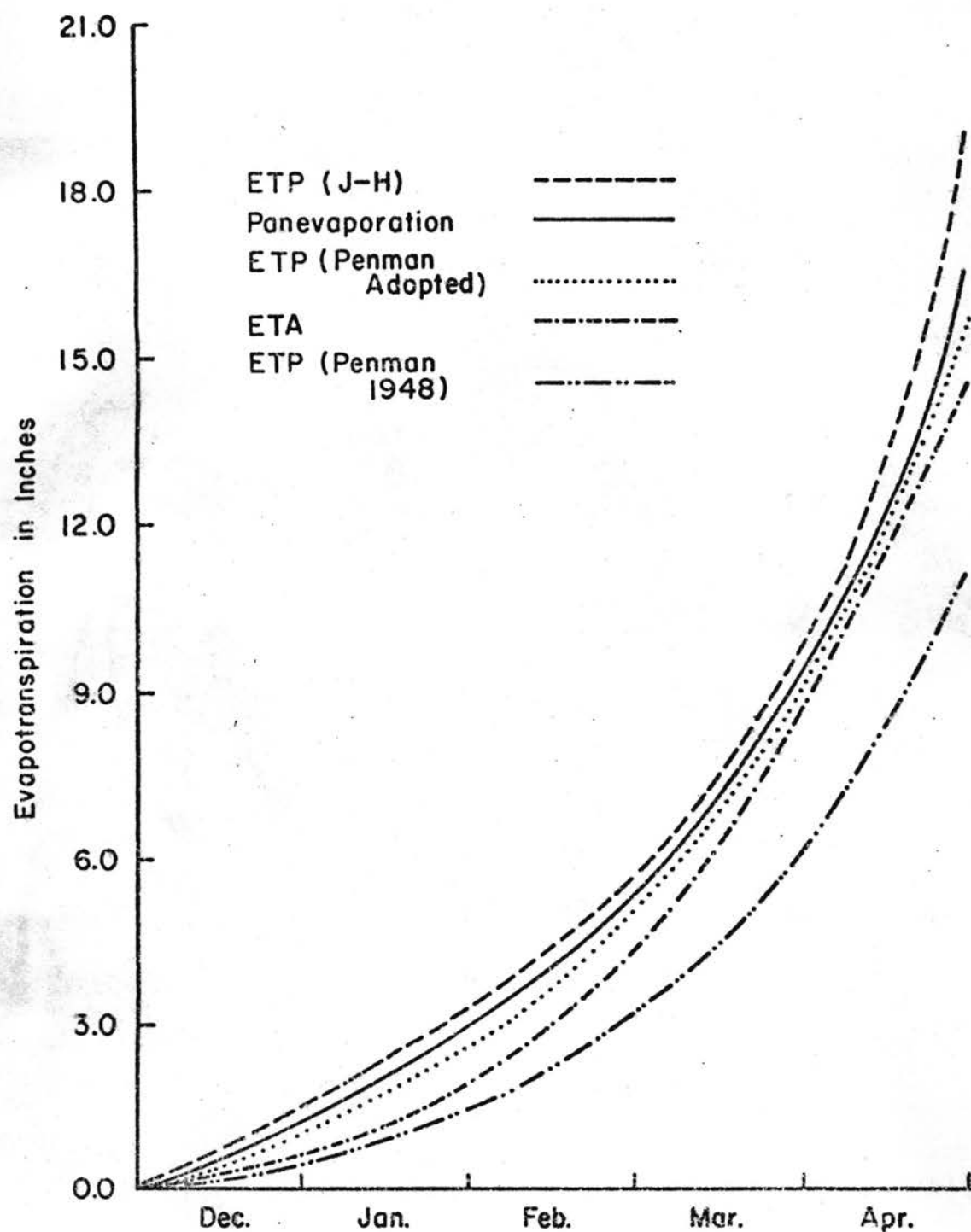


Figure 7. Cumulative Actual and Potential Evapotranspiration in Wheat Growing Season 1975-76 at Kanjra

TABLE 8-A. Crop Coefficients for Wheat (Late Mexican Variety) for Kanjra by Pan Evaporation

<u>Period</u>		<u>ETA</u> <u>inches/day</u>	<u>PAN Evaporation</u> <u>inches/day</u>	<u>Daily</u> <u>Kc</u>
December	15-21	0.013	0.07	0.18
	22-28	0.030	0.05	0.60
	29- 4	0.034	0.06	0.56
January	5-11	0.040	0.06	0.66
	12-18	0.045	0.05	0.90
	19-25	0.056	0.06	0.93
	26- 1	0.062	0.08	0.77
February	2- 8	0.068	0.05	1.36
	9-15	0.070	0.08	0.87
	16-22	0.085	0.08	1.06
	23-29	0.100	0.13	0.77
March	1- 7	0.110	0.14	0.79
	8-14	0.130	0.11	1.18
	15-21	0.150	0.12	1.25
	22-28	0.170	0.16	1.06
	29- 4	0.172	0.14	1.21
April	5-11	0.175	0.22	0.80
	12-18	0.178	0.23	0.77
	19-25	0.185	0.25	0.74
	26-30	0.192	0.24	0.80

TABLE 8-B. Crop Coefficients for Wheat (Late Mexican Variety) for Kanjra by Jensen-Haise Method

<u>Period</u>		<u>ETA</u> <u>inches/day</u>	<u>ETP (Jensen-Haise)</u> <u>inches/day</u>	<u>Daily</u> <u>Kc</u>
December	15-21	0.013 2.3mm	0.080	0.16
	22-28	0.030 5.3	0.051	0.60
	29- 4	0.034 6.04	0.064	0.53
January	5-11	0.040 7.11	0.054	0.74
	12-18	0.045 8.2	0.070	0.64
	19-25	0.056 9.6	0.066	0.85
	26- 1	0.062 10.2	0.070	0.88
February	2- 8	0.068 12.47	0.081	0.84
	9-15	0.070 12.4	0.080	0.88
	16-22	0.085 11	0.089	0.96
	23-29	0.100 8	0.099	1.01
March	1- 7	0.110	0.126	0.87
	8-14	0.130	0.130	1.00
	15-21	0.150	0.087	1.72
	22-28	0.170	0.160	1.06
	29- 4	0.172	0.178	0.96
April	5-11	0.175	0.265	0.66
	12-18	0.178	0.298	0.60
	19-25	0.185	0.303	0.61
	26-30	0.192	0.343	0.56

TABLE 8-C. Crop Coefficients for Wheat (Late Mexican Variety) for Kanjra by Penman Equation (1948)

<u>Period</u>		<u>ETA</u> <u>inches/day</u>	<u>ETP (Penman 1948)</u> <u>inches/day</u>	<u>Daily</u> <u>Kc</u>
December	15-21	0.013	0.03	0.43
	22-28	0.030	0.03	1.00
	29- 4	0.034	0.03	1.13
January	5-11	0.040	0.03	1.33
	12-18	0.045	0.03	1.50
	19-25	0.056	0.032	1.75
	26- 1	0.062	0.032	1.94
February	2- 8	0.068	0.060	1.13
	9-15	0.070	0.056	1.25
	16-22	0.085	0.057	1.49
	23-29	0.100	0.065	1.54
March	1- 7	0.110	0.106	1.04
	8-14	0.130	0.086	1.51
	15-21	0.150	0.073	2.05
	22-28	0.170	0.105	1.62
	29- 4	0.172	0.116	1.48
April	5-11	0.175	0.156	1.12
	12-18	0.178	0.155	1.15
	19-25	0.185	0.175	1.06
	26-30	0.192	0.178	1.08

TABLE 8-D. Crop Coefficients for Wheat (Late Mexican Variety) for Kanjra by Penman Equation (Adapted)

<u>Period</u>		<u>ETA</u> <u>inches/day</u>	<u>ETP (Penman)</u> <u>inches/day</u>	<u>Daily</u> <u>Kc</u>
December	15-21	0.013	0.049	0.26
	22-28	0.030	0.048	0.62
	29- 4	0.034	0.050	0.68
January	5-11	0.090	0.051	0.78
	12-18	0.045	0.051	0.88
	19-25	0.056	0.053	1.05
	26- 1	0.062	0.055	1.17
February	2- 8	0.068	0.091	0.75
	9-15	0.070	0.083	0.84
	16-22	0.085	0.085	1.00
	23-29	0.100	0.093	1.08
March	1- 7	0.110	0.148	0.74
	8-14	0.130	0.130	1.00
	15-21	0.150	0.100	1.50
	22-28	0.170	0.140	1.21
	29- 4	0.172	0.154	1.12
April	5-11	0.175	0.207	0.85
	12-18	0.178	0.205	0.79
	19-25	0.185	0.226	0.82
	26-30	0.192	0.235	0.82

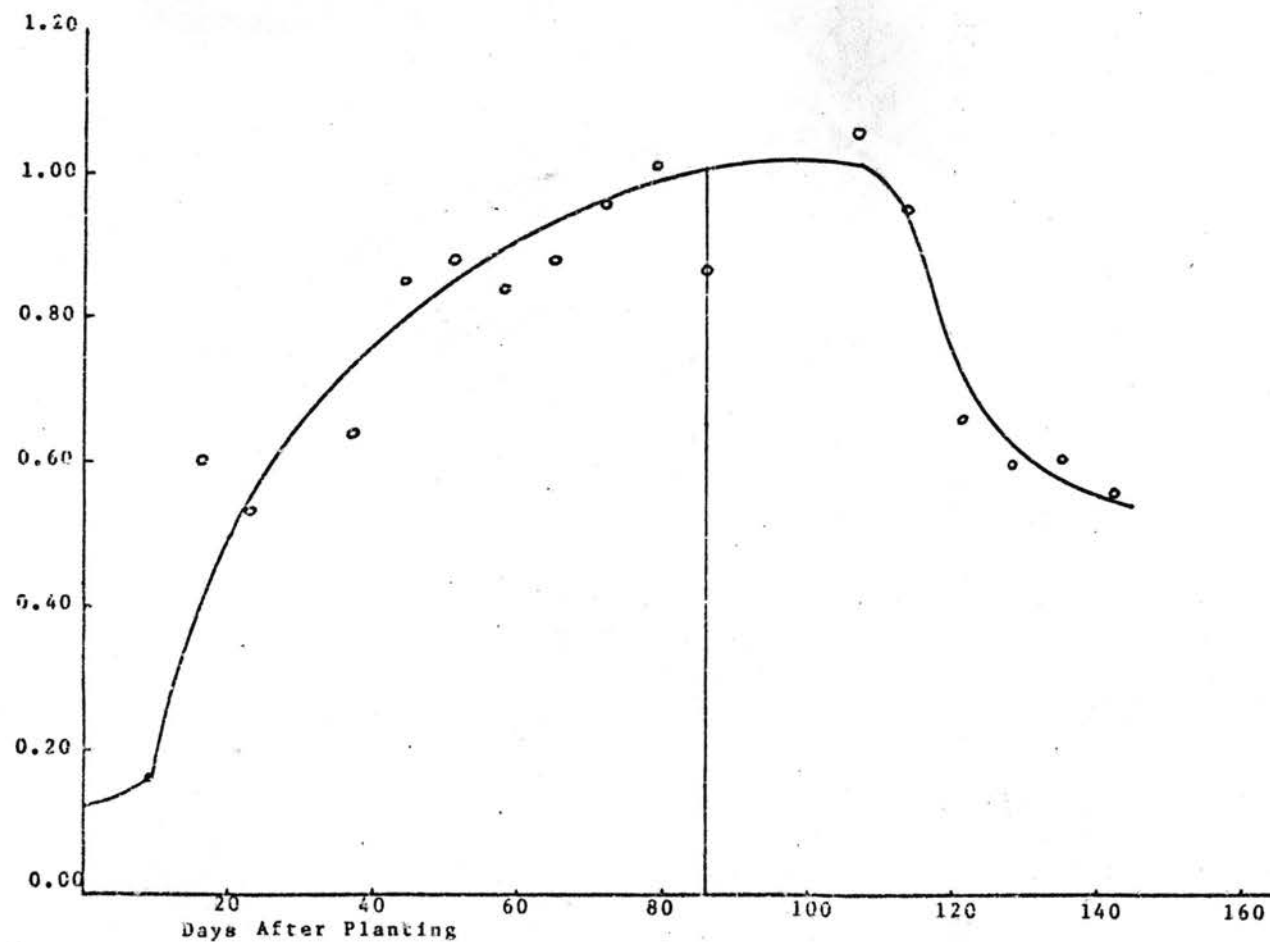


Figure 8. Experimental Crop Coefficients for Late Growing Mexican Wheat Crop by Jensen-Haise Equation

TABLE 9. Daily Evapotranspiration Values for Maize
Fodder at Kanjra by Jensen-Haise Method

<u>Period</u>		Potential Evapotranspiration (ETP) inches/day	Crop Coefficient Kc	Actual Evapotranspiration (ETA) inches/day
May	24-30	0.423	0.20	0.085
June	31- 6	0.450	0.20	0.090
	7-13	0.377	0.25	0.094
	14-20	0.316	0.30	0.095
	21-27	0.404	0.38	0.154
	28- 4	0.351	0.45	0.158
July	5-11	0.269	0.56	0.151
	12-18	0.237	0.64	0.152
	19-25	0.245	0.72	0.176
	26-31	0.240	0.82	0.197

Figure 2 of Appendix E. The irrigation scheduling reports for maize fodder for each of the three experimental fields is presented in Tables 10-A, 10-B, and 10-C.

D. Seasonal Application Efficiencies (E_A)

Application efficiency evaluations were conducted on both experimental and control plots at the Kanjra watercourse area for two growing seasons. During wheat season 1975-76, ETA were used for determining soil moisture deficiency in the root zone. Application efficiencies calculated for each individual irrigation, and then on a seasonal basis during the wheat season for both experimental and controlled plots, are shown in Tables 11-A and 11-B.

During the maize season 1976, irrigation application efficiencies were determined using the ETA values calculated from the Jensen-Haise equation and using Jensen (1963) crop coefficients. Seasonal application efficiencies showing the impact of irrigation scheduling for both experimental and controlled maize fodder plots are shown in Tables 12-A and 12-B.

E. Results of Scientific Irrigation Scheduling

The impact of scientific irrigation scheduling combined with precision land leveling in terms of savings in water, improved application efficiency and increase in per acre yield of crops is shown in Table 13. It is to be noted that the yield increases of experimental plots for wheat was partially due to fertility level and varietal difference, while in the case of the maize fodder plots,

TABLE 10-A. Scientific Irrigation Scheduling for Maize Fodder 1976 on Experimental Plot #1 Hakeem Farm

Soil Type - Silt loam

Date of sowing - May 29, 1976

Moisture content at field capacity

(weight basis) = 21.9 Percent

Moisture content at permanent wilting point

(weight basis) = 8.9 Percent

Date of Inspection	Average Evapotrans- piration Rate ET inches/day*	Rootzone Depth (feet)	Available Water Holding Capacity in root- zone (inches)	Allowable Depletion in rootzone (inches)**	Available Water in rootzone (inches)***	Deple- tion to Date	Irrigations Needed	
							Date	Amount (inches)
June, 13	0.095	1.5	2.93	1.47	1.37	1.56	June, 14	1.65
June, 21	0.124	2.0	3.98	1.99	1.92	2.06	June, 22	2.18
July, 3	0.151	2.5	5.10	2.60	4.73	0.37	July, 16	2.70
July, 13	0.164	3.00	5.90	2.95	3.24	2.66	July, 14	2.80

* Actual evapotranspiration rate calculated from Jensen-Haise equation both for 3 preceeding days and expected for 3 next days.

