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THE UNIVERSITY OF ALBERTA

A COMPARATIVE STUDY OF THREE METHODS OF SCHEDULING IRRIGATIONS FOR BARLEY

by

AUGUSTUS ARCHAMPONG ©

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "A Comparative Study of Three Methods of Scheduling Irrigations for Barley", submitted by Augustus Archampong in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Three treatments of scheduling irrigations with six replications were imposed on 18 plots of Galt barley during the 1974 growing season. The treatments applied were: (a) when plants displayed the first visual symptoms of moisture stress (check method), (b) when indicated by soil moisture budget involving the estimated evapotranspiration (budget method), and (c) when soil tensiometer readings were -400 to -500 mb (tensiometer method). The mean grain yield of the budget and the tensiometer methods were higher than that of the check method by 1.67 tonnes and 2.54 tonnes per hectare respectively. The budget and the tensiometer methods produced grains of a higher hectolitre weight (No. 1 feed barley) than the check method (No. 2 feed barley), but the treatments did not affect grain chemical content. The lower yields of the check method were due to improper timing of irrigations. The budget method, which was introduced to southern Alberta by the Irrigation Division of the Alberta Department of Agriculture, produced a slightly lower yield than the tensiometer method because the latter actually operated at a higher minimum allowable moisture.

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TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Various techniques for timing irrigations and estimating crop water needs have been applied on irrigated lands for many years. In the arid and semi-arid parts of the world, irrigation is the most effective solution to the problem of erratic rainfall distribution and the attendent low yields and crop failures. The importance of irrigation scheduling is often overlooked and the level of productivity from irrigated lands has thereby not improved significantly. Thus, the contribution of irrigation towards the solution [illegible] the world's food problem has been achieved mainly by extension of the practice of irrigation to dryland areas. The need to adopt an efficient irrigation scheduling method becomes important where water is in short supply or expensive, when the productive capacity of the land decreases due to excessive application of water and accumulation of salt, or when the cost of water application escalates due to an energy crisis. Presently, various scheduling methods investigated to solve these specific problems are available.

The criteria for scheduling irrigations depend on the type of problem. "Where water is scarce or expensive, irrigations are scheduled to maximize crop production per unit of applied water; where good land is scarcer than water, irrigations are scheduled to maximize crop production per unit of planted area" (19). In general, measurements of soil, plant and weather variables are used as criteria for scheduling irrigations. These criteria are used as a guide in establishing irrigation schedules which favour optimum crop yields and efficient water use. However, under certain conditions some factors may dominate. In southern Alberta, the introduction of the 'Irrigation Gauge' (a soil moisture budgeting procedure) resulted from observations of poor, inefficient use of water by irrigators (60). Previously, irrigation scheduling methods were based on observation of the crop and soil and other rule of thumb measurements involving personal judgement and experience of the irrigator. In recent years, an irrigation scheduling method involving the use of tensiometers has shown promising results.

The potential benefits derived from good irrigation scheduling are many. In some areas where soil salinity is a problem, the production capacity of the land has been maintained for many years through the adoption of good irrigation scheduling. The increased irrigation efficiencies associated with good irrigation scheduling methods reduce the cost of farm operations and hence increase profits. In southern Alberta, the yield of sugarbeets has increased by about 50 percent since the introduction of the 'Irrigation Gauge' (60). A potential saving of over 55 million dollars by the adoption of efficient scheduling methods in the United States of America is estimated by Splinter (59).

Irrigation scheduling practices have not changed significantly from the methods observed 15 years ago. The reasons for this slow response in regards to the adoption of scientific irrigation scheduling methods is variable and often controversial. One school of thought explains that the budget methods have been ignored by most farmers because for their (the farmers) soils and crops, they do not know the scientific data required by the method. The use of tensiometers which require less knowledge of these scientific data was therefore suggested. Investigators of this school of thought suggested that tensiometer scheduling is superior to the budget methods because the criterion for scheduling by the former methods is based on soil matric potential measurements within the zone of maximum root activity. The other school of thought argues that the budget methods are better because when scheduling irrigations by these methods, the entire field is considered as a unit rather than a composite of units, as in the case of tensiometer methods. Investigators of this school of thought have frequently pointed out that farmers by nature do not adopt new methods quickly, and even where their difficuties are overcome by the available technology and service institutions, they continue with their old methods. The reasons are that these farmers either cannot spare the time or they do not feel it is worthwhile with the present high labour costs.

Before any attempt is made to educate farmers about these new methods, it is important that sufficient agreement exists among the various investigators. The availability of comparative tests on the performance and economic returns of these scheduling methods is of fundamental importance. However, the scarcity of published literature on this subject is acute. The objective of this comparative experiment, using Galt barley as a test crop, is threefold.

1. To determine the time-soil moisture stress changes characteristic of three scheduling methods; namely, the budget method, the tensiometer method and the plant stress method.
2. To determine the influence of the respective soil moisture stress characteristics on the yield and quality of grain.
3. To determine some economic benefits of using any of the scheduling methods.

CHAPTER 2

LITERATURE REVIEW

2.1 Soil and Water Relationships.

The terminology used in describing the behaviour of water in the soil has changed over the years. The advantage of using thermodynamic terminology in describing the movement of water in the soil and in plants was foreseen by Buckingham (5). Taylor and Ashcroft (65), citing the work of Buckingham, pointed out that the simple concept of mechanical potential will no longer describe what is happening in the soil-plant system. The thermodynamic approach for describing the movement of water in the soil and in plant tissue is becoming increasingly popular in the literature (6,12, 45). A brief account of this new terminology is described below.

2.1.1 Water Potential.

In this new concept, water in the soil or in plant tissue is considered to possess a potential energy by which it is capable of doing work in an equilibrium system located at the same level relative to water in the reference state at the same temperature. The energy possessed by the soil water is called its total potential energy, or simply total water potential. The mathematical relationships describing the various components of water potential under various conditions can be very complicated but a simple representation which is pertinent to this experiment is as follows:

$$\psi_w = \psi_p + \psi_m + \psi_s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where ψ_w is the water potential, ψ_p is the pressure potential, ψ_m is the matric potential and ψ_s is the solute potential.

The loss of pressure potential in the leaves and succulent parts of plants results in wilting. Solute potential is partially responsible for movement of water within the plant. In non-saline soils, pressure potential and solute potential are negligible and thus the numerical value of the water potential is essentially the soil matric potential. Tensiometers and resistance blocks are used to measure soil matric potential indirectly. Various units for expressing water potential can be found in the literature but the most popular units are the bar (b), millibar (mb) and the centibar (cb).

2.1.2 Field Capacity.

The term field capacity, used to describe the state of the soil after the excess water has been drained by gravity, has been criticized in recent years. Taylor and Ashcroft (65) have shown that the rate of water removal from saturated soils does not reach zero in the region of field capacity but approaches a constant rate (Figure 2.1). The region of field capacity represents a range of soil moisture contents depending on soil textures. In clay soils this range is wider as it takes longer for the water to move through the soil. The term field capacity is thus very arbitrary. Values of pressure potential, reported by Lyon, Buckman, and Brady (40) averaged 0.33 atmospheres which is approximately 1/3 b. Taylor and Ashcroft (65) have recommended that the rather inexact term of field capacity should be replaced by a more precise equilibrium term such as 1/3 b percentage.

Though the use of 1/3 b percentage in place of field capacity has been accepted widely, some investigators continue to explore new concepts. Campbell and Lembke (6) have suggested that field capacity be replaced by the soil water retention limit. The new suggested term is 'retention limit' and is defined as the desorption soil water at which the leaching rate line intersects the soil drainage rate curve. The merits and demerits of this approach will be discussed later in this chapter.

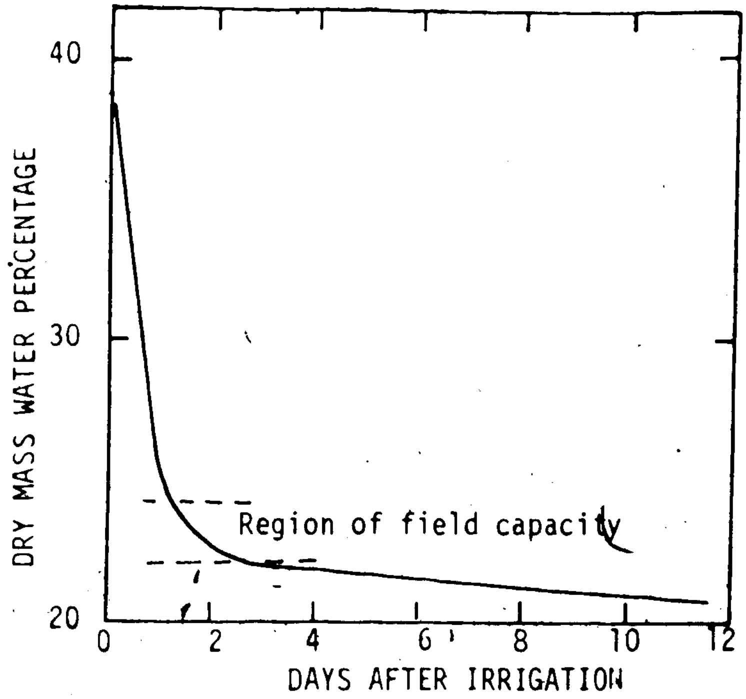

Figure 2.1a. The amount of water in a bare soil decreases rapidly for about one day after irrigation. Water continues to move out at a decreasing rate for many more days. The soil is said to be at field capacity when the rate of outflow becomes low. (Re-drawn with changes of scale after Taylor and Ashcroft, 1972.)