** Irrigations recommended before or just at 50 percent depletion.

*** Estimated through gravimetric soil moisture sampling.

TABLE 10-B. Scientific Irrigation Scheduling for Maize Fodder 1976 on Experimental Plot #2 Chirag Farm

Soil Type - Silt loam

Date of sowing - May 27, 1976

Moisture content at field capacity

(weight basis) = 21.5 Percent

Moisture content at permanent wilting point

(weight basis) = 8.5 Percent

Date of Inspection	Actual Evapotrans- piration Rate ET inches/day*	Rootzone Depth (feet)	Available Water Holding Capacity in root- zone (inches)	Allowable Depletion in rootzone (inches)**	Available Water in the rootzone (inches)***	Deple- tion to Date (inches)	Irrigation Needed	
							Date	Amount (inches)
June, 10	0.095	1.00	2.25	1.13	0.76	1.49	June, 13	1.61
June, 12	0.095	2.00	3.37	1.69	2.88	0.49	June, 24	1.69
June, 24	0.156	2.50	5.74	2.87	3.21	2.53	June, 26	2.90
June, 28	0.158	2.50	5.04	2.52	2.22	0.30	July, 12	2.50
July, 1	0.155	2.50	5.28	2.63	3.40	1.88	July, 5	2.60
July, 5	0.155	3.00	6.20	3.10	3.73	2.47	July, 8	2.40
July, 8	0.159	3.50	7.24	3.62	4.49	2.75	July, 14	3.50

* Evapotranspiration rate calculated from Jensen-Haise equation both for 3 preceeding days and expected for 3 next days.

** Irrigations recommended before or just at 50 percent depletion.

*** Estimated through gravimetric soil moisture sampling.

TABLE 10-C. Scientific Irrigation Scheduling for Maize Fodder 1976 on Experimental Plot #3 Rashid Farm

Soil Type - Silt loam

Date of sowing - May 31, 1976

Moisture content at field capacity
(weight basis) = 21.5 PercentMoisture content at permanent wilting point
(weight basis) = 8.5 Percent

Date of Inspection	Average Evapotrans- piration Rate ET' (inches/day)*	Rootzone Depth (feet)	Available Water Holding Capacity in root- zone (inches)	Allowable Depletion in rootzone (inches)**	Available Water in rootzone (inches)***	Deple- tion to Date (inches)	Irrigation Needed	
							Date	Amount (inches)
June, 18	0.124	1.50	3.42	1.71	1.74	1.68	June, 19	1.80
June, 23	0.136	2.00	4.49	2.25	3.03	1.46	June, 28	2.25
June, 28	0.158	2.00	4.26	2.13	2.31	1.95	June, 29	2.25
July, 7	0.159	2.50	5.54	2.77	4.25	1.29	July, 16	2.80
July, 16	0.163	3.00	6.52	3.26	4.98	1.54	July, 28	3.00

* Actual evapotranspiration rate calculated from Jensen-Haise equation both for 3 preceeding days and expected for 3 next days.

** Irrigations recommended before or just at 50 percent depletion.

*** Estimated through gravimetric soil moisture sampling.

TABLE 11-A. Application Efficiencies on Experimental Fields at
Kanjra Watercourse during Rabi 1975-76

Date of Inspection	Days since Last Irrigation	Evapotrans- piration during Irrigation Interval (inches)	Rainfall during Irrigation Interval (inches)	Soil Moisture Defi- ciency (inches)	Water Applied (inches)	Application Efficiency E_a (Percent)
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EXPERIMENTAL FIELD #1

January 24, 1976	44 (after sowing)	2.11	0.47	1.64	3.15	52.1
February 14, 1976	22	1.89	0.72	1.17	1.59	73.6
February 28, 1976	14	1.40	0.45	0.95	2.25	42.20
March 27, 1976	27	3.51	1.11	2.40	2.40	100.00

Seasonal E_a = 67.0%

EXPERIMENTAL FIELD #2

December 22, 1976	19 (after sowing)	0.57	-	0.57	2.02	28.22
February 8, 1976	48	2.69	1.25	1.44	2.15	66.98
March 1, 1976	22	1.98	0.50	1.48	1.80	82.22

Seasonal E_a = 59.20%

Overall Seasonal E_a = 63.10%

TABLE 11-B. Application Efficiencies on Fields Controlled by Farmers*
at Kanjra Watercourse during Rabi 1975-76

Date of Irrigation	Days since Last Irrigation	Evapotranspiration during Irrigation Interval (inches)	Rainfall during Irrigation Interval (inches)	Soil Moisture Deficiency (inches)	Water Applied (inches)	Application Efficiency (Percent)
December 22, 1975	19 (after sowing)	0.57	-	0.57	2.33	24.46
January 23, 1976	50	2.20	0.50	1.70	2.72	62.50
January 25, 1976	33	1.49	0.50	0.99	2.25	44.00
January 28, 1976	5	0.35	0.20	0.15	2.00	7.14
February 8, 1976	13	0.86	0.72	0.14	2.25	6.22
February 18, 1976	20	1.50	0.90	0.60	2.72	22.05
February 21, 1976	21	1.89	0.50	1.39	2.56	54.29
March 3, 1976	15	1.58	0.30	1.28	2.45	52.24
March 7, 1976	7	0.77	-	0.77	2.22	34.68
March 26, 1976	21	3.15	1.10	2.05	2.80	73.21
March 28, 1976	20	2.60	1.10	1.50	1.86	80.60

Seasonal Application Efficiency = 42%

*Liaqat Farm and Majeed Farm

TABLE 12-A. Irrigation Application Efficiencies on Irrigation Scheduling Experimental Fields at Kanjra Watercourse during Maize Growing Season 1976

Date of Irrigation	Available Nakka Discharge (Cusecs)	Amount of Water Applied (inches)	Moisture Deficiency in Root Zone (inches)*	Irrigation Application Efficiency Percentage
Experimental Field #1 Hakeem Farm (Head of the Watercourse)				
June 24	2.80	2.53	2.31	91.3
June 28	No record due to cut in the channel bank			
July 13	2.85	2.76	2.65	95.5
Seasonal $E_a = 93.4\%$				
Experimental Field #2 Chirag Farm (Middle of the Watercourse)				
June 11	1.69	2.10	1.59	75.7
June 26	2.52	3.30	2.90	87.9
July 8	2.50	2.93	2.75	94.17
Seasonal $E_a = 85.93\%$				
Experimental Field #3 Rashid Farm (End of the Watercourse)				
June 21	2.1	2.80	2.15	76.79
June 30	2.2	2.93	2.57	87.72
July 11	2.0	2.66	2.16	81.35
Seasonal $E_a = 82.0\%$				

*Soil moisture deficiency in the root zone estimated by gravimetric soil moisture sampling.

TABLE 12-B. Irrigation Application Efficiencies on a Field Controlled by a Farmer* at Kanjra Watercourse during Maize Growing Season 1976

Date of Irrigation	Available Nakka Discharge (Cusecs)	Amount of Water Applied (inches)	Moisture Deficiency in Root Zone (inches)	Irrigation Application Efficiency (Percent)
June 21	1.75	3.16	1.84	58.2
July 5	2.20	3.20	3.68	100.00
July 13	2.10	3.10	1.41	45.55
July 19	2.60	2.90	0.88	30.34

Seasonal Application Efficiency = 68%

*Pervez and Feroze Farm

TABLE 13. Results of On-Farm Water Management Technology Applied at Kanjra Watercourse Area

Field (Owner and Number)	Total Irrigation Water Applied during the Crop Growing Season Excluding Rauni (inches)	Total Effective Rainfall during the Season (inches)	Seasonal Application Efficiency E _a (Percent)	Average E _a (Percent)	Crop Yield (maunds/ acre)
<u>WHEAT SEASON 1975-76</u>					
Experimental Field #1 (Hakeem Farm)	9.39	3.90	67.0		38.42
Experimental Field #2 (Mehtab Farm)	9.17	3.90	59.2	63.10	39.50
Control Field #1 (Liaqat Farm)	12.67	3.90	43.6		32.0
Control Field #2 (Majeed Farm)	13.41	3.90	41.9	42.57	30.0
<u>MAIZE FODDER - 1976</u>					
<u>Irrigation Scheduling Program</u>					
Experimental Field #1 (Hakeem Farm)	7.80	7.70	93.4		458.0
Experimental Field #2 (Chirag Farm)	8.33	7.70	85.9	87.10	395.0
Experimental Plot #3 (Rashid Farm)	8.39	8.90	82.0		322.0
*Control Field #1 (Pervez Farm)	4.95	19.80	30.3		198.20
Control Field #2 (Feroze Farm)	12.30	9.46	67.9	49.12	300.0

*Control Field #1 was sown 3 weeks later than the others and received much more of the monsoon rains.

the real impact of irrigation scheduling combined with precision land leveling has been shown.

Chapter VII

DISCUSSION OF RESULTS

A. Comparison of Methods of ETP Determination

The potential evapotranspiration (ETP) rate determined from the Penman equation (1948), from the adapted Penman equation, from the Jensen-Haise equation, and estimated by evaporation from a U.S. Weather Bureau (USWB) Class A Pan were compared with the actual evapotranspiration (ETA) rate as measured by soil moisture depletion on measurements during the wheat season as shown in Figure 6. The purpose was to determine the most suitable method for ETP determination for scheduling irrigations in Pakistan. The crop consumptive use coefficient, the ratio of ETA to ETP at the time of maximum effective crop cover, was considered as the basis for comparison of ETP determination methods. From Figure 6 it is evident that the adapted Penman equation curve for ETP approached the ETA curve during the time of effective crop cover. This is followed by the Pan evaporation curve and the Jensen-Haise curve. The adapted Penman equation was, therefore, the most suitable method for determining ETP under the conditions in the case study. The practical limitation of this equation is that it involves so many variables and constants which can only be recorded at first class weather stations. Furthermore, the changed values of constants A and B from 0.18 to 0.30 and 0.55 to 0.60 in the term for energy available for evaporation $R_a (1-r) (A + E_n/N)$ from the Penman equation (1948) needs additional elaboration

and study by comparison with other data collected at other sites where crop consumptive use coefficients have already been determined experimentally by lysimeters or by intensive soil moisture sampling.

Under conditions of full crop cover, pan evaporation was practically as close to the actual evapotranspiration as the adapted Penman equation curve. Pan evaporation is a practical way for scheduling irrigations. However, considerable care must be taken to avoid losses of water due to factors unrelated to potential evapotranspiration, such as thirsty animals! The values of daily pan evaporation may have been slightly low due to the effect of a large canal and the adjoining watercourses (both within 35 meters) on two sides of the observatory where the evaporation pan was located.

The Jensen-Haise equation gave higher values of ETP throughout the growing season. This could be attributed to the quality of the Chuharkana observatory data whose 12 years average was used for equation calibration. This data may not be representative of the site conditions at Kanjra since the Chuharkana observatory, operated by WAPDA, is located 25 miles from the Kanjra watercourse. The Jensen-Haise equation calibrated from Chuharkana's 12 years of temperature data gave higher values for constants CT and TX than those reported by Clyma (1973) for this area (Appendix III).

The Penman equation (1948) gave very low values of ETP, even less than the actual evapotranspiration rate. The main reason for low ETP values by this method could be due to the fact that Penman developed his equation for the humid climates of England and accordingly its constants are for humid areas; when applied in arid and semi-arid regions like Pakistan, the equation may under-estimate ETP. The Penman equation is a more fundamental equation while the Jensen-Haise equation is completely empirical, and even Jensen, co-developer of the Jensen-Haise equation, recommends Penman's equation when reliable data for the necessary factors are available (Hart, 1975).

B. Irrigation Scheduling for Maize Fodder

Scientific irrigation schedules for maize fodder on three experimental fields at the Kanjra watercourse were prepared on the basis of the daily values of ETP as determined by the Jensen-Haise equation calibrated both for the dry and monsoon seasons. Irrigation scheduling status reports were prepared, the fields were inspected, and soil moisture determinations were conducted on a weekly basis. Weekly evapotranspiration rates for maize fodder were determined on the basis of ETP and crop coefficient values for the three preceeding days and the predicted values for the following days. While forecasting irrigation dates, consideration was not given for expected rainfall since long term monthly average rainfall data was not available for the Kanjra site. Taking this limitation into consideration, moisture sampling was done more frequently.

Irrigations were scheduled at or before 50 percent depletion of the available soil moisture so that the yield would not be adversely effected. Exact irrigation schedules could not be followed on the experimental fields since canal water availability was on a fixed schedule. This fact, accompanied by canal closure during the season, affected the irrigation applications during the maize growing season.

C. Results of Scientific Irrigation Scheduling

Table 11 shows the impact of irrigation scheduling when accompanied with precision land leveling, in terms of water savings, improved application efficiencies, and increased yields. These results are not solely due to irrigation scheduling since the fertilizer applications and wheat varieties were different in the control and experimental fields; the results, therefore, were due to the combined effect of the package of improved practices. During the maize season, scheduling was practiced on three experimental and two controlled fields. The variety of maize was constant, and fertilization of the fields were controlled at the same rate; thus, the experimental variables were the water application and precisely leveled land. The control field was sown three weeks later than the other fields and accordingly the crop was badly affected by heavy monsoon rains in August; thus, its yield and water application efficiency differ from the other control field. The mean yield for the controlled plots was 249 maunds per

acre, while the experimental mean yield was 391 maunds per acre. The yield differential attributable to precision land leveling and scientific irrigation scheduling was thus 142 maunds per acre, or nearly a 60 percent increase above the controlled plot yields. If the controlled plot #1 is discounted due to the influence of the monsoon, the yield increment attributable to precision land leveling and scientific irrigation scheduling is nearly 30 percent more than the controlled plot yield. Therefore, it is concluded that irrigation scheduling gives better results when combined with precision land leveling.

D. Discussion on Estimated Data Quality

Most of the meteorological data used for comparison of different methods of ETP determination was recorded at the newly established observatory at Kanjra. There was no provision for recording hours of daily sunshine and solar radiation for a few weeks of the wheat season. Accordingly, the missing data was borrowed from the Pilot Balloon Observatory at Lahore and WAPDA's Meteorological Observatory at Chuharkana; the quality of this data cannot be guaranteed. The Sol-a-meter installed at Kanjra Observatory was affected by shade for almost a half hour during the day. The integrator of the Sol-a-meter stopped working during the season; accordingly, observations of solar radiation were recorded after every 30 minutes and a curve drawn for the day and solar radiation per day was graphically integrated. These

limitations with the recording instruments would definitely have affected the quality of the recorded data. For determining actual evapotranspiration using gravimetric soil moisture sampling, soil samples were analyzed at the Soil Testing Laboratory of WASID division of WAPDA for soil moisture retention curves. The discrepancies in the data of soil moisture retention characteristic curves as shown at Appendix B-2 represents the poor quality of the data. All these practical limitations in the quality of the estimated and the recorded data may be kept in mind when reviewing the results.

Chapter VIII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary

Water is the limiting factor in the agricultural economy of most of the late developing countries and Pakistan is no exception. There are a multitude of factors which determine the agricultural production of any particular area and On-Farm Water Management appears to be the most important constraint to increased food production. Efficient use of present irrigation water supplies has become more important in Pakistan as the demand for irrigation water has increased and new sources of supply become harder to find and more expensive to develop.

Over-irrigation in both quantity and frequency is an important contributor to the debilitating effects of waterlogging and under-irrigation is an important contributor to salinity in the Indus Basin. The main causes of over-irrigation and under-irrigation resulting in very low irrigation application efficiencies, or incomplete irrigations, include unlevelled farmers' fields, inefficient traditional irrigation methods, fixed irrigation schedules, uncertainty of the water supplies and lack of farmers' knowledge of crop water requirements. A large portion of the water wasted due to over-irrigation can be saved through scientific irrigation scheduling by applying the amount of water required to meet the consumptive use requirements of crops. The correct amount of water applied to fill the

crop root zone soil moisture reservoir, plus the amount necessary for adequate leaching, can help to maintain a favorable salt balance. The tremendous amount of losses in 78,000 poorly maintained earthen watercourses in Pakistan with an average of 60 percent delivery efficiency has been discussed in this study, as well as the extent of field losses on unleveled fields and the losses resulting from over-irrigation due to the unawareness by the farmers about the crop water needs. Resulting application efficiencies are sometimes as low as 20 percent, but which due to frequent under-irrigation average 75 percent.

There is a paucity of research information regarding crop consumptive use requirements in the country. Consumptive use coefficients for almost all the crops have not been experimentally determined for scheduling irrigations. Accordingly, different methods of determining irrigation water requirements using climatic data were compared for the wheat season and crop coefficients determined for use by the extension workers in scheduling irrigations in the study area. By utilizing four different methods of determining potential evapotranspiration using climatic data, compared with actual evapotranspiration for the wheat season, a suitable method for use in Pakistan by extension agents has been recommended in this study.

Scientific irrigation scheduling and application efficiencies on three selected farms have been compared with those used on traditional farmers' fields in terms of

increased crop yields and savings of water in the study area. The problems and constraints which can seriously affect the implementation of scientific irrigation scheduling service in Pakistan have been described along with a few recommendations.

B. Conclusions

One of the important factors in the new strategy for agricultural development is efficient water utilization and management on the farm. On-farm water management technology has been a neglected field in Pakistan. Agencies engaged in the irrigation system of Pakistan have been successful in developing water resources, but efforts have not been made to achieve optimum returns per unit of water made available at the canal mogha outlet. Irrigation water distribution beyond the mogha has been left to the farmers without the benefit of technical assistance.

The irrigation water conveyance system from the canals and distribution in watercourses is very ineffective. On the average, over 40 percent of the water is wasted in the watercourses due to leaky structures, spillage, seepage and faulty design of the watercourses. Water discharge measurements are completely lacking both at the watercourse and farm level, so farmers are unaware of the extent of losses in conveyance or application to fields.

Both farmers and extension agencies engaged in agricultural development programs are unaware of the consumptive use water requirements of crops and their variations

according to the stage of crop growth. Farmers are generally of the opinion that applying more water will result in higher crop yields. Generally, consideration is not given to the rain water while applying irrigations, thus resulting in very low application efficiencies during monsoon rainfall occurrences.

The irrigation water delivery system is very rigid and ineffective. Water is supplied according to a fixed schedule and fixed time irrespective of crop water requirements, which is probably the major constraint for implementing irrigation scheduling programs. Studies for two growing seasons indicate that if enough water is made available to the farmers at the canal outlet, they themselves will switch over to the demand system by closing the mogha when water is not needed.

The results of the study indicate that the required benefits of an irrigation scheduling program will accrue only when it is combined with other components of on-farm water management technology, i.e., land leveling, watercourse improvement, and farm drainage. An irrigation scheduling program without other components of on-farm water management technology has a marginal effect on improving irrigation application efficiencies, water savings, fertilizer use efficiency, and thus, higher crop yields.

Analysis of the data reveal that pan evaporation can be used as a measure for potential evapotranspiration accompanied by occasional soil moisture samplings as a

basis for an irrigation scheduling program. Where climatic data are available, the Jensen-Haise method is adequate for an extensive commercial scientific irrigation scheduling service. The adapted Penman method appears to be capable of giving an even better basis for irrigation scheduling, but requires further testing.

The results of the demonstration show that irrigation scheduling combined with land leveling increased application efficiency by 38 percent on a seasonal basis and yield by 48 percent when compared with the traditional farmers fields having the same fertility level and crop variety.

C. Recommendations

This study of a watercourse area during two crop growing seasons, with emphasis on application efficiencies, potential evapotranspiration determinations, and scientific irrigation scheduling on selected farms, has led to the following recommendations:

1. Flow Measurements

At present, farmers are unaware of the extent of losses in the watercourses and the amount of water they are applying to their crops. Discharge measurement structures should be installed on the watercourses and also at some of the field nakkas enabling the farmers to understand the magnitude of losses. It is ridiculous to advise a farmer to apply 2.5 inches of water when he is not able to measure the water flowing in his watercourse. An irrigation scheduling program, therefore, should be accompanied by flow measurement

facilities at the watercourse and farm level, which should lead to an awareness of losses and eventually to improved application efficiencies.

2. Changes in the Warabundi System

Water is made available to the farms on a fixed time schedule according to the land owned by the farmers, which does not meet the plant needs effectively. It causes wastage of water when crops are at initial stages of growth. Annual canal closure for cleaning and repair usually occurs during the time when the wheat crop needs irrigation, but fortunately it occurs when atmospheric moisture demands are low. At present, it is difficult to modify the existing irrigation system to switch-over to a demand water supply system. On individual canals and distributaries, this can be followed by knowing the crop water requirements of the individual areas and thus closing the moghas by the farmers when water is not needed. This arrangement worked well in the case of this study area due to an excessive water supply. Remaining with the present allocation system, the possibility of storing water in ponds at the head of the watercourse for use at a later stage needs consideration.

3. Research Needs for On-Farm Water Management

There is inadequate research information regarding the components of on-farm water management strategy i.e., land leveling, watercourse improvement and farm extension advisory services including irrigation scheduling. Research

work is being conducted for determining crop consumptive use requirements for important crops with crop coefficients being determined using climatological data and soil moisture sampling, so that the extension service can implement scheduling programs using the research data. Similarly, research should be conducted on the economics of precision land leveling and watercourse improvement in terms of savings of water and increased crop yields.

An irrigation advisory service for individual farms should be included in on-farm water management development project activities. On-farm water management research should provide the extension organization and the farmers with the information of water needs of crops according to the stage of growth and soil conditions.

4. Establishment of an Irrigation Scheduling Pilot Program

Before starting the scientific irrigation scheduling services in the country, certain pilot watercourse command areas should be selected under the On-farm Water Management Development Project to provide scheduling services in combination with land leveling and watercourse improvement.

Weather observatories should be established in each of the pilot project areas to record meteorological data for scheduling irrigations. The project should provide irrigation advisory services free of cost to the farmers. Farmers could be organized to form water users associations which would fix the irrigation schedules on the watercourse

area with the assistance of the project staff. At a later date, the pilot project area could be extended to other watercourses, until ultimately the entire distributary was covered.

5. Changes in Institutional Infrastructure

As is the case with many other late developing countries, the planning and administration of the canal system is implemented by the Irrigation Department in Pakistan. There is no control after the water leaves the mogha. It is recommended that an organization be created within the existing infrastructure of the Irrigation or Agriculture Department, namely an "Irrigated Agriculture Service" to be entrusted with the control of water distribution beyond the mogha. As a preliminary means of determining the feasibility of such a service, the control of some watercourses should be given to the On-Farm Water Management Development Project with all the necessary powers explained in the Canal and Drainage Act - 1873 as amended. When farmers' institutions such as Water Users Associations are developed, the water distribution control can be entrusted to these institutions. It is recommended that the necessary amendments should be made in the Canal Act - 1873 for providing a Board of Directors for Canal Water distribution involving representation of the farmers, water management specialists, and representatives of the Irrigation Department for operating the irrigation system at the watercourse, distributary, minor, and canal levels.

There is a big potential for improving on-farm water management in Pakistan. The Government of Pakistan is now fully aware of the extent of water losses in the water-course system and on farmers' unlevelled fields. Results of on-farm water management research studies by the Colorado State University Field Party in cooperation with the Mona Reclamation Experimental Project, and some of the crops research institutes in Pakistan, have provided a basis for implementation of large scale water management programs assisted by international organizations such as USAID, World Bank and UNDP. The watercourse study project being done by the Master Planning and Review Division of WAPDA and the On-Farm Water Management Development Project by Provincial Governments of Punjab, Sind and NWFP have started functioning recently. Irrigation Advisory Services, including Irrigation Scheduling Services for the irrigators, is one of the major objectives of the On-Farm Water Management Development Program.

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APPENDIX A

METEOROLOGICAL DATA AND SOILS DATA COLLECTED AT THE KANJRA STUDY SITE

- TABLE 1. Meteorological Data Collected at the Kanjra Study Site
- FIGURE 1. Variation in Mean Daily Solar Radiation during Wheat Season 1975-76 at Kanjra
- FIGURE 2. Variation in Mean Daily Relative Humidity during Wheat Season 1975-76 at Kanjra
- FIGURE 3. Variation in Mean Daily Temperature during Wheat Season 1975-76 at Kanjra
- TABLE 2. Laboratory Results of Soil Physical Properties from Four Farms at the Kanjra Study Site
- FIGURE 4. Variation of Field Determined Mean Dry Bulk Density of Soil during Wheat Season 1975-76 at Kanjra
- TABLE 3. Summary of Mean Available Moisture Percentage for Experimental and Control Plots

TABLE 1. Meteorological Data Collected at the Kanjra Study Site

DAY ¹	PREC. ²	PAN ³	SS	HRS ⁴	WRUN ⁵	MT EMP ⁶	MRH ⁷	DAYTIME ⁸
76	0.0	0.06		9.10	9.0	-1.0	61.5	10.2
77	0.0	0.07		7.00	21.0	55.5	56.8	10.2
78	0.0	0.08		9.20	17.0	57.0	60.5	10.2
79	0.0	0.08		7.80	12.0	55.5	60.7	10.2
80	0.0	0.06		8.60	6.0	56.5	59.2	10.2
81	0.0	0.07		9.40	7.2	58.0	57.9	10.2
82	0.0	0.07		6.80	14.7	58.5	58.2	10.2
83	0.0	0.08		9.30	15.3	55.0	69.3	10.2
84	0.0	0.06		9.10	17.1	55.5	65.5	10.2
85	0.0	0.04		4.70	6.2	53.5	63.1	10.2
86	0.0	0.04		-1.00	5.2	55.5	77.5	10.2
87	0.0	0.04		5.70	18.3	58.5	73.2	10.2
88	0.0	0.0		0.0	12.8	58.0	80.2	10.2
89	0.02	0.0		0.20	25.5	50.0	87.3	10.2
90	0.0	0.05		6.95	17.2	57.0	75.0	10.2
91	0.0	0.05		6.75	15.3	56.5	75.0	10.2
92	0.0	0.04		2.88	7.4	56.0	75.0	10.2
93	0.0	0.03		3.70	10.3	56.5	75.7	10.2
94	0.0	0.05		0.0	24.0	55.0	77.8	10.2
95	0.0	0.08		8.90	19.7	55.5	70.1	10.2
96	0.0	0.09		9.30	17.3	55.0	65.8	10.2
97	0.0	0.08		9.40	24.0	54.0	64.4	10.2
98	0.0	0.05		9.50	29.7	51.5	66.9	10.2
99	0.0	0.05		9.00	9.5	54.5	66.4	10.3
100	0.0	0.04		3.10	6.7	53.5	71.6	10.3
101	0.0	0.06		8.40	10.3	51.0	69.1	10.3
102	0.0	0.07		8.20	12.5	52.0	69.4	10.3
103	0.0	0.08		2.40	5.4	55.5	71.8	10.3
104	0.40	0.05		0.40	24.3	55.0	75.5	10.3
105	0.01	0.01		1.60	36.2	57.5	85.1	10.3
106	0.0	0.03		0.10	17.6	57.5	87.7	10.4
107	0.0	0.05		2.30	16.5	58.5	81.4	10.4
108	0.0	0.05		5.30	14.0	54.0	76.9	10.4
109	0.0	0.07		10.20	32.9	53.0	72.1	10.4
110	0.0	0.09		9.70	19.2	51.5	74.0	10.4
111	0.0	0.07		10.10	15.7	53.0	67.0	10.5
112	0.0	0.08		9.30	12.5	54.5	67.3	10.5
113	0.0	0.09		9.30	23.2	55.0	69.8	10.5
114	0.0	0.04		5.00	3.7	55.5	70.9	10.5
115	0.0	0.02		1.40	13.9	57.0	76.3	10.5
116	0.0	0.05		1.70	38.7	57.0	81.2	10.6
117	0.0	0.07		1.40	16.9	58.5	76.6	10.6
118	0.05	0.05		0.0	48.3	54.0	89.7	10.6
119	0.0	0.06		5.10	36.7	53.5	82.7	10.6

TABLE 1. Continued

120	0.0	0.05	9.13	34.9	54.0	76.7	10.7
121	0.0	0.06	9.73	25.3	54.0	72.7	10.7
122	0.50	0.06	5.70	25.5	58.5	75.0	10.7
123	0.22	0.05	0.70	9.3	53.5	91.7	10.7
124	0.0	0.06	8.60	17.6	56.0	81.5	10.7
125	0.0	0.04	5.70	23.3	55.5	82.5	10.7
126	0.0	0.07	3.90	21.5	57.0	77.5	10.8
127	0.15	0.08	7.23	34.9	62.0	72.5	10.8
128	0.0	0.10	3.60	43.4	58.0	66.5	10.8
129	0.0	0.12	3.40	29.3	62.0	68.5	10.8
130	0.0	0.09	5.50	46.3	61.0	70.0	10.9
131	0.0	0.04	5.62	46.7	58.0	74.5	10.9
132	0.0	0.07	9.90	25.3	58.5	71.5	11.1
133	0.0	0.09	9.33	15.0	59.0	67.0	11.0
134	0.0	0.06	5.70	16.3	63.5	68.5	11.0
135	0.0	0.05	3.40	29.3	59.5	74.5	11.1
136	0.0	0.02	3.40	44.2	58.0	80.0	11.1
137	0.05	0.05	0.0	105.6	59.0	79.5	11.1
138	0.0	0.02	4.00	41.9	58.5	73.5	11.2
139	0.0	0.07	3.30	30.6	60.5	75.5	11.2
140	0.25	0.09	4.40	30.1	60.5	80.0	11.2
141	0.05	0.07	1.70	36.9	57.5	85.0	11.2
142	0.0	0.03	5.10	46.9	56.5	81.5	11.2
143	0.0	0.11	9.50	55.7	55.0	65.0	11.3
144	0.0	0.12	10.80	50.1	57.0	66.0	11.3
145	0.0	0.09	4.10	23.7	56.0	65.5	11.3
146	0.0	0.09	7.80	25.9	60.5	63.5	11.3
147	0.0	0.03	1.40	41.4	62.0	69.0	11.3
148	0.15	0.13	4.60	71.3	57.5	75.5	11.4
149	0.0	0.09	10.00	51.8	52.5	61.0	11.4
150	0.0	0.14	0.10	59.2	52.5	56.0	11.4
151	0.0	0.20	10.90	79.0	54.5	57.5	11.5
152	0.0	0.03	13.93	57.5	60.0	59.0	11.5
153	0.0	0.15	9.60	43.9	60.5	64.5	11.5
154	0.0	0.13	10.30	41.3	66.5	64.5	11.5
155	0.0	0.10	8.90	5.2	71.0	62.0	11.6
156	0.0	0.11	3.50	15.4	68.0	67.5	11.6
157	0.0	0.17	9.80	50.3	61.5	62.5	11.6
158	0.0	0.04	10.80	21.3	62.5	62.0	11.6
159	0.0	0.14	9.30	24.8	66.5	56.0	11.7
160	0.0	-1.13	1.60	74.3	61.0	73.5	11.8
161	0.37	-1.15	9.90	39.0	62.0	71.0	11.8
162	0.0	0.12	9.93	35.3	59.0	63.5	11.9
163	0.0	0.08	3.20	32.6	58.0	66.0	11.9
164	0.0	0.15	10.63	25.6	67.0	59.5	11.9
165	0.05	-1.00	0.60	40.0	-1.0	82.5	12.0
166	0.0	-1.00	6.90	47.0	57.5	73.0	12.0
167	0.14	0.09	0.0	32.0	57.5	86.5	12.0
168	0.55	0.09	2.63	19.2	58.0	83.0	12.1
169	0.0	0.13	9.90	33.7	63.0	71.5	12.1
170	0.0	0.10	5.50	22.1	62.5	71.5	12.1