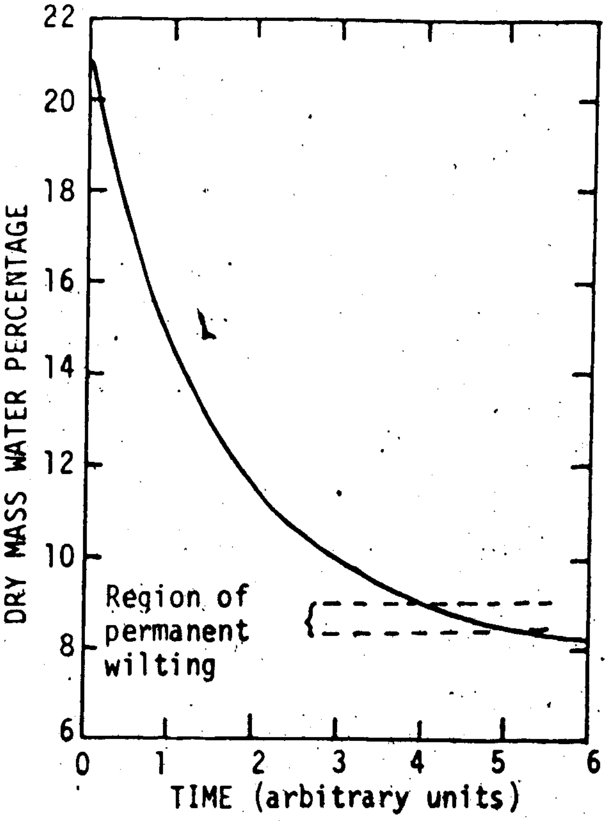

Figure 2.1b. Average water percentage in the top 30 cm of soil in which alfalfa is rooted to a depth of 3 m. Permanent wilting occurs when the removal rate becomes low. (Re-drawn with change of scale after Taylor and Ashcroft, 1972.)

2.1.3 Wilting Point.

The permanent wilting percentage is a range of values of soil water content over which the removal rate is slow and, like field capacity, it is an inexact term. Permanent wilting for most crops occurs at 15 b (21). However, unlike field capacity, it is not sufficient to use a specific equilibrium term like '15 b percentage'. The reasons are that the permanent wilting point not only depends on the amount of water in the soil but also on the rate at which the water moves to the plant root. Where water movement through the soil surrounding a sparse concentration of roots in deep soil is rapid enough, plants might recover overnight even though the water percentage in the soil near the surface is so low that little or no water can be taken up. On the other hand, where movement of water is not rapid enough, recovery overnight may not be permitted, even though the water concentration may be above permanent wilting percentage as determined in the laboratory (21). With subsequent growth, plants that are deep rooting pick up lesser moisture from the upper zones of the soil while uptake of moisture in the lower depths is increased. Thus, even though the moisture percentage of the surface zones may be less than the permanent wilting percentage, the plant may draw water from new depths to maintain sufficient pressure potential in the leaf tissue. Hence, to determine the wilting point, the nature of the plant in a dynamic system should be related to the rate of change in the system.

Campbell and Lembke (6) have suggested that the permanent wilting point be replaced by the efficient soil water extraction limit of the crop. The recommended term is the 'extraction limit' and is defined as the desorption soil water potential at which plant growth is first restricted by water stress.

The new concept of field capacity and wilting point has a future because, apart from fitting in the new thermodynamic terminology, the concept opens new horizons. Campbell and Lembke (6) claim that irrigation - drainage system models using the retention limit and the extraction limit can accommodate waste water disposal by providing for the most efficient use of water and nutrients consistent with optimum plant growth. However, the extent to which this new concept is feasible needs to be substantiated by experimental results.

2.1.4 Available Water.

The available moisture is the range of moisture levels between field capacity and the permanent wilting point. Soil water outside these limits is either lost by excessive drainage or is not easily available to the plant. Water that is lost by excessive drainage may leach nutrients from the plant root zone and thus retard plant growth. The management of soil water within the available range is the prime objective of irrigation scheduling.

2.1.5 Minimum Allowable Moisture.

The relative ease with which plants can take up moisture from the soil is a subject of controversy. The two extreme views are (a) equal availability over the available range as reported by Veihmeyer and Hendrickson (73) and cited by Shaw (56); and (b) linear decrease of availability with depletion of the available range (68). Thus the minimum allowable moisture which is optimal for maximum crop production is not clearly defined in many irrigation handbooks and the specific recommendations differ. While Hammon and Code (20) recommended a 25 percent minimum for all row crops grown in Colorado, Taylor and Slater (67) from Utah State suggested a 30 percent minimum for all crops. On the other hand, Jensen et al, (33) recommended a 35 percent minimum for all crops grown in the Columbia Basin. Hobbs et al (24) have shown that for all crops, other than potatoes, there is a tendency for no yield benefits at minimum allowable moisture levels that are higher than 50 percent of the available moisture, Again further investigations (27) using data collected for eight years confirmed this earlier finding. The choice of 50 percent minimum allowable moisture by the Irrigation Extension Service of the Alberta Department of Agriculture is a step in the right direction.

2.2. Classification of Irrigation Scheduling Methods.

The field of consumptive use of water, and hence irrigation scheduling, has been investigated by scientists and engineers for many years. However, a specific classification of the various scheduling methods is not yet available. A comprehensive classification of the various soil, plant and evaporative techniques as criteria for scheduling irrigation was attempted by Haise and Hagan (19). The classification of the various methods of determining evapotranspiration is well established in the literature (17,32,55,65). These classifications are not always useful to the irrigation engineer. The irrigation engineer needs to know whether a particular method of scheduling clearly indicates the time and the amount of each irrigation, and whether the method lends itself to both actual measurements and direct computations. In a discussion of some irrigation scheduling methods, Taylor and Ashcroft (65) vaguely suggested some type of classification when they distinguished between methods that are based on rule of thumb measurements involving personal judgement and other methods that are based on the actual or the potential consumptive use. By classifying the existing scheduling methods, future investigators will be aware of the class to which their prospective new scheduling methods will belong and hence aim for the more acceptable class. An attempt is made here to classify the present irrigation scheduling methods.

2.2.1 Criterion for Classification.

The criterion for the classification is based on the ability of the method to indicate both time and amount of each irrigation. For those methods that indicate the time and amount of irrigation, as well as permitting both measurements and calculations of these values, the term 'exact' is proposed (Table 2.1). The term 'non exact' is proposed for methods that indicate the time of irrigation but leave the determination of the irrigation amount to guess work. 'Non-exact' methods would not necessarily involve any kind of measurements or calculations. An intermediate class is created for methods that indicate both the time and the amount of each irrigation but the basis of calculation is either not clearly defined or very approximate. The term 'approximation' method is proposed for this class. A more detailed discussion of the three classes of irrigation scheduling methods is given below.

2.2.2 'Exact' Methods.

By 1950, the superiority of 'exact' methods over other scheduling methods had already been noticed. Criddle and Haise (13) observed that the scheduling methods that perform best make use of a knowledge of the consumptive use of the crop, the amount of water that can be stored in the root zone reservoir, the minimum allowable soil moisture content and the length of time that the water must be in contact with the soil to replace the amount used. Presently irrigation

TABLE 2.1: CLASSIFICATION OF IRRIGATION SCHEDULING METHODS.