TABLE 1. Continued

171	0.0	0.04	0.0	14.5	62.0	77.5	12.2
172	0.0	0.14	7.10	20.0	-1.0	74.0	12.2
173	0.0	0.14	10.20	23.0	64.0	67.5	12.2
174	0.0	0.15	8.60	25.7	67.5	64.5	12.3
175	0.0	0.23	5.50	16.5	67.5	60.5	12.3
176	0.0	0.19	10.50	34.5	67.5	67.5	12.3
177	0.0	0.15	9.90	38.5	68.5	62.5	12.4
178	0.0	0.10	1.70	61.6	68.5	65.0	12.4
179	0.0	0.17	9.40	30.4	68.5	62.0	12.4
180	0.0	0.17	7.80	24.4	69.5	67.5	12.4
181	0.0	0.08	1.90	48.9	66.5	62.0	12.5
182	0.0	0.24	10.60	14.3	68.5	61.0	12.5
183	0.0	0.22	10.00	43.0	66.0	78.5	12.5
184	0.0	0.17	9.60	23.9	66.0	69.5	12.5
185	0.0	0.18	11.10	25.8	63.0	76.0	12.5
186	0.0	0.11	9.80	9.0	71.5	68.5	12.6
187	0.10	0.13	0.0	89.3	69.5	67.5	12.6
188	0.13	0.08	3.00	71.6	70.5	63.0	12.7
189	0.0	0.10	11.10	148.0	69.0	61.5	12.7
190	0.0	0.18	10.50	38.8	68.5	61.0	12.8
191	0.0	0.19	11.10	18.2	75.0	60.0	12.8
192	0.25	0.24	7.60	99.6	73.0	62.5	12.8
193	0.0	0.24	10.60	20.6	68.0	68.5	12.9
194	0.0	0.19	11.50	23.0	69.5	62.5	12.9
195	0.0	0.25	11.10	44.0	69.0	55.0	12.9
196	0.0	0.24	10.70	24.4	72.5	55.0	13.0
197	0.0	0.19	9.70	6.1	75.5	50.0	13.0
198	0.0	0.24	11.00	18.5	75.0	52.5	13.0
199	0.0	0.24	9.80	20.9	85.5	52.0	13.1
200	0.0	0.25	8.90	37.3	77.0	47.5	13.1
201	0.0	0.22	8.10	14.4	77.0	57.5	13.1
202	0.0	0.21	10.00	13.7	81.5	52.5	13.2
203	0.0	0.24	11.20	12.5	84.0	55.5	13.2
204	0.0	0.22	11.10	8.5	85.0	55.5	13.2
205	0.0	0.25	8.10	46.5	87.0	63.0	13.2
206	0.27	0.28	9.90	80.0	81.5	72.5	13.3
207	0.0	0.30	5.70	113.8	94.0	62.5	13.3
208	0.0	0.30	3.40	47.4	76.0	57.5	13.3
209	0.0	0.25	12.00	24.5	82.0	60.0	13.4
210	0.15	0.18	11.20	54.1	83.0	56.5	13.4
211	0.0	0.24	9.00	19.3	79.0	45.0	13.5
212	0.0	0.25	11.00	20.3	83.0	50.0	13.5
213	0.0	0.22	11.70	21.5	81.5	47.5	13.5

- 1/DAY = day of the year
2/PREC = precipitation (inches)
3/PAN = pan evaporation (inches)
4/SS HRS = sunshine hours
5/WRUN = wind run (miles/day)
6/M TEMP = mean daily temperature (°F)
7/M RH = mean relative humidity
8/DAYTIME = hours from sunrise to sunset

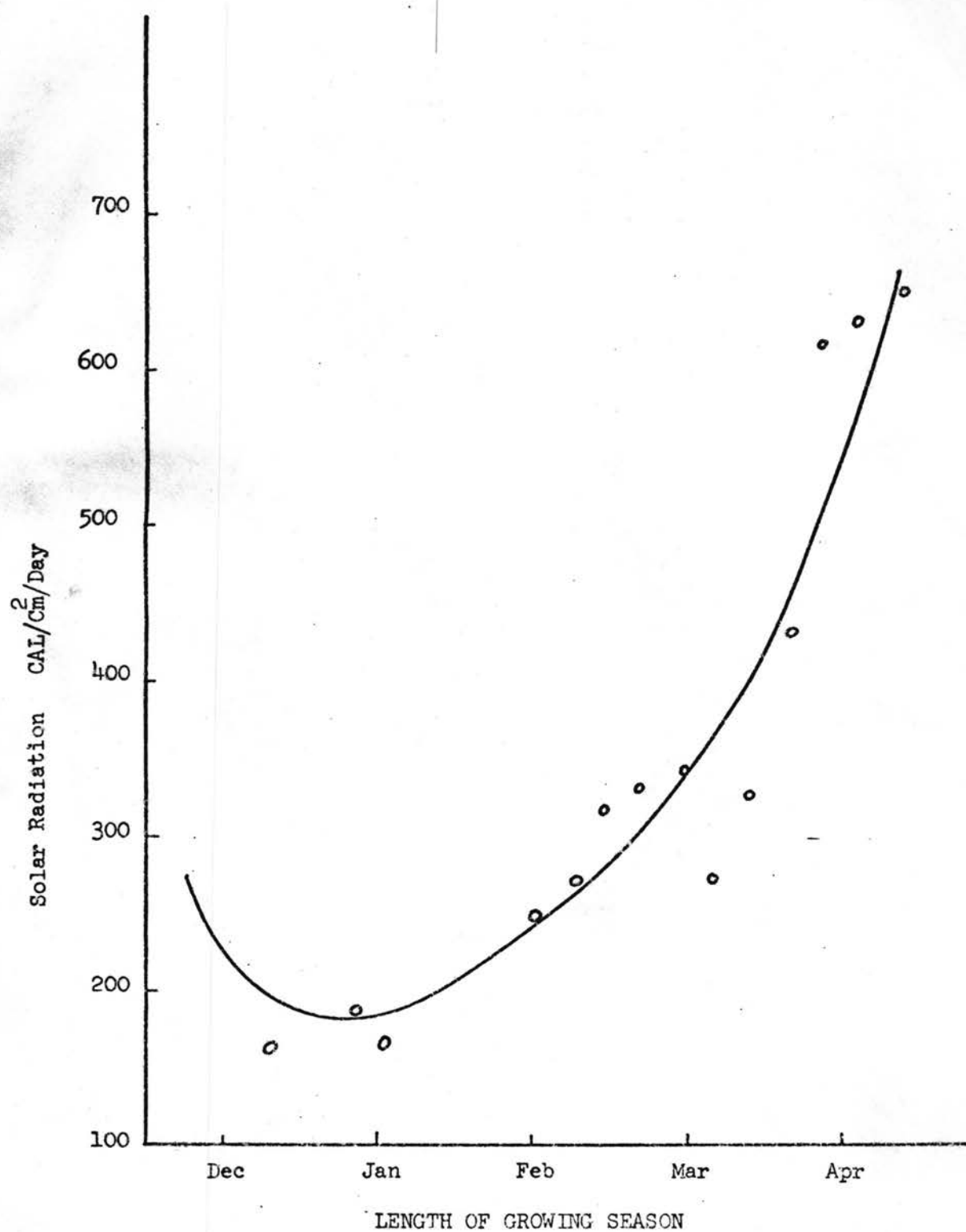


Figure 1. Variation in Mean Daily Solar Radiation during Wheat Season 1975-76 at Kanjra

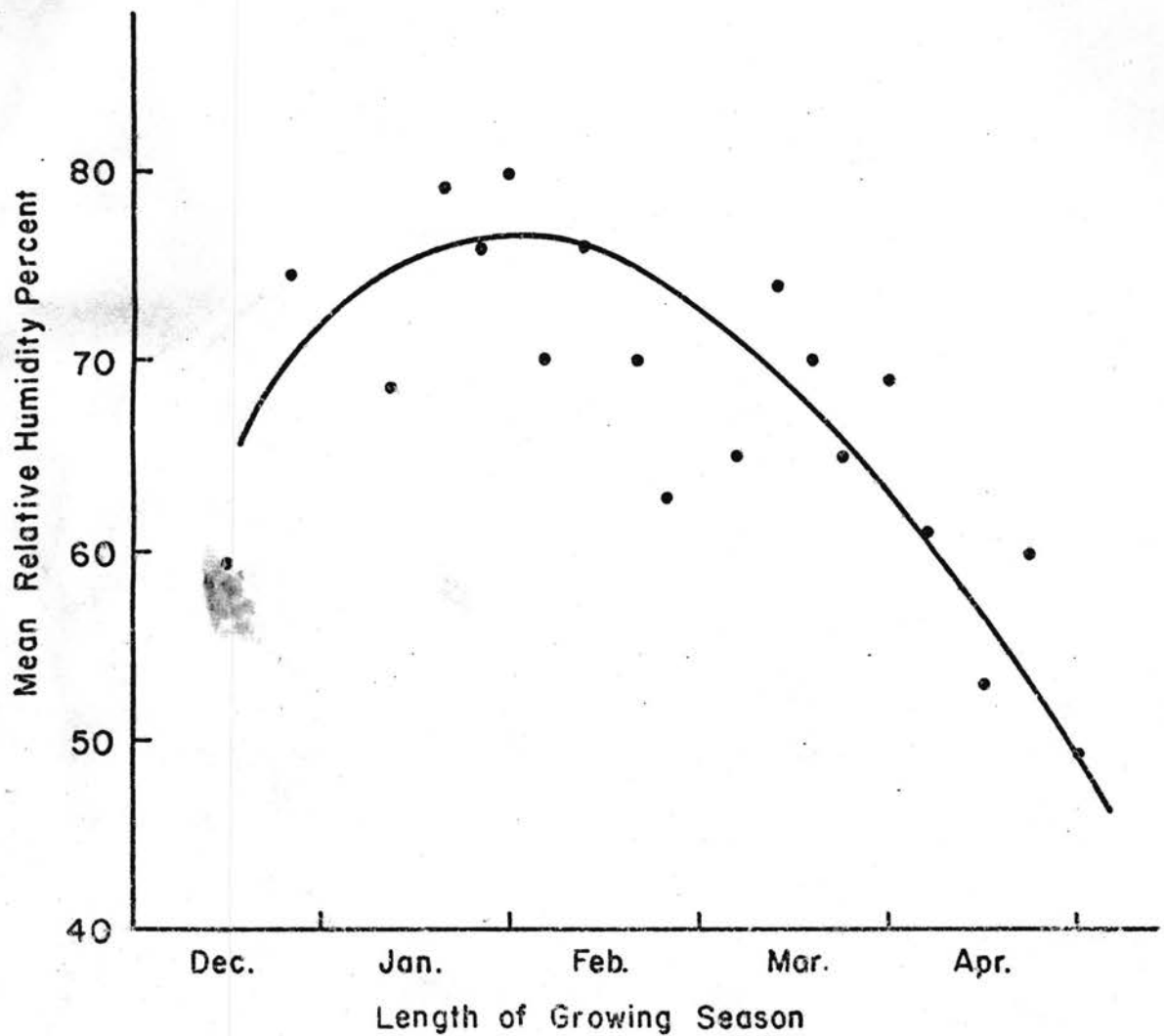


Figure 2. Variation in Mean Daily Relative Humidity during Wheat Season 1975-76 at Kanjra

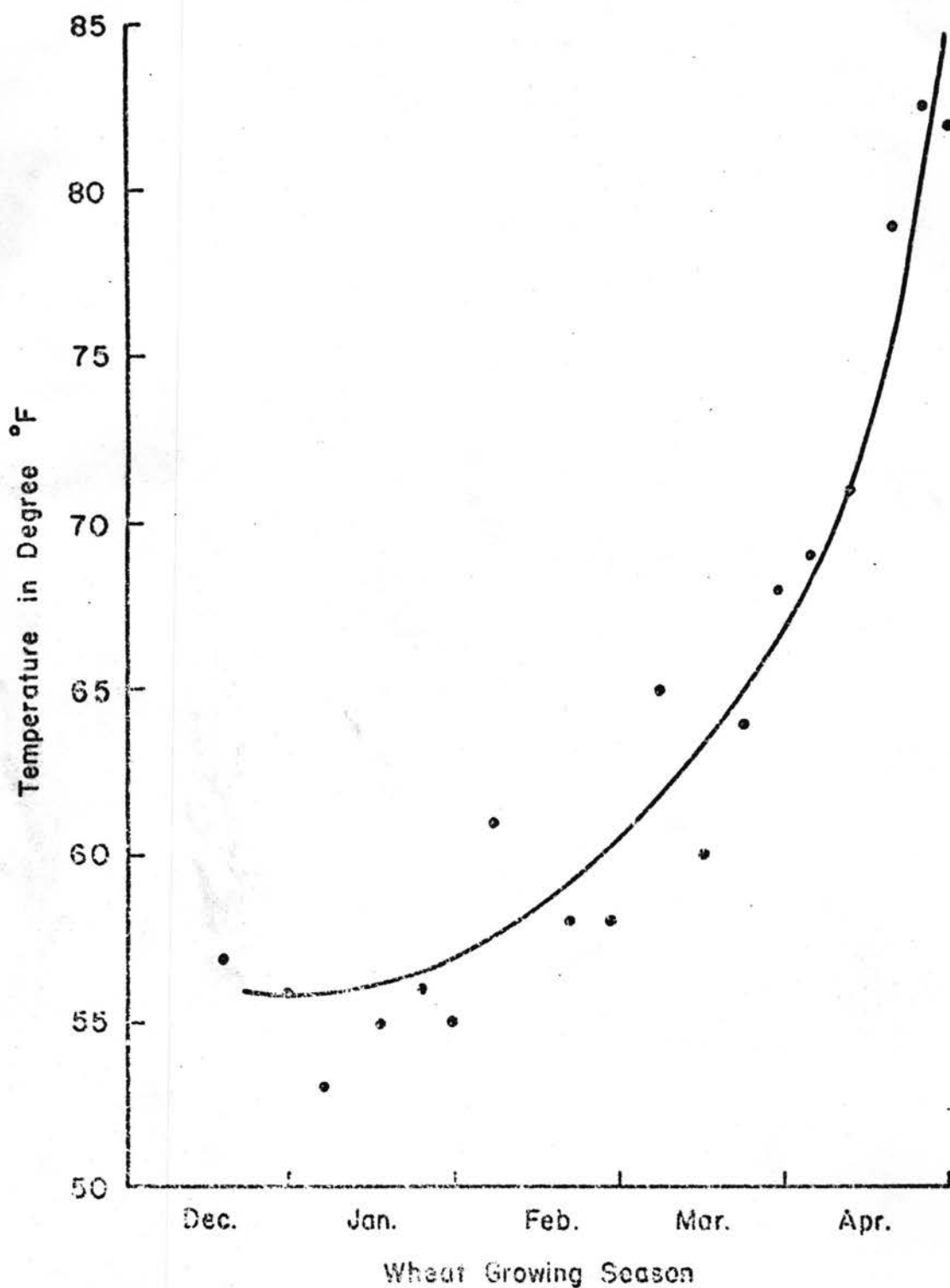


Figure 3. Variation in Mean Daily Temperature during Wheat Season 1975-76 at Kanjra