Class	Method	Criterion	Investigator
Exact Methods			
	1. Irrigation Scheduling Board	Evaporation from U.S. Class A pan	Pruitt (48,49) Jensen et al (33) Chang (9)
	2. Irrigation Gauge	Evaporation from Gen atmometer	Steed (60) Hobbs & Krogman (26)
	3. Soil Moisture Budgeting	Evaporation from the Bellani plate	Wilcox & Korven (74)
	4. The Water Balance	Thornthwaite formula	Thornthwaite et al (68)
	5. Soil Water Balance	Penman's equation	Richardson and Richie (54)
Approximation Methods			
	1. The Two Tensiometer Method	Soil matric potential	Richards and Marsh (53) Taylor and Ashcroft (65)
	2. The Oven Pan Method	Evaporation from the 'oven' pan	Wolfe and Evans (75)
Non-Exact Methods			
	1. Plant Stress Method	Plant wilting	Farmers of S. Alberta, as cited by Dubetz and Krogman (14)
	2. Irrigation With Fixed Rotation Schedules	The rotation plan	Farmers in Nebraska, as cited by Corey (11)
	3. Irrigate When the Neighbor Does	The neighbors scheduling plan	Farmers of Nebraska, as cited by Corey (11)
	4. Soil-Feel Method	Feel of the soil	U.S. Soil Conservation Service (70,71)
	5. Stress Day Index (S.D.I.)	S.D.I.	Hiler (22,23)
	6. Plant Movement	Leaf angle measurement	Hendrickson (21)

guides based on these concepts have been developed by various agencies in North America.

'Exact' methods must make use of more than one measurable soil plant and/or meteorological technique as the criteria for scheduling irrigations. In some scheduling methods, the measurable criteria may be entirely soil based parameters such as soil moisture content and soil water potential. Determination of soil moisture content is tedious and time consuming; hence, a combination of soil and climate based parameters as criteria for scheduling irrigation are by far the most popular. The subject of soil, plant and weather variables as criteria for scheduling irrigations will be treated in the latter part of this chapter. Basically, the procedure employed in the examples of the 'exact' methods given in Table 2.1 are similar and thus only the method that is tested in this experiment is discussed.

2.2.3 The 'Irrigation Gauge'.

The 'Irrigation Gauge' was introduced to southern Alberta in the early 1960's in response to observations of poor and inefficient use of water by irrigation farmers. The method employs a simple meteorological parameter (evaporation) in conjunction with a simple water budget system that balances the amount of water lost through evapotranspiration against that stored from rainfall and irrigation within the root zone reservoir.

Soil-water-plant relations for the main types of crops grown in southern Alberta have been determined by researchers of the Canada Department of Agriculture. From these findings crop water use has been related to concurrently measured evaporation from various evaporative devices. Using ratios determined from these established relationships, measured evaporation and the budget procedure, crop water requirements can be predicted with reasonable accuracy for any desired time interval (26). The ratios for converting evaporation to evapotranspiration for various crops has been reported by Sonmor (58).

Over the years, the 'Irrigation Gauge' has been improved as research findings bring more facts to light. In 1970, the minimum allowable moisture of barley, among other crops, was established (27). The results of a comprehensive test of this budget procedure against other scheduling methods was presented by Dubetz and Krogman (14). The benefits derived from the use of the 'Gauge' have been presented by Steed (60) and Hobbs and Krogman (25). The present official version of the 'Gauge' can be obtained through personal communication with the Irrigation Division of the Alberta Department of Agriculture.

The results obtained from 'exact' methods are reproducible. A Student-t test performed on the yields of potatoes obtained by Hobbs and Krogman (27) and Dubetz and Krogman (14) did not yield any significant difference (P = 0.40). The methods are completely objective because the scheduling procedures are solely based on measured parameters and mathematical calculations. The results are reduced to specific numerical figures rather than ranges of figures. For example, an irrigation should be applied on a specific date or it is too late, and a calculable amount of water may be needed to achieve the desired level of soil moisture content.

2.2.4 'Approximation' Methods.

'Approximation' methods were introduced with the invention of the tensiometer by Richards and Gardner as cited by Israelson and Hansen (32). The successful use of an 'oven pan' on sprinkler irrigated systems was also reported by Wolfe and Evans (75). A unique feature of 'approximation' methods is that they do not require any prior knowledge of soil parameters: they depend solely on the readings of an instrument to determine the time of irrigation and the irrigation amount. Usually the irrigator does not know how much water to apply but the irrigation water is turned on when the instrument reading indicates to do so. Again the water is turned off when the instrument reading indicates to end the irrigation. Since the instrument reading is the only rule of thumb in this type of scheduling procedure, the degree of success to which irrigation can be scheduled depends largely on the instrument sensitivity and the proper location. The two tensiometer method of Richards and Marsh (53) is discussed below.

2.2.5 The Two Tensiometer Method.

Richards and Marsh (53) placed two tensiometers, one in the active root zone (30 cm) and the other near the bottom of the root zone (60 cm), to measure soil matric potentials. Water was applied when the soil matric potential at the 30-cm depth approached 0.5 b but did not penetrate to the 60 cm depth until the application time was nearly doubled twice within the season (Figure 2.2). The degree of success of this scheduling procedure depends largely on the instrument sensitivity and the soil properties at the instrument location. Even when the problem of sensitivity is eliminated by selecting instruments with small time constants (35,46), other soil properties such as the infiltration rate, hydraulic conductivity, slope of the land and soil heterogeneity can affect the time taken for the irrigation water to reach the tensiometer porous cup. Thus the irrigation amount may be either inadequate or in excess of the desired amount when the tensiometer reading indicates when irrigation should be ended. The measurement of the irrigation amount by this method is, therefore, very approximate.

In southern Alberta, Dubetz and Krogman (14) adopted a different

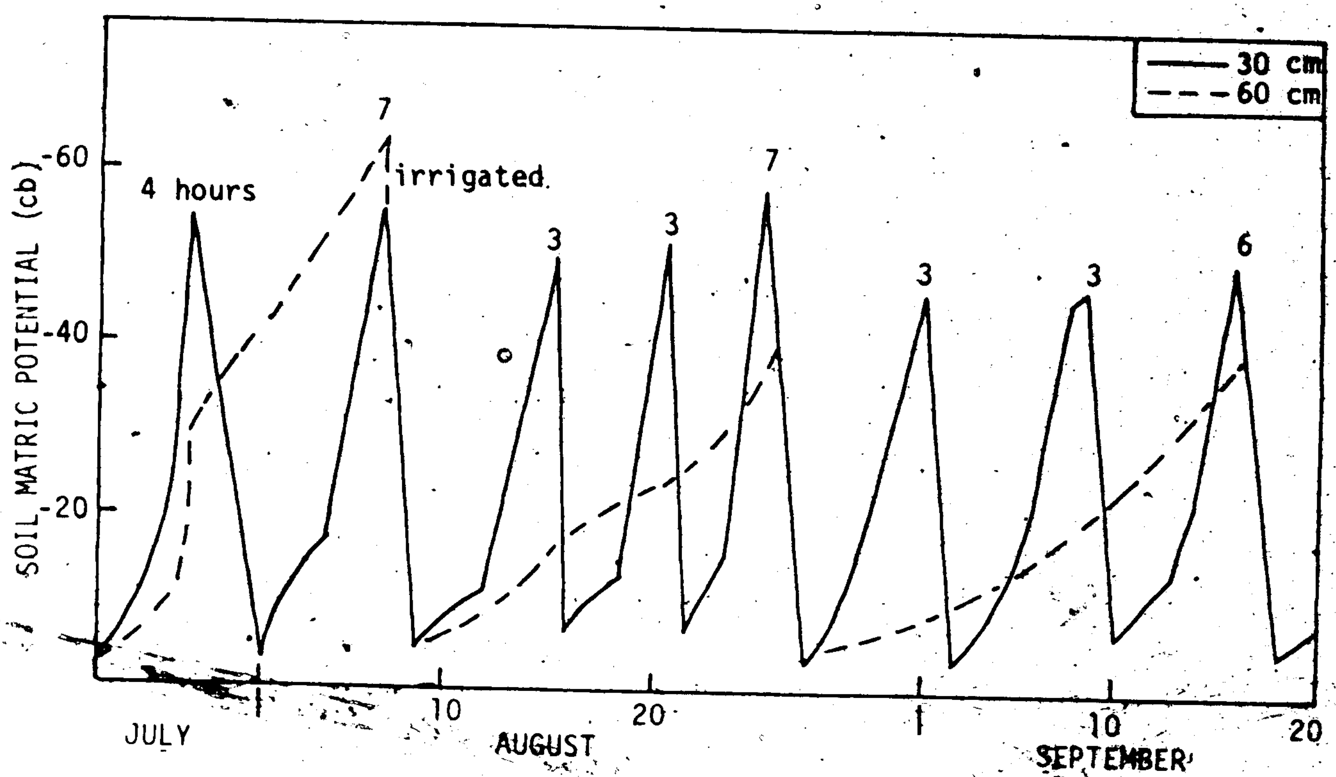

Figure 2.2. Soil matric potential data copied from an avocado grower's record for a soil having limited drainage below a depth of 60 cm (re-drawn with change of scale after Richards and Marsh, 1961).

approach. They applied an irrigation amount of 10 cm when tensiometer readings at the 30 cm depth was between -400 and -500 mb. The irrigation amount was chosen by a rule of thumb involving judgement and experience of the investigators. The transfer value of this method can be improved greatly by the use of soil moisture characteristic curves plotted from field data. From the soil moisture characteristic curve the irrigation amount may be calculated for any rooting depth using an upper and lower preselected soil water potential within which the soil moisture is to be managed. The upper limit is field capacity and the lower limit is the allowable soil water potential at which plant growth will not be impaired. The concept of field capacity has been discussed earlier. Various ranges of values of soil water potential required for optimum growth in Utah State have been compiled by Taylor (63). For small grains the irrigation water is applied when soil matric potential reaches -400 to -500 millibars: this range may be changed to -8 to -12 b at the time of ripening. These figures were based on instrument readings at the depth of maximum root activity for crops growing on soils that are low in salt content and well fertilized. Caution should be exercised when adopting these values for different areas in view of the possible effects of soil, plant and climatic factors that affect the relation between soil water suction and plant water potential. Some studies are needed to determine the magnitude of these effects and their importance in irrigation scheduling.