TABLE 2. Laboratory Results of Soil Physical Properties from Four Farms at the Kanjra Study Site (Results of Soil Moisture Retention)

Depth of Soil Profile	Moisture Retained at 1/3 Atmosphere Percentage on Weight Basis				Moisture Retained at 15 Atmosphere Percentage on Weight Basis				
a. Experimental Plot #1 at Hakeem Farm									
	Rep(a)	Rep(b)	Rep(c)	Average	Rep(a)	Rep(b)	Rep(c)	Average	
0 - 6"	22.3	23.1	23.0	22.8	9.0	8.2	11.7	9.7	
6" - 12"	23.1	25.7	19.3	22.7	8.1	9.1	8.0	8.4	
12" - 24"	22.5	22.1	19.5	21.4	9.8	10.8	8.1	9.2	
24" - 36"	19.3	21.2	23.4	21.3	9.2	11.2	11.0	10.5	
36" - 48"	20.2	20.2	22.2	20.9	7.7	8.3	8.7	8.2	
48" - 60"	20.5	21.5	23.3	21.8	7.3	6.3	9.1	7.6	
60" - 72"	22.1	22.1	22.1	22.1	9.0	7.0	10.2	8.7	
	Mean value = 21.9%				Mean value = 8.9%				
b. Experimental Plot #2 at Mehtab Farm									
0 - 6"	20.5	20.7	20.9	20.7	9.3	11.5*	9.3	9.3	
6" - 12"	23.0	21.4	24.5	23.0	7.2	6.8	7.3	7.1	
12" - 24"	22.2	22.6	21.7	22.2	7.8	8.0	7.0	7.6	
24" - 36"	22.6	23.8	26.2*	23.2	8.6	10.1	9.0	9.2	
36" - 48"	21.8	25.3*	22.6	22.2	9.0	11.4*	8.7	8.8	
48" - 60"	20.0	22.2	22.0	21.4	8.4	8.0	10.1	8.8	
60" - 72"	20.8	24.7	28.2	22.1	8.0	9.0	8.6	8.5	
	Mean value = 22.2%				Mean value = 8.5%				

*Values discarded considering laboratory errors

Source: Laboratory analysis at Soil Testing Laboratory of WASID division of WAPDA

TABLE 2. Continued

Depth of Soil Profile	Moisture Retained at 1/3 Atmosphere (Average of 3 Replications) Percentage on Weight Basis	Moisture Retained at 15 Atmosphere (Average of 3 Replications) Percentage on Weight Basis
c. Control Plots #1 and 2		
Control Plot #1 at Liaqat Farm		
0 - 6"	23.7	8.0
6" - 12"	23.5	10.0
12" - 24"	23.1	14.0*
24" - 36"	23.8	6.1
36" - 48"	20.2	5.1
48" - 60"	26.1*	5.8
60" - 72"	27.5*	7.9
	Mean value = 22.9%	Mean value = 7.3%
Control Plot #2 at Majeed Farm		
0 - 6"	18.9	8.3
6" - 12"	13.6	8.0
12" - 24"	19.2	9.0
24" - 36"	16.2	9.6
36" - 48"	18.0	9.1
48" - 60"	18.5	9.3
60" - 72"	20.1	7.7
	Mean value = 18.5%	Mean value = 8.8%

*Values discarded considering laboratory errors as advised by laboratory in charge.

Source: Laboratory analysis of soil samples at Soil Testing Laboratory of WASID division of WAPDA, Lahore.

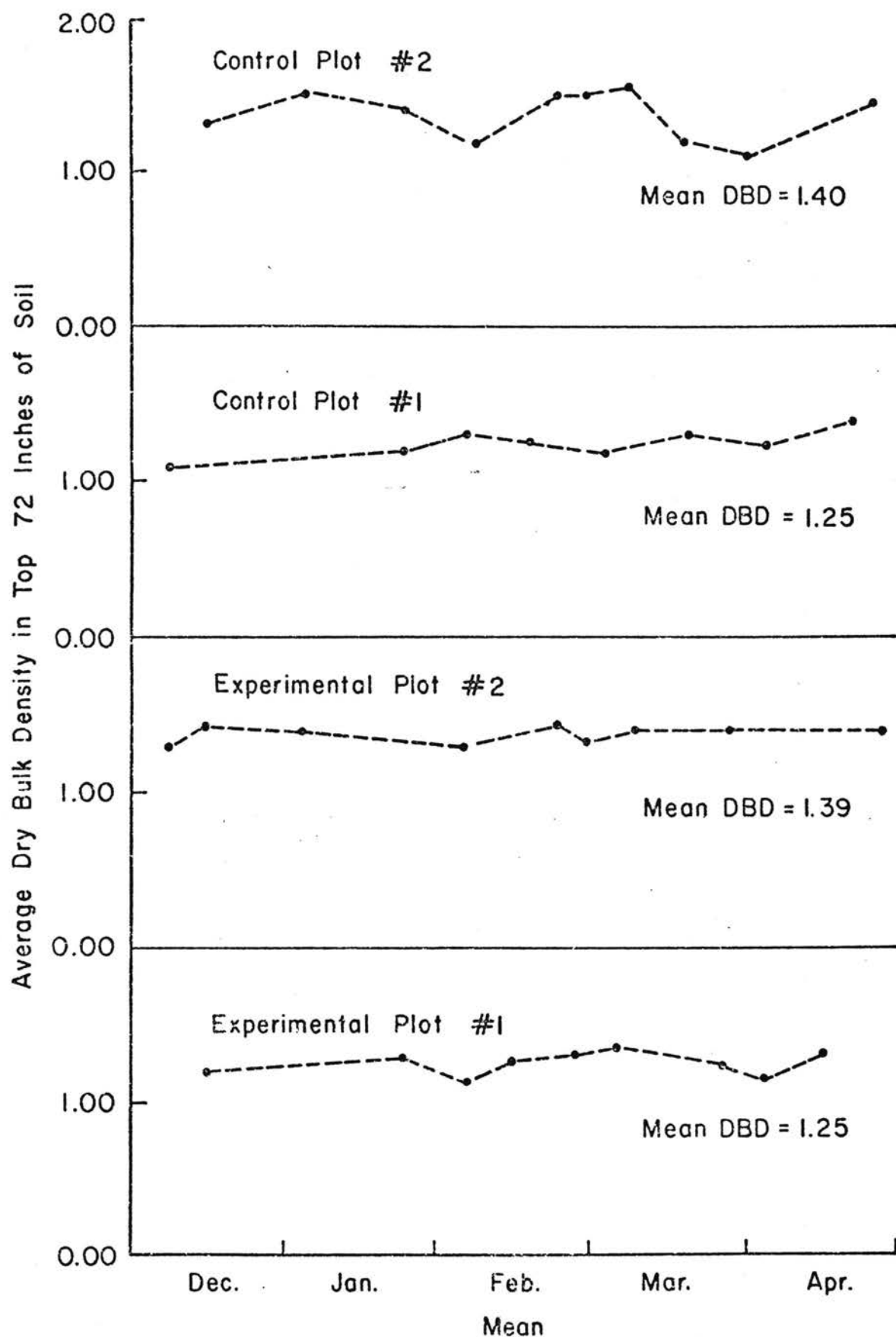


Figure 4. Variation of Field Determined Mean Dry Bulk Density of Soil during Wheat Season 1975-76 at Kanira

TABLE 3. Summary of Mean Available Moisture Percentage for Experimental and Control Plots

	Hakeem Farm Expt. Plot #1	Mehtab Farm Expt. Plot #2	Liaqat Farm Control Plot #1	Majeed Farm Control Plot #2
1. Field Capacity (% on weight basis)	21.9	22.2	22.9	18.5
2. Permanent Wilting Point (% on weight basis)	8.9	8.5	7.3	8.8
3. Available Soil Moisture (% on weight basis)	13.0	13.7	15.6	9.7
4. Mean Dry Bulb Density	1.25	1.39	1.25	1.40
5. Available Moisture (% on volume basis)	16.25	19.04	19.50	13.58
6. Available Soil Moisture (inches/foot)	1.95	2.28	2.34	1.63
7. Range of Dry Bulb Density	0.20	0.12	0.30	0.50
8. Range of Available Soil Moisture (% on volume basis)	3.25	2.20	5.85	6.79
9. Range of Available Soil Moisture (inches/foot)	0.39	0.27	0.70	0.82

APPENDIX B

CALIBRATION OF JENSEN-HAISE EQUATION FOR CHUHARKANA METEOROLOGICAL STATION OF WAPDA

- TEXT 1. Calibration Procedure for Jensen-Haise Equation
- TABLE 1. Long-Term Average Daily Maximum Temperatures for Chuharkana Observatory
- TABLE 2. Long-Term Average Daily Minimum Temperatures for Chuharkana Observatory
- TABLE 3. Summary Data for Calibration of Jensen-Haise Evapotranspiration Equation
- TABLE 4. Physical Properties of Water Vapor after List (1963)
- TABLE 5. Coefficients for Jensen-Haise Evapotranspiration in Pakistan

APPENDIX B

CALIBRATION OF JENSEN-HAISE EQUATION FOR CHUHARKANA METEOROLOGICAL STATION OF WAPDA

TEXT 1. Calibration Procedure for Jensen-Haise Equation

The main limitation of the Jensen-Haise equation is that since it is an empirical equation, and its constants may not be applicable in different climatic conditions, which makes the calibration of the equation essential for application to a certain climatic region.

Pakistan has two distinct seasons, dry season and monsoon or wet season. It was, therefore, considered necessary to calibrate the equation for use in two seasons. Jensen and Haise (1963) and Jensen (1966) recommend the month with maximum temperature to be used for calibration of the equation.

The meteorological data for Chuharkana Observatory of WAPDA, which is 20 miles from the Kanjra watercourse area, reveals (Table 1, Appendix B) that the months of June and August are the ones with maximum temperatures in arid and monsoon seasons respectively. For calibration of the equation we need to determine the values of C_T and T_X constants in the Jensen-Haise equation viz.,

$$ETP = C_T (T - T_X) R_S$$

where ETP = the potential evapotranspiration for reference crop in inches/day

C_T = the air temperature coefficient which is constant for a given area

T = mean daily air temperature

T_X = constant for a given area which is merely the linear equation--intercept on the temperature axis in the solar radiation--air temperature relationship

R_S = the daily solar radiation expressed as the equivalent depth of evaporation (inches/day).

C_T can be estimated from temperature data during the month of maximum mean air temperature using

$$C_T = \frac{1}{C_1 + C_2 \cdot C_H} - i$$

where $C_1 = 68 - 3.6 E/1000$ for temperatures in degrees F

where E = elevation of area in feet above sea level

$$C_2 = 13^\circ\text{F}$$

C_H = humidity index and can be calculated from the following expression:

$$C_H = \frac{50 \text{ mb}}{e_{s2} - e_{s1}}$$

where e_{s2} = saturation vapor pressure in millibars at the mean maximum air temperature during the warmest month

e_{s1} = saturation vapor pressure in millibars at the mean minimum air temperature during the same month.

T_X can be calculated from the equation

$$T_X = 27.5^\circ\text{F} - 0.25(e_{s2} - e_{s1}) \text{ F/mb} - E/1000 - 11$$

Calibration of Equation for Chuharkana

1. Arid season: Mean maximum temperature for the month of June (from Table 1, Appendix B) = 105°F . Mean minimum temperature for June (from Table 2, Appendix B) = 81°F .
From Table 4, Appendix B

$$e_{s2} = 76.43 \text{ mb}$$

$$e_{s1} = 36.62 \text{ mb}$$

$$\text{Therefore } C_H = \frac{50 \text{ mb}}{76.43 - 36.62} = 1.256$$

Elevation for Chuharkana = ± 800 ft msl. Therefore,

$$C_1 = 68 - 3.68 \left(\frac{800}{1000} \right) = 65.12$$

Putting the values of C_1 , C_2 and C_H in equation (i),

$$C_T = \frac{1}{65.12 + 13(1.256)} = 0.0122$$

and putting values of e_{s2} , e_{s1} and e in equation (ii) we get

$$\begin{aligned} T_X &= 27.5^\circ\text{F} - 0.25(76.43 - 36.62) \frac{\text{F}}{\text{mb}} - \frac{800}{1000} \\ &= 16.75^\circ\text{F} \end{aligned}$$

Substituting the values of C_T and T_X in Jensen's equation we get calibrated equation for arid season

$$ETP = 0.012(T - 16.75) R_S$$

2. Monsoon season: From Tables 1 and 2, Appendix B, mean maximum temperature for month of highest temperature, i.e., August = 94.0°F . Mean minimum temperature for the same month = 80°F . From Table 4, Appendix B

$$e_{s2} = 54.86 \text{ mb}$$

$$e_{s1} = 35.328 \text{ mb}$$

$$\text{Therefore } C_H = \frac{50}{54.86 - 35.328} = 2.559, \text{ and}$$

$$C_1 = 68 - 3.6\left(\frac{800}{1000}\right) = 65.12$$

$$C_2 = 13^\circ\text{F}$$

$$\text{Therefore } C_T = \frac{1}{65.12 + 13(2 - 559)} = 0.010, \text{ and}$$

$$T_X = 27.5 - 0.25(54.86 - 35.328) - \frac{800}{1000} = 21.82^\circ\text{F}.$$

$$\text{Hence } \text{ETP} = 0.010(T - 21.82) R_S.$$

TABLE 1. Long-Term Average Daily Maximum Temperatures for Chuharkana Observatory

Month	<u>YEARLY DATA</u>												Average
	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	
January	--	71	--	67	70	65	60	66	65	65	65	--	66
February	75	--	--	68	73	--	64	69	70	--	65	--	69
March	84	82	--	79	78	--	77	84	77	82	78	--	80
April	99	94	97	83	87	86	87	90	97	96	86	93	91
May	106	101	--	95	99	--	96	98	100	101	100	101	100
June	111	111	102	--	101	107	--	108	102	102	104	103	105
July	103	106	--	95	97	98	--	100	99	--	96	95	99
August	98	99	93	92	94	93	94	95	94	95	93	90	94
September	93	94	--	92	90	94	99	95	94	99	92	94	94
October	94	98	90	90	87	87	--	90	91	93	87	88	90
November	80	--	78	80	77	--	--	81	80	80	79	77	79
December	70	--	--	69	68	--	--	71	71	71	67	62	69

Source: WAPDA, Water and Soil Investigation Division, Surface Water Hydrology Project, Annual Reports of River and Climatological Data of West Pakistan (1962-73).