The new approach of the tensiometer method that is discussed above is an 'exact' method, because it is capable of determining both time and amount of irrigation prior to the time that the irrigation water is applied. Also calculations can be made to adjust the irrigation amount when the irrigation is late. This new approach is adopted in this experiment.

2.2.5 'Non-Exact' Methods.

This class of methods include some of the oldest irrigation scheduling methods that are known in irrigation agriculture. Methods of the 'non-exact' class involve the application of one or more soil - and plant-water criteria for scheduling irrigations. A unique feature of the methods of this class is that the parameters that are used as criteria for scheduling irrigations are either not measured or even when measurements are taken, the readings only indicate when to irrigate. The irrigation amount is purely guess work supported by the judgment and experience of the irrigator.

The two main parameters usually used as criteria for scheduling irrigations within the 'non-exact' class are plant water indicators and soil appearance and feel. This topic will be discussed again in the latter part of this chapter. In southern Alberta, Dubetz and Krogman (14) scheduled irrigations for potatoes when the foliage turned dark green and wilted. Other criteria used in scheduling irrigations in the 'non exact' class are irrigating by the calendar, irrigating on fixed rotation schedules and irrigating when the neighbour does (11).

'Non-exact' methods have very little transfer value and yield of crops irrigated by the methods often lack consistency. Yields may vary from total crop failure to amounts comparable to those obtained from the use of 'exact' methods. The yields of potatoes that were irrigated by visual observation of the crop and soil varied from 15.15 to 27.70 t/ha (14). This range is likely to widen among growers and with different growing areas.

2.3 Soil, Plant and Meteorological Parameters as Criteria for Scheduling Irrigation.

Irrigation scheduling methods by the three classes discussed earlier involve the use of some soil, plant and/or meteorological parameters. When selecting the criteria for scheduling irrigation, the need to make the selections in relation to the existing conditions has been stressed by Haise and Hagan (19). Where water is scarce or expensive, irrigations should be scheduled to maximize crop production per unit of applied water; where good land is scarcer than water, irrigations should be scheduled to maximize crop production per unit of planted area. A comprehensive literature review of the various soil, plant and weather variables as criteria for scheduling irrigations has been compiled by Haise and Hagan (19). A repetition of this material is avoided here. However, it is pertinent to discuss those parameters that are employed in this experiment.

2.3.1 Plant-Water Indicators.

For many years, plant water indicators have been used widely as criteria for scheduling irrigation. Mederski (45) has shown that the relative rates of water intake and loss by plants determine their internal water balance which represents the integrated interaction of plants with the environment. Thus plant-water stress may be used as a criterion in determining irrigation needs if the internal water balance can be determined.

The general approaches to the use of plants as indicators of crop water needs have been outlined by Hagan and Laborde (18). Thus:

(i) select an indicator of plant water deficit which can be observed before growth is checked,

(ii) measure plant growth seeking to irrigate just prior to retardation in growth,

(iii) correlate plant growth responses with internal water balance using such information as an advanced criterion for irrigation.

Plant-water indicators that have been used as criteria for scheduling irrigations include visual indicators of water stress, e.g. wilting and plant colour change; plant growth indicators, e.g. leaf, stem and trunk growth; leaf reflectance and temperature; and plant-water measurements e.g. water content, and plant-water potential. A summary of various plant measurements and techniques investigated to schedule irrigations for various crops has been compiled by Hagan and Laborde (18).

One of the most obvious signs of plant-water stress is wilting, a physical manifestation of low pressure potential in the leafy and succulent parts of plants. A number of stages of wilting have been reported by Hendrickson and Veihmeyer (21). Gardner and Ehlig (15) showed that wilting actually occurs when the pressure potential is between two to three bars (-200 to -300 joules/kg). The symptoms of wilting include drooping, buckling, wrinkling, rolling up of leaf margins and colour change. Although some of these visual signs of plant water indicators have been applied widely as criteria for scheduling irrigations, it has frequently been shown that most plants may be retarded before visible wilting occurs.

The use of plant water indicators as criteria for scheduling irrigations is a fundamental approach, but the lack of adequate and convenient techniques for plant-water measurement handicaps research and the use of this method as a practical guide to irrigation.

2.3.2 Soil Water Indicators.

The first scientific approach to the irrigation scheduling problem involve the use of some soil water indicators. The three major groups that were applied in this experiment are soil appearance and feel, soil water content and soil water suction.

2.3.2.1 Soil Appearance and Feel.

Visual observation of soil appearance in drought areas of the field by using [illegible], shovels and augers to examine rooting depth and wetness of the soil have been used to improve practices where under-or over-irrigation practices prevail (70,71). Visual observations of soil and plant appearance as criteria for scheduling irrigations are widely applied by irrigators in southern Alberta (14).

2.3.2.2 Soil Water Content.

Soil water content has been used as a criterion for scheduling irrigation in numerous experiments. Soil water content may be determined either on a dry mass basis or on a volume basis, and the relationship between the two is given by:

$$\theta_v = \theta_m A$$

where θ_v is the soil water ratio, volume basis, θ_m is the soil water ratio, mass basis and A is the apparent specific gravity of the soil.

Soil water content on a dry mass basis may be determined by gravimetric sampling. This involves soil sampling and oven drying (at 105 - 110°C) to determine the ratio of the sample which is water. The mathematical relationship is as follows:

$$\theta_m = \frac{M_{s+w} - M_s}{M_s} = \frac{M_{s+w}}{M_s} - 1$$

where M_{s+w} is the mass of wet soil (solids plus water) and M_s is the mass of dry soil (mass of solids). The description of various tubes and augers designed to take soil samples can be found in the literature (38,65). Gravimetric soil sampling has been used by some researchers to study plant response to irrigation, but because the method involves tedious procedures of soil sampling, it has not been accepted by farmers for routine use. Other soil moisture determinations that are expressed on a dry mass basis include the 'Speedy' moisture tester and the portable electrical probe. In this experiment gravimetric soil samplings were used to study soil moisture conditions in some selected plots during the growing period.

Although the determination of soil moisture percentage on a volume basis can be done directly from core samples, other indirect methods are more popular. These methods include the neutron method, gamma ray attenuation and the hot wire method. A brief account of the neutron method which is employed in this research is discussed below.

The physics of the neutron approach to the determination of soil moisture on a volume basis was presented by Gardner and Kirkham (16). The procedure involves the scattering of high energy neutrons from a probe which is lowered in a steel or aluminum access tube.and detection of the thermal neutron flow from a counter. As the neutrons pass through the soil mass, they are thermalized by the hydrogen portion of the soil water. Thus for a constant rate of emission of high energy neutrons and the geometry of the area, the rate at which thermal neutrons are detected is proportional to the number of hydrogen nuclei present in the vicinity of the source and detector. Some calibration curves that relate the count rate of thermal neutrons to the water ratio have been determined by many investigators (66,72).

The shortcomings of the neutron probe are radiation hazards, high cost and maintenance problems. Other problems are the difficulty encountered in installing the access tube in stoney areas; also the access tube can obstruct normal farm practices. These shortcomings have generally restricted the use of the neutron probe to a research tool. However, advantage can be taken of light-weight commercial rate meters and depth probes on large farms, such as those of corporations, if skilled technicians are available.

The depth of water in the crop root zone may be computed using any of the above two ratios of soil water content. The mathematical relationships are given as:

$$d = \theta_m A D$$

$$d = \theta_v D$$

where d is the surface depth of water in the depth of soil D under consideration.

2.3.3 Soil Water Potential.

Soil water potential as a criterion for scheduling irrigations has an advantage over the use of soil water content. Many investigators have frequently shown that plants have a better response to soil water potential than to soil water content (19,65). In fact, use of the soil water approach to schedule irrigation assumes no variation between soil water content and its potential in soils of all textural groups. This assumption is very gross. Examination of the graph in Figure 2.3 shows that the matric potential is lower at 25 percent available water depletion for loam soil than for 50 percent depletion of sandy loam. The limitation of soil water content in scheduling irrigations can be overcome by relating water content to soil water potential. A list of various matric potentials at which water should be applied for many

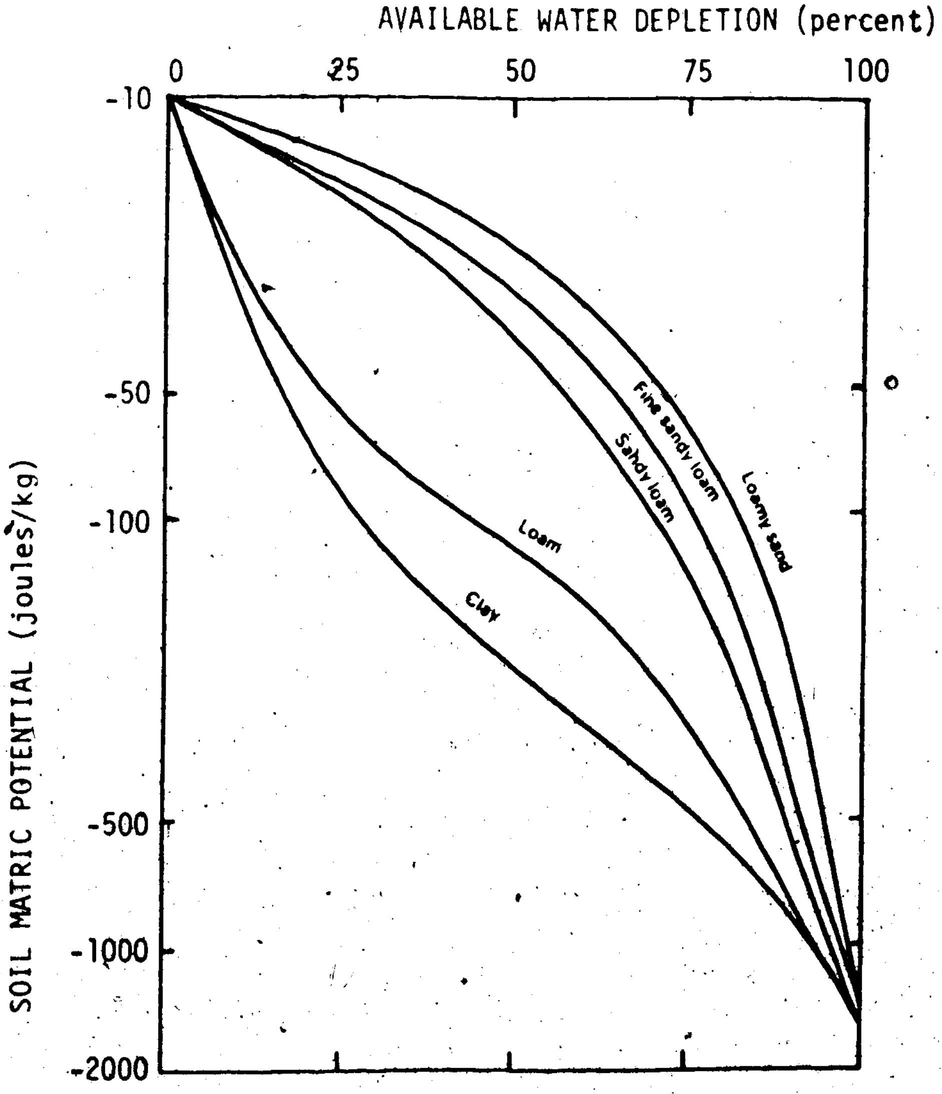

Figure 2.3: Water characteristic curves for several soils in terms of percentage available water removed. (Re-drawn with change of scale after Richards and Marsh, 1961).

common crops has been compiled by Taylor (63).

One major problem that is associated with the use of soil water potential as a criterion for scheduling irrigation is the selection of the location for the monitoring device. An arithmetic integration of soil water potential measured at various depths in the root zone to obtain a simple integrated value was proposed by Taylor (64). The difficulties involved in this method was pointed out by Haise and Hagan (19) who recommended the use of instruments placed at the depth of maximum root activity. The feasibility of this recommendation can be substantiated by experimental results. In southern Alberta, Dubetz and Krogman (14) have shown that the best yields of potatoes are obtained by tensiometer scheduling, based on instrument readings at a depth of 30 cm. An earlier study by Kunkel et al (37) showed that most of the potato roots (70 percent) are found in the top 30 cm of the soil. Generally the instrument is applied for crops with a shallow root zone and resistance blocks are recommended for deep rooted crops. However, it is the range of measurement of water potential that is limiting and not the depth of measurements. Tensiometers that are designed to measure soil water potential at a depth of 120 cm are available.

The tensiometer, also known as a mechanical root, gives a direct reading of soil matric potential up to one bar. However, more satisfactory readings are obtained at readings below 0.8 b (31). Perceptible progress has been made in the technology of tensiometers in recent years, and new units that perform adequately are available commercially. The principle by which the tensiometer functions is well established and documented in the literature (31,32,63) and hence unnecessary duplication of this subject matter is avoided here.

The tensiometer is practical and useful in irrigation scheduling, particularly where high value crops are grown. Some scheduling procedures employing the use of tensiometers have been cited earlier (14,53). The estimated use of tensiometers by 1956, were over 38,000 units in the United States of America and about 7,000 units in other countries (19).

2.3.4 Meteorological Approaches.

Evaporation and other weather variables such as solar radiation and vapour pressure have been used to estimate evapotranspiration. This is not surprising because there is a high correlation between evapotranspiration and these variables (Table 2.2). Most 'exact' methods make use of the four-point determination suggested by Haise and Hagan (19), thus:

(i) short term evapotranspiration rates at various stages of plant development,

(ii) soil water retention characteristics,

(iii) permissible soil water deficit in relation to evaporative demand, and

(iv) the effective rooting depth of the crop grown.

Meteorological parameters that are used as criteria for scheduling irrigations should be able to supply information about point (i) above.

Various theoretical and empirical methods have been developed to estimate evapotranspiration. These methods are classified as:

(i) mass transfer methods,

(ii) energy balance methods,

(iii) combination methods, and

(iv) empirical methods based on meteorological data.

The first three methods involve a complicated theoretical approach to the energy balance between the heat transfer to and from the plant and its environment. Many of the variables are extremely difficult to measure and the results are not accurate when calculations are made on the short-term basis. The empirical approach is by far the least sophisticated and most favoured for scheduling irrigation. Solar energy and evaporation from various surfaces are the main parameters that have been used to estimate evapotranspiration for the purpose of irrigation scheduling. Between the two parameters, evaporation from various surfaces appears to be the most highly favoured even though it has been shown that solar radiation has a similar potential (26,34).

TABLE 2.2 CORRELATION OF EVAPOTRANSPIRATION BY ALFALFA WITH EVAPORATION AND OTHER WEATHER VARIABLES. (after Steed, 1967).

Type of evaporating surface or weather variable	Correlation coefficient, r
Class A pan	.883**
4-ft buried tank	.863**
Bellani atmometer	.866**
Temperature	.838**
Sunshine	.834**
Wind	.134
Vapor pressure deficit	.781*

** Significant at P = 0.01
* Significant at P = 0.05

The devices for measuring evaporation include open pans, atmometers, water bodies and wetted soils. On citing the findings of many workers, Tanner (62) confirmed that over appropriate time periods evaporation from such devices has a high correlation to evapotranspiration from vegetation amply supplied with water. Evaporation data from water bodies and soil are mainly used in watershed studies. On the other hand, evaporation data from open pans and atmometers are more favoured in the field of irrigation. Pruitt (50) presented an extensive review of pan evaporation as a method of estimating evapotranspiration. The disadvantages of the open pan are the cumbersome size, large heat capacity, poor response to wind velocity, solar energy, vapour pressure deficit and temperature. To reduce the effect of these weak points, a method of estimating open-pan evaporation using radiation and other climate data was proposed by Christiansen (10). Other investigators pursued the development of other devices.

The development of the atmometer to measure the amount of water evaporation into the atmosphere was first reported by Holkais et al (29). Atmometers are simple, portable and inexpensive, and are free of the disadvantages of the open pan. By the end of the 1950's atmometers of various types were in use (7,8) and an extensive testing of these devices under various climatic conditions became necessary. In Canada, most investigators became interested in the black Bellani plate which was introduced by Holmes and Robertson (30). Korven and Wilcox (36) reported that the Bellani plate gave the best results (equal to the class A pan), and is now being used widely for experimental purposes in the province of British Columbia.