TABLE 2. Long-Term Average Daily Minimum Temperatures for Chuharkana Observatory

Month	<u>YEARLY DATA</u>												Average
	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	
January	--	40	--	43	39	34	40	40	40	34	40	--	39
February	50	--	--	43	51	--	42	45	44	--	40	--	45
March	59	58	--	51	53	--	52	57	52	52	54	--	54
April	67	68	69	61	62	61	61	62	62	68	61	64	64
May	74	74	--	69	70	--	67	71	71	77	72	76	72
June	81	85	79	--	79	78	--	81	78	85	79	83	81
July	82	87	--	80	80	81	--	82	80	--	79	80	81
August	80	85	81	79	79	79	80	80	78	81	77	78	80
September	77	78	--	74	72	75	74	74	74	63	71	77	74
October	63	69	59	65	61	61	--	66	61	62	59	61	62
November	53	--	45	53	45	--	--	53	45	49	51	49	49
December	45	--	--	38	36	--	--	41	36	41	44	41	40

Source: WAPDA, Water and Soil Investigation Division, Surface Water Hydrology Project, Annual Reports of River and Climatological Data of West Pakistan (1962-73).

TABLE 3. Summary Data for Calibration of Jensen-Haise Evapotranspiration Equation

Long-Term Average Temperatures (F°) at Chuharkana Observatory

Month	Maximum Temp. (F°)	Minimum Temp. (F°)	Mean Temp. (F°)
January	66	39	52.5
February	69	45	57.0
March	80	54	67.0
April	91	64	77.5
May	100	72	86.0
June	105	81	93.0
July	99	81	90.0
August	94	80	87.0
September	94	74	84.0
October	90	62	76.0
November	79	49	64.0
December	69	40	54.5

TABLE 4. Physical Properties of Water Vapor after List (1963)

<u>Temperature</u>		<u>Saturation Vapor Pressure Over Water (mb)</u>
<u>Degrees (F°)</u>	<u>Degrees (C°)</u>	
32	0.0	6.11
41	5.0	8.72
50	10.0	12.27
59	15.0	17.04
68	20.0	23.37
77	25.0	31.67
81	27.5	36.62
86	30.0	42.43
94	34.5	54.86
95	35.0	56.24
104	40.0	73.78
105	40.6	76.43
113	45.0	95.86
122	50.0	123.40

1 bar = 10^6 dynes cm^{-2}

1 milli bar (mb) = 0.7501 mm Hg

TABLE 5. Coefficients for Jensen-Haise Evapotranspiration in Pakistan

Location	C_T		C_T	
	Arid	Monsoon	Arid	Monsoon
Lahore	0.0124	0.0107	16.27	21.02
Lyallpur	0.0122	0.0107	16.68	20.98
Sargodha	0.0125	0.0112	15.47	19.92
Multan	0.0123	0.0111	16.01	20.22
Peshawar	0.0124	0.0119	16.62	20.08

*Arid climate applies to September through June and Monsoon is for July and August.

Source: Clyma, Wayne (1973). Evapotranspiration and Irrigation Water Requirements for Pakistan, Bulletin of Irrigation, Drainage and Flood Control. Research Council. Lahore, Pakistan

APPENDIX C

COMPUTER PROGRAM LISTINGS

TABLE 1. Program Listing for Determination of Potential Evapotranspiration by Method of Penman (1948)

TABLE 2. Program Listing for Determination of Potential Evapotranspiration by Penman Equation Using Adapted Coefficients after Mateer (1969)

TABLE 1. Program Listing for Determination of Potential Evapotranspiration by Method of Penman (1948)*

```

0001      REAL H,T,A,EA,ED,EEA,DELTA,ET,J2,TEMP,R, DAY,RH,WR,SS,DL,RA,ETP
0002      INTEGER L,N
0003      DIMENSION RF(213),PAN(213),SS(213),WR(213),TEMP(213),RH(213),
          DL(213)
          C      INSERT INPUT DATA- METEOROLOGICAL,SOIL,CROP AND SEASON DAY
0004      DO 9L=76,213,1
0005      9 READ(1,100) RF(L),PAN(L),SS(L),WR(L),TEMP(L),RH(L),DL(L)
0006      100 FORMAT(1X,3F5.2,3F5.1,F6.2)
0007      WRITE(3,200)
0008      200 FORMAT(1H1,20X,'DAY',2X,'PREC.',2X,'PAN',2X,'SS HRS',3X,'WRUN',2X,
          1'MTEMP',3X,'MRH ',2X,'DAYTIME',1X,'POTENTIAL ET',2X,'ETP')
0009      10 DAY=0.0
0010      H=0.0
0011      T=0.0
0012      A=0.0
0013      EA=0.0
0014      ED=0.0
0015      EEA=0.0
0016      DELTA=0.0
0017      ET=0.0
0018      U2=0.0
0019      DO 9999 L=76,213,1
0020      20 R=0.25
0021      30 A=-0.10+0.00535*TEMP(L)
0022      40 EA=A*TEMP(L)
0023      50 ED=RH(L)*EA/100.
0024      60 U2=WR(L)*1.1669
0025      70 DAY=SS(L)/DL(L)
0026      110 IF(TEMP(L).GE.50.AND.TEMP(L).LE.55) T=13.2
0027      120 IF(TEMP(L).GE.55.AND.TEMP(L).LE.60) T=13.71
0028      130 IF(TEMP(L).GE.60.AND.TEMP(L).LE.65) T=14.24
0029      140 IF(TEMP(L).GE.65.AND.TEMP(L).LE.70) T=14.81
0030      150 IF(TEMP(L).GE.70.AND.TEMP(L).LE.75) T=15.38

```

*Reference: Israelson and Hansen (1963)

TABLE 1. Continued

```

0031      160 IF(TEMP(L).GE.75.AND.TEMP(L).LE.80) T=15.95
0032      170 IF(TEMP(L).GE.80.AND.TEMP(L).LE.85) T=16.55
0033      180 IF(TEMP(L).GE.85.AND.TEMP(L).LE.90) T=17.11
0034      210 IF(L.GE.76.AND.L.LE.92) RA=7.6
0035      220 IF(L.GT.92.AND.L.LE.123) RA=8.2
0036      230 IF(L.GT.123.AND.L.LE.152) RA=11.2
0037      240 IF(L.GT.152.AND.L.LE.183) RA=12.5
0038      250 IF(L.GT.183.AND.L.LE.213) RA=14.7
0039      310 EEA=0.35*(EA-ED)*(1+0.0098*(U2))
0040      320 DELTA=-0.59+0.01822*TEMP(L)
0041      330 H=RA*(1.-R)*{0.18+0.55*DAY}-T*(0.56+0.1*SQRT(FQ))+{0.10+0.9*DAY}
0042      340 ET=1/(DELTA+H)+{0.27*EEA}/(DELTA+0.27)
0043      350 ETP=ET/25.4
0044      400 WRITE(3,500) L,RF(L),PAN(L),SS(L),WR(L),TEMP(L),RH(L),DL(L),ET,ETP
0045      500 FORMAT(20X,I3,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.1,2X,F5.1,2X,F5.1,3X,
           1F5.1,3X,F6.3,6X,F5.3)
0046      9999 CONTINUE
0047      600 STOP

```

TABLE 2. Program Listing for Determination of Potential Evapotranspiration by Penman Equation Using Adapted Coefficients after Mateer (1969)*

```

0002      INTEGER L,N
0003      DIMENSION RF(213),PAN(213),SS(213),WR(213),TEMP(213),RH(213),
          IDL(213)
          C      INSERT INPUT DATA- METEOROLOGICAL, SOIL, CROP AND SEASON DAY
0004      DO 9L=76,213,1
0005      9 READ(1,100) RF(L),PAN(L),SS(L),WR(L),TEMP(L),RH(L),DL(L)
0006      100 FORMAT(6X,3F5.2,3F5.1,F6.2)
0007      WRITE(3,200)
0008      200 FORMAT(/,1H1,2X,'DAY',2X,'PREC.',2X,'PAN',2X,'SS HRS',3X,'WRUN',
          2X,'MTEMP',13X,'MRH',2X,'DAYTIME',1X,'POTENTIAL',2X,'ET')
0009      10 DAY=0.0
0010      H=0.0
0011      T=0.0
0012      A=0.0
0013      EA=0.0
0014      ED=0.0
0015      EEA=0.0
0016      DELTA=0.0
0017      ET=0.0
0018      U2=0.0

```

*Reference: Israelson and Hansen (1963); modified coefficients after Mateer (1969)