In southern Alberta most investigators were not satisfied with the performance of the widely accepted Bellani plate; the main weak points being the flooding of the disc in strong winds and susceptibility to frost damage. Another weak point is the inconvenience of having to fill the water reservoir daily to prevent flooding due to changes in air pressure in the water reservoir. The Gen atmometer which was invented and manufactured in southern Alberta was designed to eliminate these weak points. A detailed account of the Gen instrument is presented by Smith et al (57). In the budget procedure that is selected for this comparative test (the 'Irrigation Gauge') evapotranspiration estimates computed from the Gen instrument evaporation data is used as a criterion for scheduling irrigation.

2.4 The Test Crop - Barley (Hordeum vulgare).

In view of the short time available for this experiment the choice of a crop with a relatively short growing season is an advantage. Barley is an annual short season crop (90 days from planting to maturity) and has a seasonal consumptive use of 40 - 60 cm in Southern Alberta (28). The mean daily evapotranspiration at various stages of growth and percentage ground cover is presented by Hobbs and Krogman (28, Figure 2.4). The effective root zone is 120 cm but the crop may lodge on irrigation, especially during the heading stage (2). Barley does very well in relatively fertile sandy loam soil and may reach a height of 90 - 120 cm at maturity.

Usually the crop is ready for harvest when on denting the kernel with the thumb nail, the original shape is restored (41). The yield per hectare in Alberta varies from about 61 to 117 hl per hectare (1).

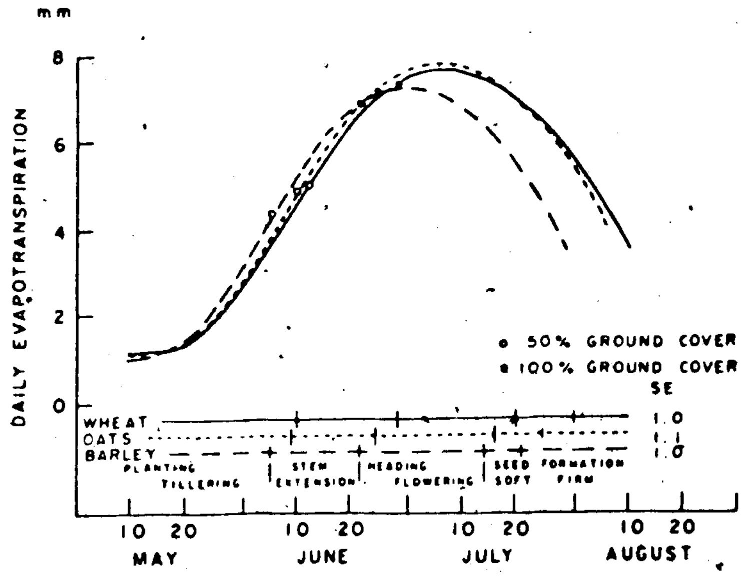

Figure 2.4. Mean daily evapotranspiration for wheat, oats, and barley, showing stages of plant growth and percent ground cover at various dates. (after Hobbs and Krogman, 1974).

The chemical content and physical properties of the kernels vary with location. In Alberta, the statistical documentation of these parameters have been complied by Martin et al (43).

2.5 Summary.

A thermodynamic terminology was introduced to enhance subsequent discussion of soil and water relationships. The currently accepted values of field capacity and wilting point are 1/3 and 15b respectively. The minimum allowable moisture for barley is 50 percent of the available range. Three classes of irrigation scheduling methods were discussed and names were proposed for these classes, thus:

(i) 'exact' - methods that indicate time and amount of irrigation,

(ii) 'approximation' - methods that indicate the time but accuracy in the estimation of the irrigation amount is questioned.

(iii) 'non exact' - methods that indicate the time but needs experience and judgement to estimate the irrigation amount.

In southern Alberta the two widely known scheduling procedures, namely the budget ('Irrigation Gauge') and the plant stress methods fall under the first and the last classes respectively. Use of tensiometers in scheduling irrigations is new in southern Alberta but experimental results indicate a good potential. A modified version of Dubetz and Krogman's tensiometer method which will increase the transfer value has been proposed but the lack of sufficient comparative tests on these available methods still is needed.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experiment Location and Time.

The research was carried out during the summer of 1974. The location was at the Canada Department of Agriculture Irrigation Research Substation, Vauxhall, Alberta. Vauxhall is a small farming community sited approximately at latitude 50° 03' N and longitude 112° 08' W and at an average elevation of 780 meters above sea level. The land consists of medium to coarse-textured soils underlain by glacial till of relatively low conductivity and moderate to high salinity. The slowly permeable till close to the surface could contribute to perched water tables within the root zone if the soil is subjected to heavy irrigations (4,51).

The trial was laid out on a Brown Chernozemic loam (Chin Series) developed on alluvial-lacustrine material (14). This type is representative of much of the irrigated area of southern Alberta. The average soil density varies from 1.5 to 1.6 gm/cc and the available water holding capacity to the 120 cm depth is 13 to 18 cm (14).

3.2 Climate.

Vauxhall has an average annual precipitation of 31.8 cm. Approximately 50 percent (16.9 cm) of the total occurs during the summer months and 25 percent occurs during the critical growing months of May and June when the crops are young and shallow rooted. The highest rainfall amount, averaging 6.4 cm occurs in June (Figure 3.1). These average values were calculated from 21 year data (1953 - 1974) as published by the Canada Atmospheric Environment Services (47).

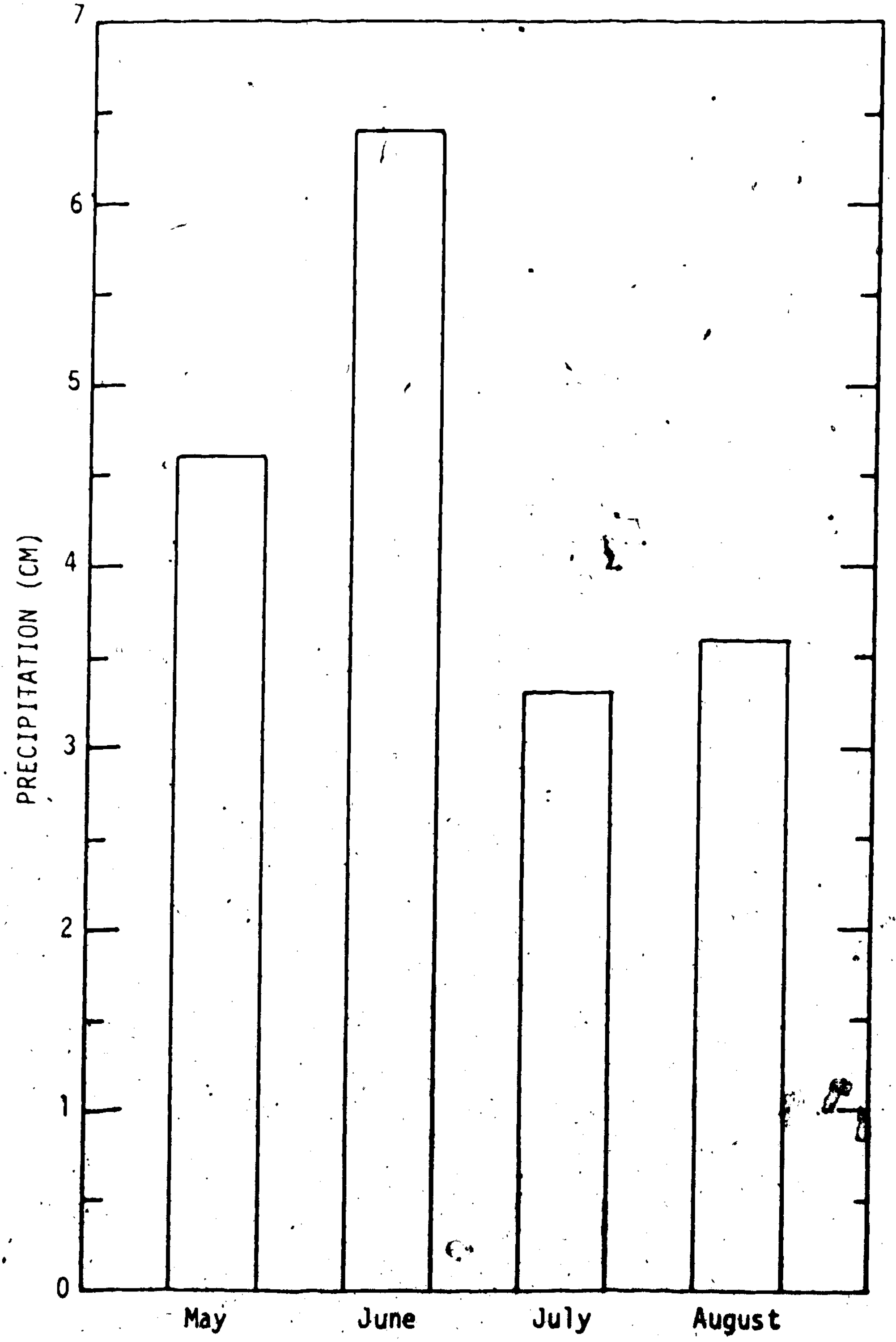

Figure 3.1. Average total monthly precipitation for Vauxhall, Alberta.

The range of the average mean temperature varies from 3.3 to 26.7°C (22 years data) during the summer months, the coolest and the hottest months being May and July respectively. The number of sunshine hours per month varies from 218 to 399 and the lowest and the highest values are in May and June respectively. The average wind velocity varies from 10.9 to 11.4 km/hr with the maximum and minimum occurring in May and July respectively.

3.3 Experimental Procedures.

A randomized block design was planned for the experiment. This consisted of three plots per block running from north to south and six replications, running from east to west (Figure 3.2). Each experimental unit consisted of a 9.1 m by 9.1 m plot, bordered with dykes on all four sides and two access tubes from which soil moisture content was monitored by a neutron* scattering probe.

The treatments consisted of three irrigation scheduling methods, namely:

(i) tensiometer**: plots irrigated when soil matric potential as measured with mercury filled manometer tensiometer read -400 to -500 mb

(ii) the budget, also called the 'Irrigation Gauge', i.e. plots irrigated when about half the available soil water was depleted as calculated by soil moisture budgeting,

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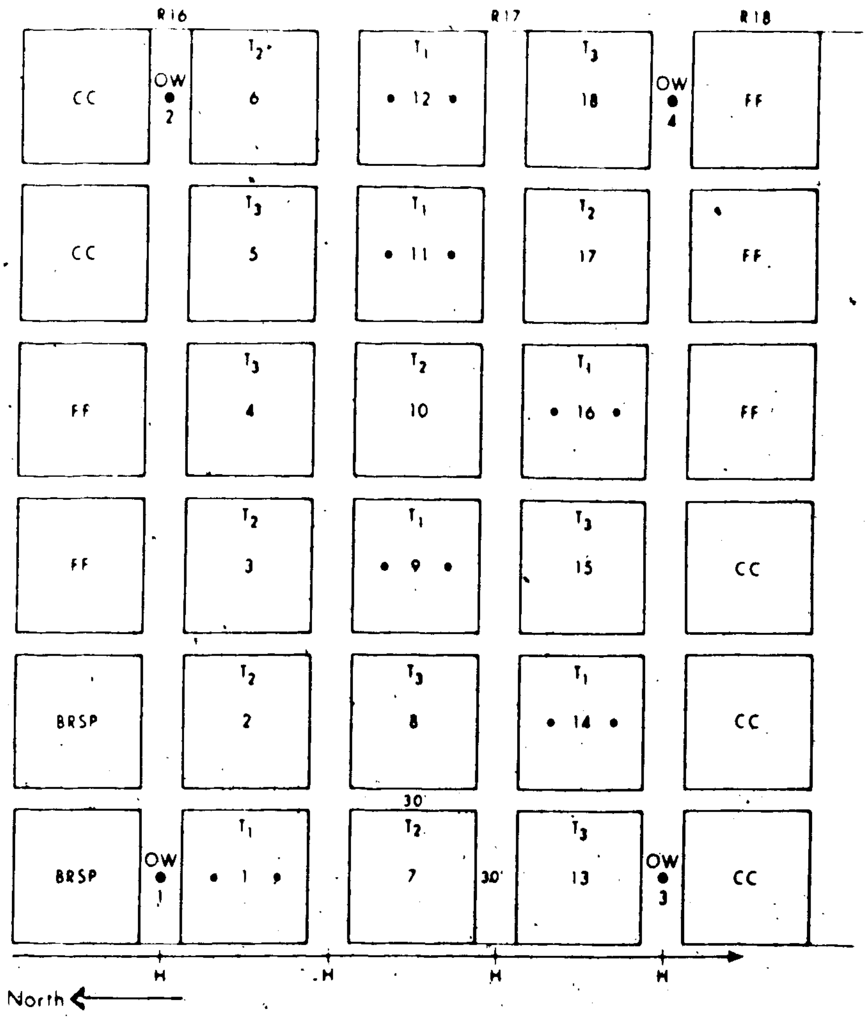
* Neutron Scattering probe; model P19; Nuclear Chicago Corporation, Chicago, Ill., U.S.A.

** Tensiometer: Soil Moisture Equipment Company, 3005 De La Vina Street, Santa Barbara, Calif., U.S.A.



Legend: Dimension of each experiment plot: 9.1 m x 9.1 m
T_1 - Tensiometer Method
T_2 - 'Irrigation Gauge' Method
T_3 - 'Farmer Method'
OW - Observation Well
BRSP - Barley Root Study Plot
R - Range
H - Hydrant
. - Tensiometer
CC - Crop of Corn
FF - Fallow

Figure 3.2a. Field layout.

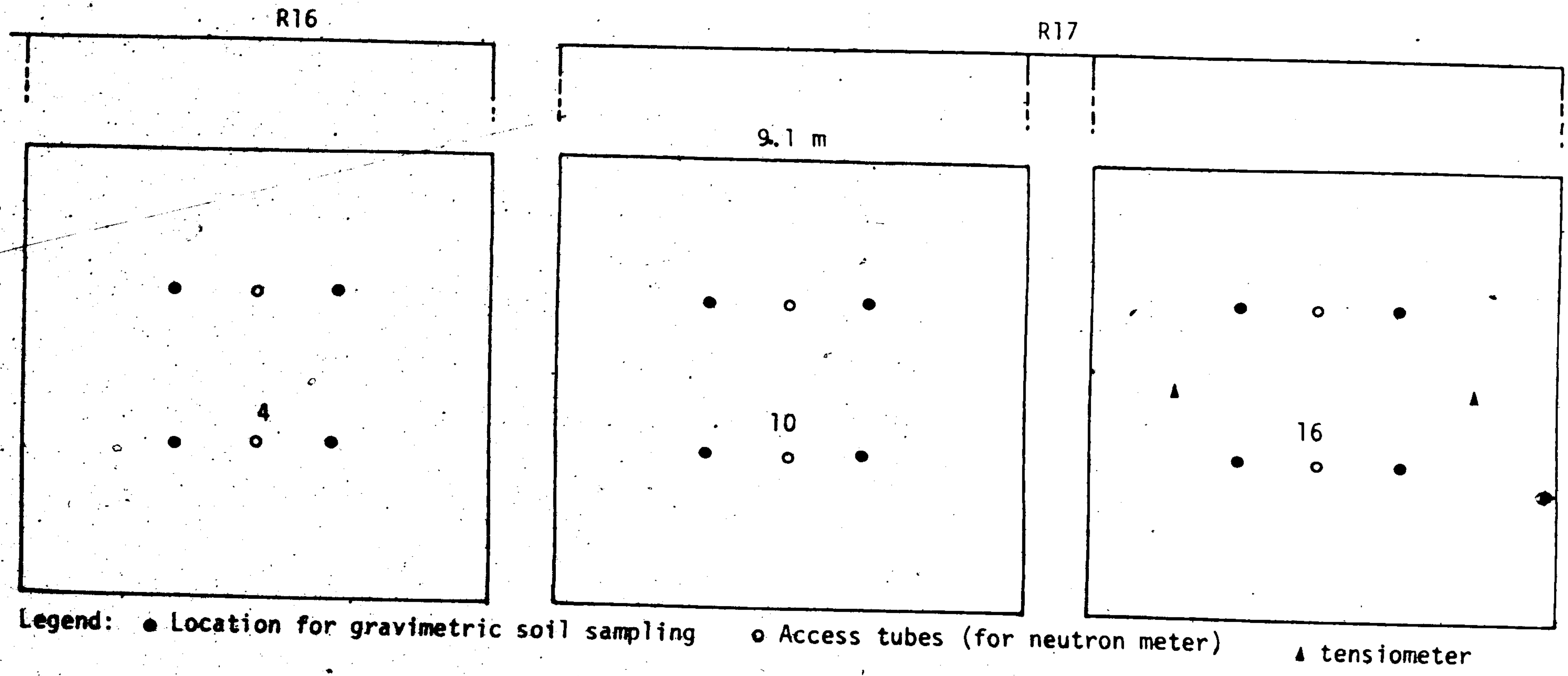


Figure 3.2b. Detailed field layout of plots 4, 10 and 16.