TABLE 2. Continued

```

0019 DO 9999 L=76.213,1
0020 20 R=0.25
0021 30 A=-0.10+0.00533*TEMP(L)
0022 40 EA=A*TEMP(L)
0023 50 ED=RH(L)*EA/100.
0024 60 U2=WR(L)*1.1669
0025 70 DAY=SS(L)/DL(L)
0026 110 IF(TEMP(L).GE.55.AND.TEMP(L).LE.55) T=13.2
0027 120 IF(TEMP(L).GE.55.AND.TEMP(L).LE.60) T=13.71
0028 130 IF(TEMP(L).GE.60.AND.TEMP(L).LE.65) T=14.24
0029 140 IF(TEMP(L).GE.65.AND.TEMP(L).LE.70) T=14.81
0030 150 IF(TEMP(L).GE.70.AND.TEMP(L).LE.75) T=15.38
0031 160 IF(TEMP(L).GE.75.AND.TEMP(L).LE.80) T=15.95
0032 170 IF(TEMP(L).GE.80.AND.TEMP(L).LE.85) T=16.55
0033 180 IF(TEMP(L).GE.85.AND.TEMP(L).LE.90) T=17.11
0034 210 IF(L.GE.76.AND.L.LE.92) RA=7.6
0035 220 IF(L.GT.92.AND.L.LE.123) RA=8.2
0036 230 IF(L.GT.123.AND.L.LE.152) RA=11.2
0037 240 IF(L.GT.152.AND.L.LE.183) RA=12.5
0038 250 IF(L.GT.183.AND.L.LE.213) RA=14.7
0039 310 EEA=0.35*(EA-ED)*(1+0.0098*(J2))
0040 320 DELTA=-0.59+0.01822*TEMP(L)
0041 330 H=RA*(1.-R)*(0.30+0.60*DAY)-T*(0.56-.092*SQRT(ED))*(0.10+0.9*DAY)
0042 340 ET=((DELTA*H)+(0.27*EEA))/(DELTA+0.27)
0043 400 WRITE(3,500) L,RF(L),PAN(L),SS(L),WR(L),TEMP(L),RH(L),DL(L),ET
0044 500 FORMAT(2X,I3,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.1,2X,F5.1,2X,F5.1,3X,
1F5.1,3X,F6.1,6X,F5.3)
0045 9999 CONTINUE
0046 600 STOP
0047 END

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APPENDIX D

AVAILABLE SOIL MOISTURE DISTRIBUTION OVER TIME FOR WHEAT CROP FOR 1975-76 RABI SEASON

- FIGURE 1. Available Soil Moisture with Respect to Time in Experimental Plot Number One at Hakeem Farm
- FIGURE 2. Available Soil Moisture with Respect to Time in Experimental Plot Number Two at Mehtab Farm
- FIGURE 3. Available Soil Moisture with Respect to Time in Control Plot Number One at Liaqat Farm
- FIGURE 4. Available Soil Moisture with Respect to Time in Control Plot Number Two at Majeed Farm
- TABLE 1. Available Soil Moisture Variations in Experimental Plot Number One at Hakeem Farm
- TABLE 2. Available Soil Moisture Variations in Experimental Plot Number Two at Mehtab Farm
- TABLE 3. Available Soil Moisture Variations in Control Plot Number One at Liaqat Farm
- TABLE 4. Available Soil Moisture Variations in Control Plot Number Two at Majeed Farm

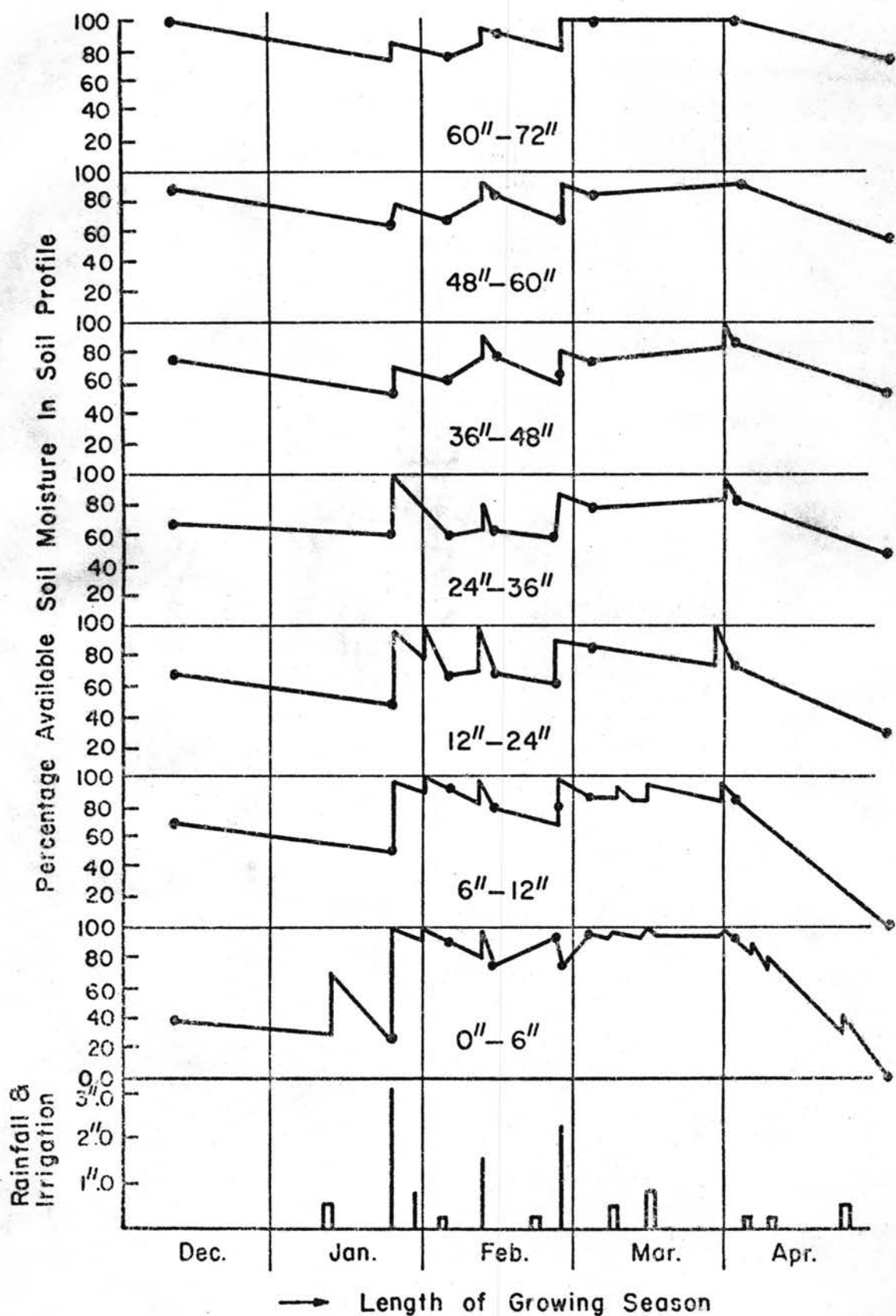


Figure 1. Available Soil Moisture with Respect to Time in Experimental Plot Number One at Hakeem Farm

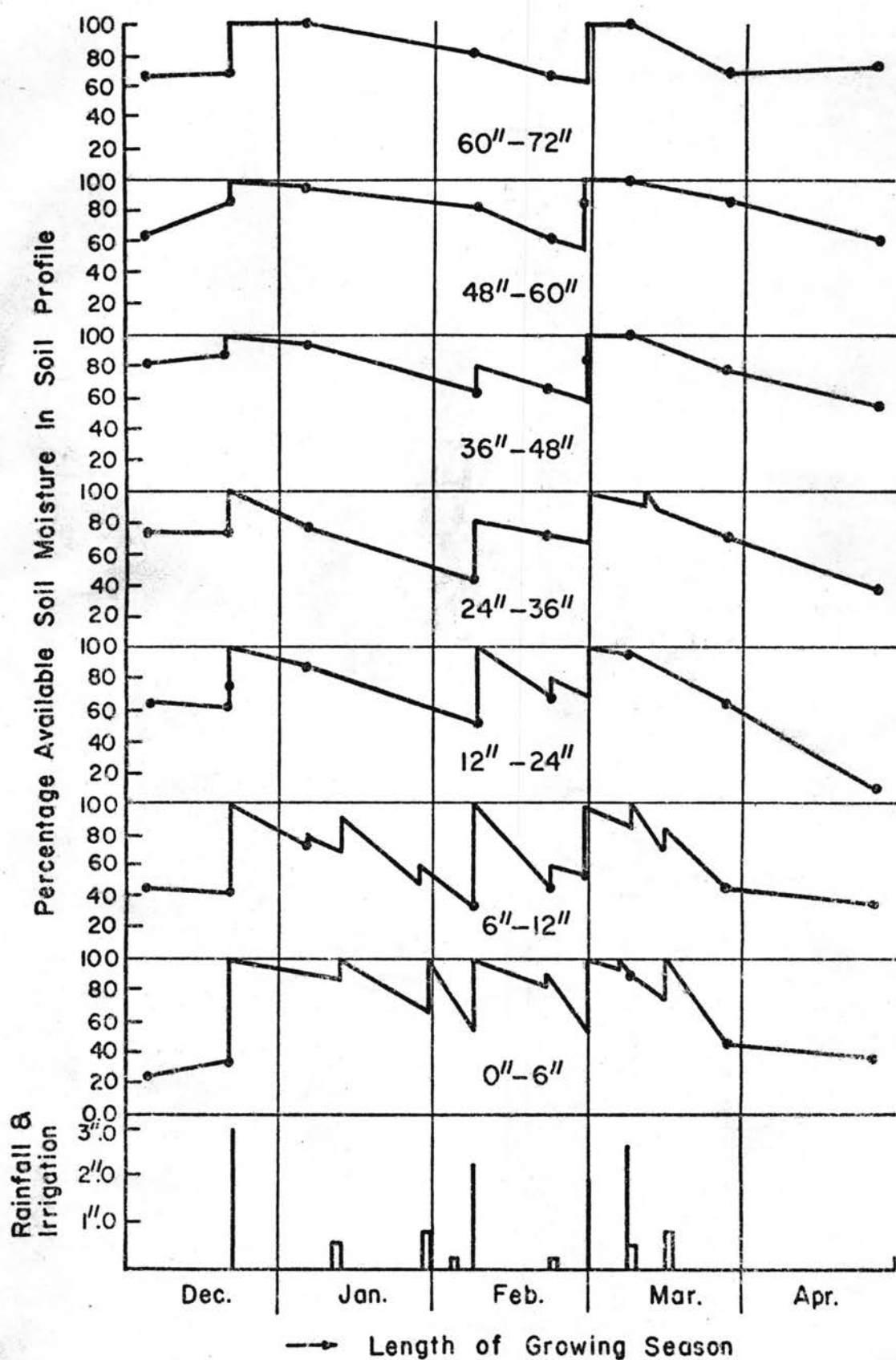


Figure 2. Available Soil Moisture with Respect to Time in Experimental Plot Number Two at Mehtab Farm

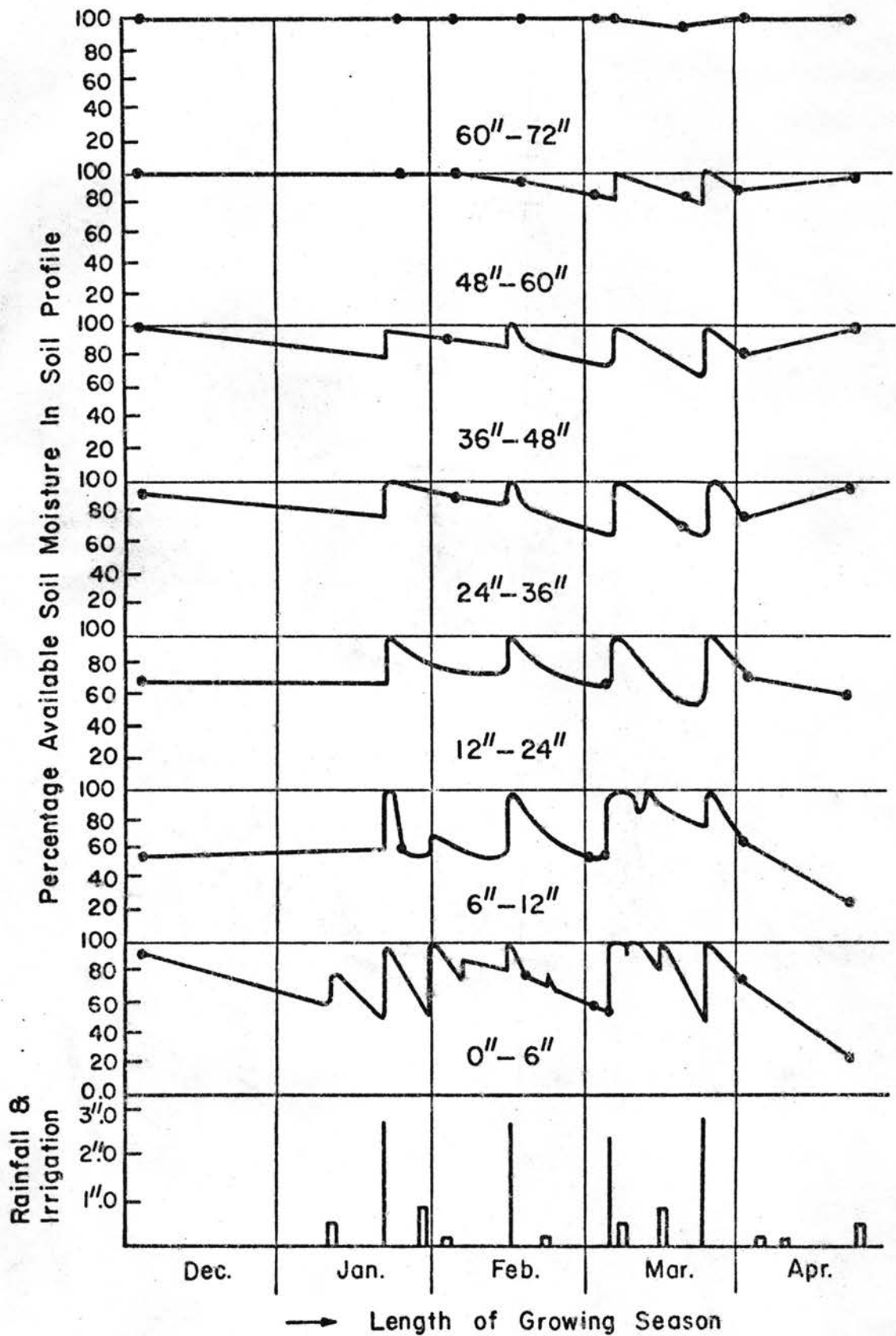


Figure 3. Available Soil Moisture with Respect to Time in Control Plot Number One at Liaquat Farm

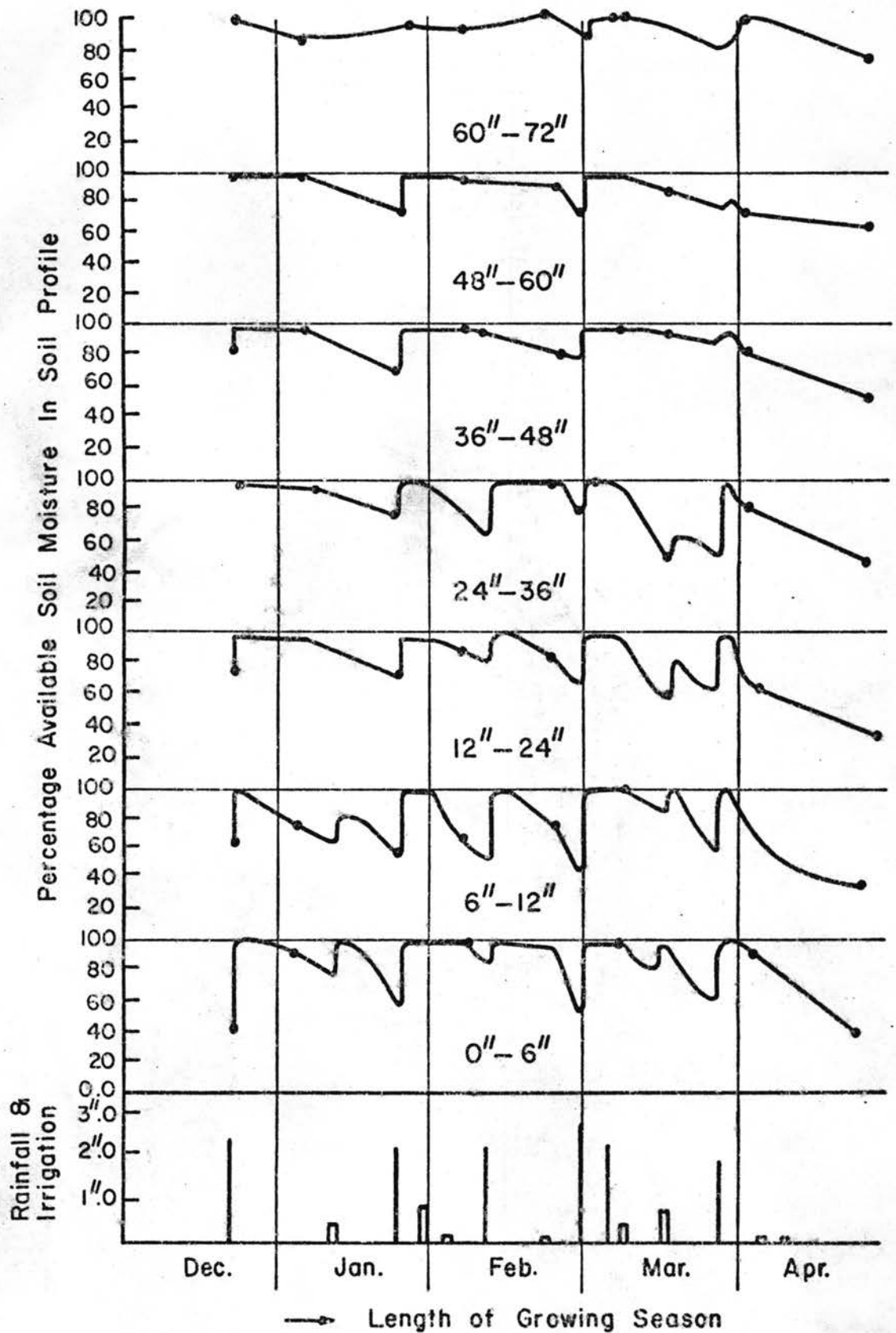


Figure 4. Available Soil Moisture with Respect to Time in Control Plot Number Two at Majeed Farm

TABLE 1. Available Soil Moisture Variations in Experimental Plot Number One at Hakeem Farm (Mean of 3 Replications)

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
December 10, 1975							
Inches available	0.36	0.43	1.31	1.23	1.35	1.67	0.20
Storage capacity	0.94	0.94	1.87	1.87	1.87	1.88	1.88
Percent available	38.46	46.10	69.88	65.78	72.37	88.60	100.00
January 24, 1976							
Inches available	0.27	1.09	0.97	1.14	0.20	1.28	1.44
Storage capacity	0.99	1.98	1.98	1.98	1.98	1.98	1.98
Percent available	27.30	54.95	48.90	57.50	50.30	64.44	72.63
February 5, 1976							
Inches available	0.78	0.78	1.15	1.01	1.08	1.18	1.30
Storage capacity	0.87	0.87	1.75	1.75	1.75	1.75	1.75
Percent available	91.47	91.50	66.00	58.00	62.00	67.00	74.00
February 14, 1976							
Inches available	0.68	0.75	1.28	1.17	1.47	1.57	1.65
Storage capacity	0.95	0.95	1.90	1.90	1.90	1.90	1.90
Percent available	72.11	79.20	67.50	61.40	77.40	82.14	86.74
February 27, 1976							
Inches available	0.96	0.74	1.31	1.26	1.29	1.42	1.84
Storage capacity	1.06	1.06	2.12	2.12	2.12	2.12	2.12
Percent available	90.80	70.30	61.70	59.60	60.61	66.70	86.90
February 28, 1976							
Inches available	0.70	0.77	1.53	1.42	1.27	1.30	1.43
Storage capacity	0.975	0.975	1.95	1.95	1.95	1.95	1.95
Percent available	71.20	79.00	78.46	72.95	65.30	66.70	73.33

TABLE 1. Continued

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
March 4, 1976							
Inches available	1.005	0.89	1.68	1.63	1.49	1.68	2.08
Storage capacity	1.025	1.025	2.05	2.05	2.05	2.05	2.05
Percent available	98.0	86.70	82.15	79.70	72.50	81.90	100.00
April 2, 1976							
Inches available	0.81	0.74	1.25	1.41	1.49	1.59	1.96
Storage capacity	0.875	0.875	1.75	1.75	1.75	1.75	1.75
Percent available	93.0	84.60	71.54	80.70	85.15	91.0	100.00
May 3, 1976							
Inches available	0.00	0.00	0.53	0.90	1.13	1.24	1.52
Storage capacity	1.02	1.02	2.04	2.04	2.04	2.04	2.04
Percent available	0.00	0.00	26.0	44.0	56.0	61.0	74.0
March 27, 1976							
Inches available	0.49	0.49	1.04	1.31	1.19	1.45	1.55
Storage capacity	1.005	1.005	2.01	2.01	2.01	2.01	2.01
Percent available	49.10	49.10	52.0	0.65	59.0	72.01	77.00

TABLE 2. Available Soil Moisture Variations in Experimental Plot Number Two at Mehtab Farm (Mean of 3 Replications)

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
December 4, 1975							
Inches available	0.29	0.53	1.35	1.59	1.72	1.58	1.61
Storage capacity	1.08	1.08	2.16	2.16	2.16	2.16	2.16
Percent available	27.0	49.0	63.0	74.0	80.0	73.0	75.6
December 20, 1975							
Inches available	0.40	0.55	1.81	1.75	2.04	1.99	1.82
Storage capacity	1.20	1.20	2.40	2.40	2.40	2.40	2.40
Percent available	33.0	46.0	75.0	73.0	85.0	83.0	76.0
January 5, 1976							
Inches available	1.07	0.84	2.04	1.82	2.14	2.23	2.32
Storage capacity	1.14	1.14	2.28	2.28	2.28	2.28	2.28
Percent available	94.0	73.0	89.0	79.0	94.0	98.0	100.0
February 8, 1976							
Inches available	0.57	0.39	1.04	1.07	1.30	1.70	1.63
Storage capacity	1.02	1.02	2.04	2.04	2.04	2.04	2.04
Percent available	56.0	38.0	51.0	52.0	64.0	83.0	80.0
February 23, 1976							
Inches available	0.94	0.57	1.61	1.78	1.58	1.47	1.60
Storage capacity	1.20	1.20	2.40	2.40	2.40	2.40	2.40
Percent available	78.0	48.0	67.0	74.0	66.0	61.0	67.0
February 29, 1976							
Inches available	0.63	0.61	1.55	1.95	1.88	2.00	1.98
Storage capacity	1.14	1.14	2.28	2.28	2.28	2.28	2.28
Percent available	55.0	54.0	68.0	86.0	82.0	88.0	86.0

TABLE 2. Continued

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
March 8, 1976							
Inches available	1.06	0.97	2.29	2.23	2.49	2.35	2.57
Storage capacity	1.18	1.18	2.36	2.36	2.36	2.36	2.36
Percent available	90.0	82.0	97.0	94.0	106.0	100.0	109.0
March 27, 1976							
Inches available	0.51	0.52	1.50	1.61	1.78	1.97	1.54
Storage capacity	1.14	1.14	2.28	2.28	2.28	2.28	2.28
Percent available	45.0	46.0	66.0	71.0	78.0	86.0	68.0
April 26, 1976							
Inches available	0.43	0.42	0.27	0.90	1.26	1.41	1.59
Storage capacity	1.14	1.14	2.28	2.28	2.28	2.28	2.28
Percent available	38.0	37.0	12.0	39.0	55.0	62.0	70.0

TABLE 3. Available Soil Moisture Variations in Control Plot Number One at Liaqat Farm (Mean of 3 Replications)

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
December 3, 1975							
Inches available	1.01	0.63	1.51	1.96	2.32	2.40	2.41
Storage capacity	1.06	1.08	2.16	2.16	2.16	2.16	2.16
Percent available	94.0	58.0	70.0	91.0	100.0	100.0	100.0
January 26, 1976							
Inches available	0.53	0.67	1.52	1.76	1.78	2.38	2.46
Storage capacity	1.12	1.12	2.24	2.24	2.24	2.24	2.24
Percent available	47.0	60.0	68.0	79.0	80.0	100.0	100.0
February 5, 1976							
Inches available	0.92	0.64	1.81	2.11	2.15	2.42	2.80
Storage capacity	1.19	1.19	2.38	2.38	2.38	2.38	2.38
Percent available	77.0	54.0	76.0	89.0	90.0	100.0	100.0
February 18, 1976							
Inches available	0.98	0.68	1.73	2.01	2.05	2.32	2.67
Storage capacity	1.22	1.22	2.44	2.44	2.44	2.44	2.44
Percent available	80.0	56.0	71.0	82.0	84.0	95.0	100.5
March 2, 1976							
Inches available	0.67	0.63	1.45	1.60	1.69	2.02	2.68
Storage capacity	1.16	1.16	2.32	2.32	2.32	2.32	2.32
Percent available	58.0	54.0	63.0	69.0	73.0	87.0	100.0
March 5, 1976							
Inches available	2.65	0.65	1.57	1.83	1.97	2.27	2.30
Storage capacity	1.16	1.16	2.32	2.32	2.32	2.32	2.32
Percent available	56.0	56.0	68.0	79.0	85.0	98.0	100.0

TABLE 3. Continued

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
March 19, 1976							
Inches available	0.78	0.66	1.21	1.66	1.74	2.01	2.34
Storage capacity	1.19	1.19	2.38	2.38	2.38	2.38	2.38
Percent available	66.0	55.0	51.0	70.0	73.0	84.0	98.0
April 1, 1976							
Inches available	0.87	0.73	1.64	1.73	1.85	2.06	2.57
Storage capacity	1.16	1.16	2.32	2.32	2.32	2.32	2.32
Percent available	75.0	63.0	71.0	75.0	80.0	89.0	111.0
April 23, 1976							
Inches available	0.36	0.58	1.58	2.47	2.25	2.65	3.33
Storage capacity	1.30	1.30	2.60	2.60	2.60	2.60	2.60
Percent available	28.0	45.0	61.0	95.0	98.0	102.0	128.0

TABLE 4. Available Soil Moisture Variations in Control Plot Number Two at Majeed Farm (Mean of 3 Replications)

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
December 4, 1975							
Inches available	0.11	0.12	0.60	0.68	0.64	0.72	0.80
Storage capacity	0.42	0.42	0.84	0.84	0.84	0.84	0.84
Percent available	26.0	29.0	71.0	81.0	76.0	86.0	95.0
December 21, 1975							
Inches available	0.33	0.50	1.20	1.93	1.33	1.51	1.96
Storage capacity	0.78	0.78	1.56	1.56	1.56	1.56	1.56
Percent available	42.0	64.0	77.0	124.0	85.0	97.0	126.0
January 5, 1976							
Inches available	0.76	0.60	1.65	1.64	1.90	1.73	1.49
Storage capacity	0.84	0.84	1.68	1.68	1.68	1.68	1.68
Percent available	90.0	71.0	98.0	98.0	113.0	103.0	89.0
January 24, 1976							
Inches available	0.48	0.44	1.23	1.29	1.20	1.30	1.63
Storage capacity	0.84	0.84	1.68	1.68	1.68	1.68	1.68
Percent available	57.0	52.0	73.0	77.0	71.0	77.0	97.0
February 7, 1976							
Inches available	0.79	0.49	1.27	1.03	1.48	1.37	1.35
Storage capacity	0.73	0.73	1.46	1.46	1.46	1.46	1.46
Percent available	108.0	67.0	87.0	71.0	101.0	94.0	92.0
February 25, 1976							
Inches available	0.89	0.70	1.55	1.79	1.56	1.65	1.81
Storage capacity	0.90	0.90	1.80	1.80	1.80	1.80	1.80
Percent available	99.0	78.0	86.0	99.0	87.0	92.0	101.0

TABLE 4. Continued

Sampling Date	Inches of Water Equivalent			Depth Increment			
	0 - 6"	6" - 12"	12" - 24"	24" - 36"	36" - 48"	48" - 60"	60" - 72"
February 29, 1976							
Inches available	0.48	0.40	1.18	1.44	1.75	1.33	1.69
Storage capacity	0.90	0.90	1.80	1.80	1.80	1.80	1.80
Percent available	53.0	44.0	66.0	80.0	97.0	74.0	94.0
March 5, 1976							
Inches available	0.88	0.78	1.68	1.78	1.62	1.87	1.97
Storage capacity	0.90	0.90	1.80	1.80	1.80	1.80	1.80
Percent available	98.0	87.0	93.0	99.0	90.0	100.0	100.0
March 7, 1976							
Inches available	1.35	0.95	1.79	1.75	2.02	2.13	2.25
Storage capacity	0.90	0.90	1.80	1.80	1.80	1.80	1.80
Percent available	100.0	100.0	100.0	97.0	100.0	100.0	100.0
March 12, 1976							
Inches available	0.55	0.60	0.79	0.85	1.35	1.25	1.08
Storage capacity	0.72	0.72	1.44	1.44	1.44	1.44	1.44
Percent available	76.0	83.0	55.0	59.0	94.0	88.0	75.0
April 1, 1976							
Inches available	0.63	0.28	0.88	1.09	1.08	0.96	1.42
Storage capacity	0.66	0.66	1.32	1.32	1.32	1.32	1.32
Percent available	95.0	42.0	67.0	83.0	82.0	73.0	100.0
April 26, 1976							
Inches available	0.33	0.29	0.69	0.84	0.93	1.10	1.30
Storage capacity	0.88	0.88	1.76	1.76	1.76	1.76	1.76
Percent available	38.0	31.0	39.0	48.0	53.0	63.0	74.0

APPENDIX E

DATA UTILIZED FOR SCIENTIFIC IRRIGATION SCHEDULING OF MAIZE FODDER CROP FROM OTHER SOURCES

FIGURE 1. Crop Coefficients for Maize (after Jensen and Haise, 1963)

FIGURE 2. Assumed Root Zone Accumulated Depth Over Time for Maize (after Kincaid and Heerman, 1974)

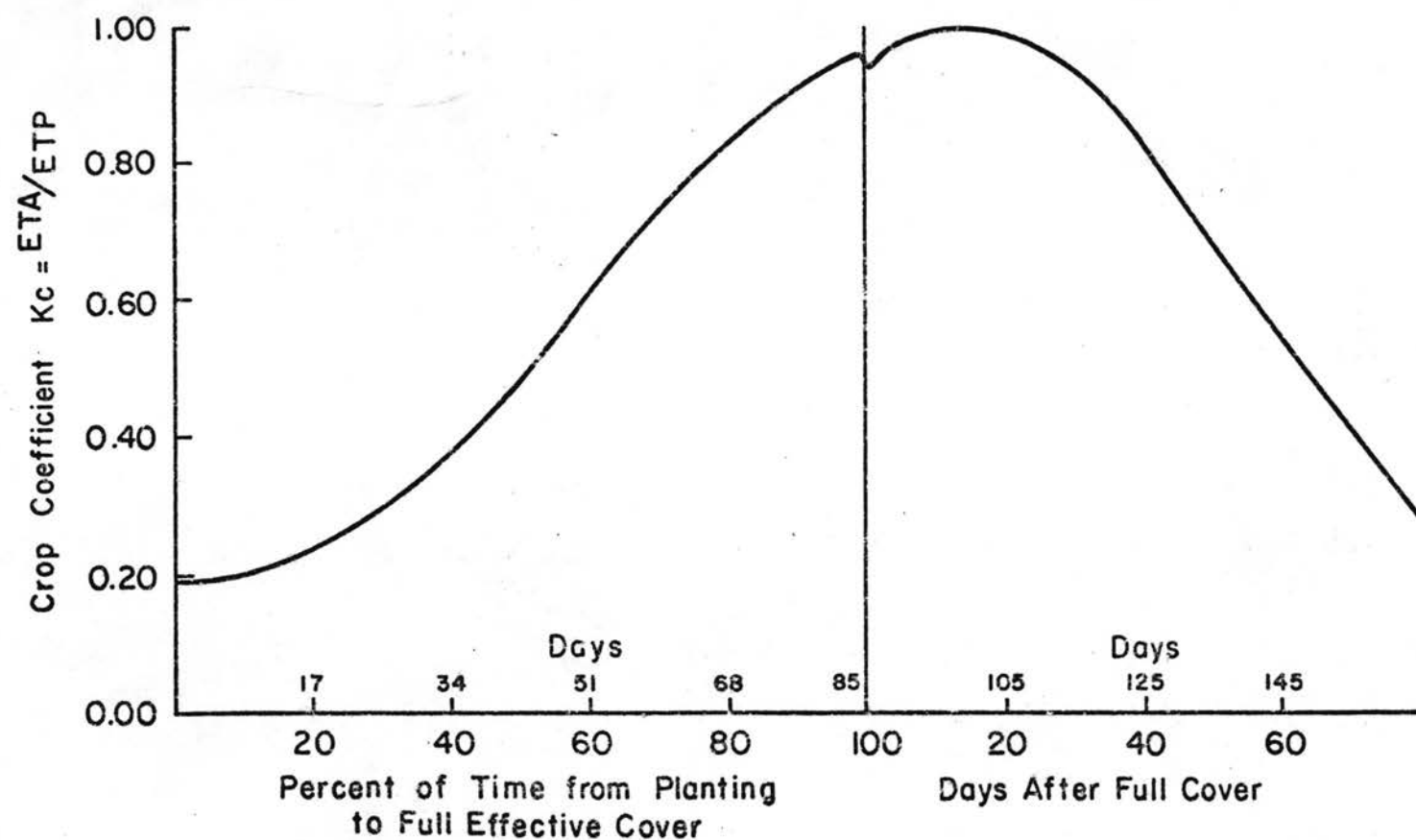


Figure 1. Crop Coefficients for Maize (after Jensen and Haise, 1963)

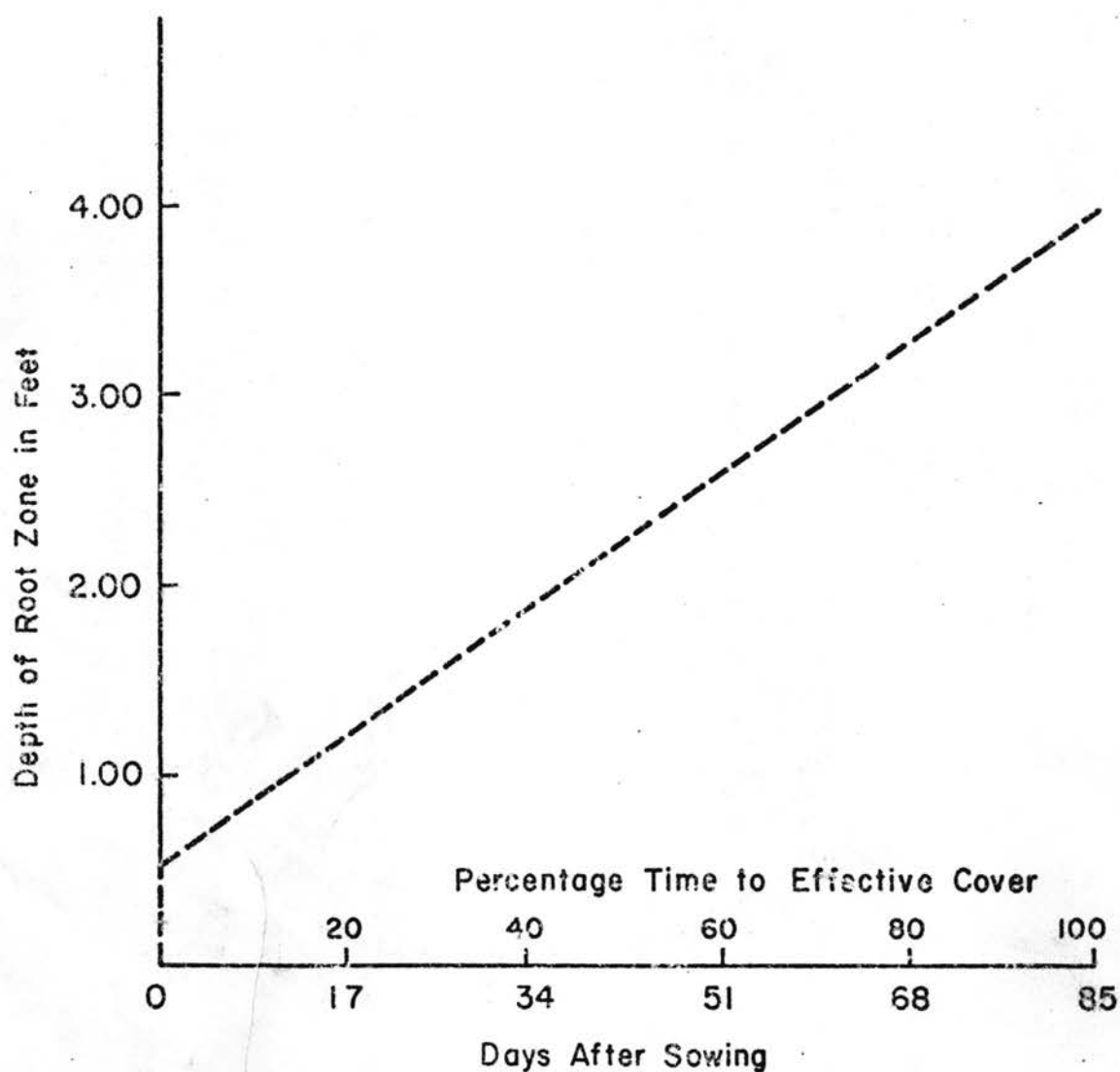


Figure 2. Assumed Root Zone Accumulated Depth over Time for Maize (after Kincaid and Heerman, 1974)