(iii) the 'Farmer method', i.e. plots irrigated when the plants displayed first visual symptoms of moisture stress. This was used as a check on the other two methods.

The procedure for the tensiometer treatment was similar to that described by Dubetz and Krogman (14) but the amount of irrigation was calculated from soil moisture characteristic curves derived from plot data. The data for each plot consisted of values of gravimetric soil moisture content at matric potentials of 0.10, 0.30 and 15 bars. The procedure for these determinations were adopted from the U.S.D.A. Handbook No. 60 (69) employing the use of the pressure plate* (1/10 and 1/3 b) and pressure membrane** (15 b) soil moisture extractors.

The procedure used for the budget method was obtained by personal communication from the Irrigation Division of the Alberta Department of Agriculture. This required measurements of some initial soil parameters, namely soil-moisture content to the depth of 120 cm at the time of planting, and the available moisture. The initial soil moisture content was determined by oravimetric means (65). The available moisture was determined by the difference between gravimetric moisture content at soil matric potentials of 1/3 b and 15 b. The procedure for determining the 1/3 and 15 b moisture percentages were as cited earlier.

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* Pressure plate extractor. Cat. No. 1200.

** Pressure membrane extractor. Cat. No. 1000. Soil Moisture Equipment Company, 3005 De La Vina Street, Santa Barbara, California, U.S.A.

Daily evapotranspiration, in cm, was calculated by multiplying evaporation, in cubic centimeters, from a Gen atmometer by the appropriate evapotranspiration ratio. For barley, the evapotranspiration ratios for the various stages of growth are given as:

up to June 1	0.00381*, i.e. 40 percent shade
June 2 to June 24	0.00584*, i.e. shot blade stage
June 25 to July 30	0.00711*, i.e. leading soft dough
July 31 to harvest	0.00457*, i.e. firm dough ripening.

Daily evapotranspiration and rainfall values were entered in the appropriate columns as discussed earlier (Chapter 2 and Appendix 6). Rainfall amounts in excess of that required to raise the soil moisture content to 1/3 b percentage were considered lost to deep percolation and hence were not entered; also rainfall amounts which were less than 0.3 cm were considered as traces and were deleted.

Irrigations were applied when the difference between the net soil water content at the time of planting or the last day of irrigation and any subsequent day was equal or approximately equal to 50 percent of the available moisture. The crop root zone was then recharged to the 1/3 b percentage by irrigating with an amount of water equal to half of the available moisture. Calculations were based on a crop root zone of 90 cm for the first six weeks after emergence and 120 cm thereafter.

The procedure for the check method was obtained by personal communication with some of the farmers in the Vauxhall District. This was supplemented with the experience and judgement of both the author and some of the older workers at the Research Station. The method required an application of 10.2 cm of water when visual signs of wilting were displayed by the plants between 0900 to 1000 hrs. For barley, the leaf

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* The original figure has been converted to metric.

blade turned dark green, slightly wrinkled and curled in at the edges.

The fertilizer treatment for all plots was based on regular farm practice in the area and consisted of 56 kg N and 56 kg P per ha, broadcasted uniformly and harrowed in before planting. The seeding rate was also based on regular farm practice in the area and consisted of drilling 1.80 hl/ha of seed barley (Galt variety), giving a population of about 2,325,000 plants per hectare. The row spacing was 15 cm thus allowing for an average of 60 rows per plot. The method of irrigation in all three treatments consisted of flooding the plots from 15.2 cm light weight aluminum gated pipe, giving a fairly uniform spread comparable to a border dyke system.

The criterion for judging the grains' readiness for harvest and swathing was based on the recommendations of Lyster (41). Two types of samples were obtained at the time of harvest, namely:

(a) harvesting two rows on either side of a plot with a sickle after a 1.3-m strip of crop on all four sides had been trimmed off,

(b) harvesting the rest of the plot by means of a motorized cutter bar. After swathing, the first sample was used in the determination of the grain/total weight, by weighing both grain and straw together and reweighing after threshing. The second sample, i.e., the larger sample, was also threshed and the yield of grain per hectare was determined.

3.4 Auxiliary Experimental Procedures.

For the purposes of soil characterization and enhancing of data analysis, the following experimental procedures were carried out.

(i) Analysis of soil particle distribution. The revised hydrometer method (3) was adopted using a Hamilton Beach dispersion machine*, cylinders and a streamlined hydrometer**.

(ii) Gravimetric soil sampling. Before each irrigation on plots 4, 10 and 16, gravimetric soil samples were taken to study soil moisture conditions throughout the growing season.

(iii) Neutron moisture measurement. Measurements were made every two weeks when the instrument was available on all plots throughout the season using a neutron scattering probe. The procedure is as described by Holmes, Taylor and Richards (31). The access tubes were made from 3.8 cm aluminum tubing driven to a depth of 120 cm, sealed at the bottom end and provided with a cover at the top.

(iv) Water table measurements. In view of difficulties involved in obtaining the services of a hydraulic drill, it was not possible to install the observation wells until June 27. A 2.5 cm perforated PVC pipe was used for the well lining. Readings were taken by the aid of an air sounder.

(v) Study of root development. This was done weekly on two extra plots set aside for the study. Irrigation

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* The unit was built locally by the Canada Department of Agriculture, Research Division, Lethbridge, Alberta.

** Hamilton Beach Company, Racine, Wisconsin. Hydrometer and cylinders are manufactured by the Taylor Instrument Co., Rochester, N.Y.

scheduling on the root development study plots was by the budget method. It involved excavation of a square or rectangular hole in the soil with one wall passing through the crown of a barley plant. The excavation was stopped when a gentle spraying of the said wall did not expose roots at the bottom of the hole. Measurement of the rooting depth was then taken by means of a tape measure.

3.5 Statistical Analysis.

An analysis of variance was performed on the yield and consumptive use data, and for the multiple comparison of means, Duncan's procedure (61) was used. ~~A~~ Student's t-test was performed on some of the yield data of this investigation and also those of earlier investigators (14,27).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results of Auxiliary Experiments.

The soil mechanical composition, as determined by the Bouyoucus method (3), varied from loam to sandy loam (Table 4.1). The available soil moisture varied from 9.7 to 22.1 cm. The readings of the neutron moisture sampling were used as a check on the data of the gravimetric sampling. Both readings have been presented graphically in Figure 4.1. In most cases, the neutron meter readings were slightly higher than the gravimetric, possibly caused by differences in site selection for sampling. Taylor et al (66) have suggested that a 10 percent error or more should be expected.

The data from the measurement of the water table are presented in Table 4.2. The water table was highest at OW1 and lowest at OW3 with OW2 and OW4 having intermediate positions. The high water table at OW1 was caused by a leakage from the lateral line (Figure 3.2a) and was not noticed until the second week of June. The drop in the height of the water table at OW1 was due to deep percolation and the use of moisture by the crop after the leakage was repaired. The rising of water in OW4 was possibly caused by deep percolation losses from the adjacent corn plots that were subjected to frequent irrigations.

4.2 Irrigation Amount.

The methods for determining the irrigation amount for the three scheduling methods have been described earlier. The results are as shown in Table 4.3. An example calculation for the tensiometer method is presented in Appendix 4. These irrigation amounts, that are computed

TABLE 4.1: MEASUREMENT* OF SOIL MOISTURE CONTENT (AT FIELD CAPACITY AND WILTING POINT), AVAILABLE MOISTURE AND SOIL PARTICLE SIZE ANALYSIS DATA AT VAUXHALL, ALBERTA, 1974.

Plot No.	1/3b M.C. (cm)	15b M.C. (cm)	A.M. (cm)	% Sand	% Silt	% Clay	Textural Class
1	17.3	7.6	9.7	71	18	11	SL
2	20.3	7.9	12.4	67	19	14	SL
3	18.8	6.9	11.9	71	19	9	SL
4	32.3	12.5	19.8	47	33	20	L
5	27.7	10.7	17.0	54	30	16	L
6	32.3	13.5	18.8	52	21	27	SCL
7	29.7	12.7	17.0	48	30	22	L
8	29.2	13.0	16.2	58	24	18	SL
9	31.8	11.7	20.1	54	32	14	SL
10	29.0	11.4	17.6	59	23	18	SL
11	26.4	11.2	15.2	57	25	18	SL
12	36.1	14.5	21.6	43	32	25	L
13	39.4	17.3	22.1	49	26	25	SCL
14	26.4	11.4	15.4	42	32	26	L
15	36.6	17.8	18.8	46	29	25	L
16	27.9	12.2	15.7	55	31	14	SL
17	37.9	17.5	20.4	43	31	26	L
18	26.7	11.2	15.5	57	26	17	SL

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* Based on soil sampling to the 120 cm depth at four locations as shown on Figure 3.2b.

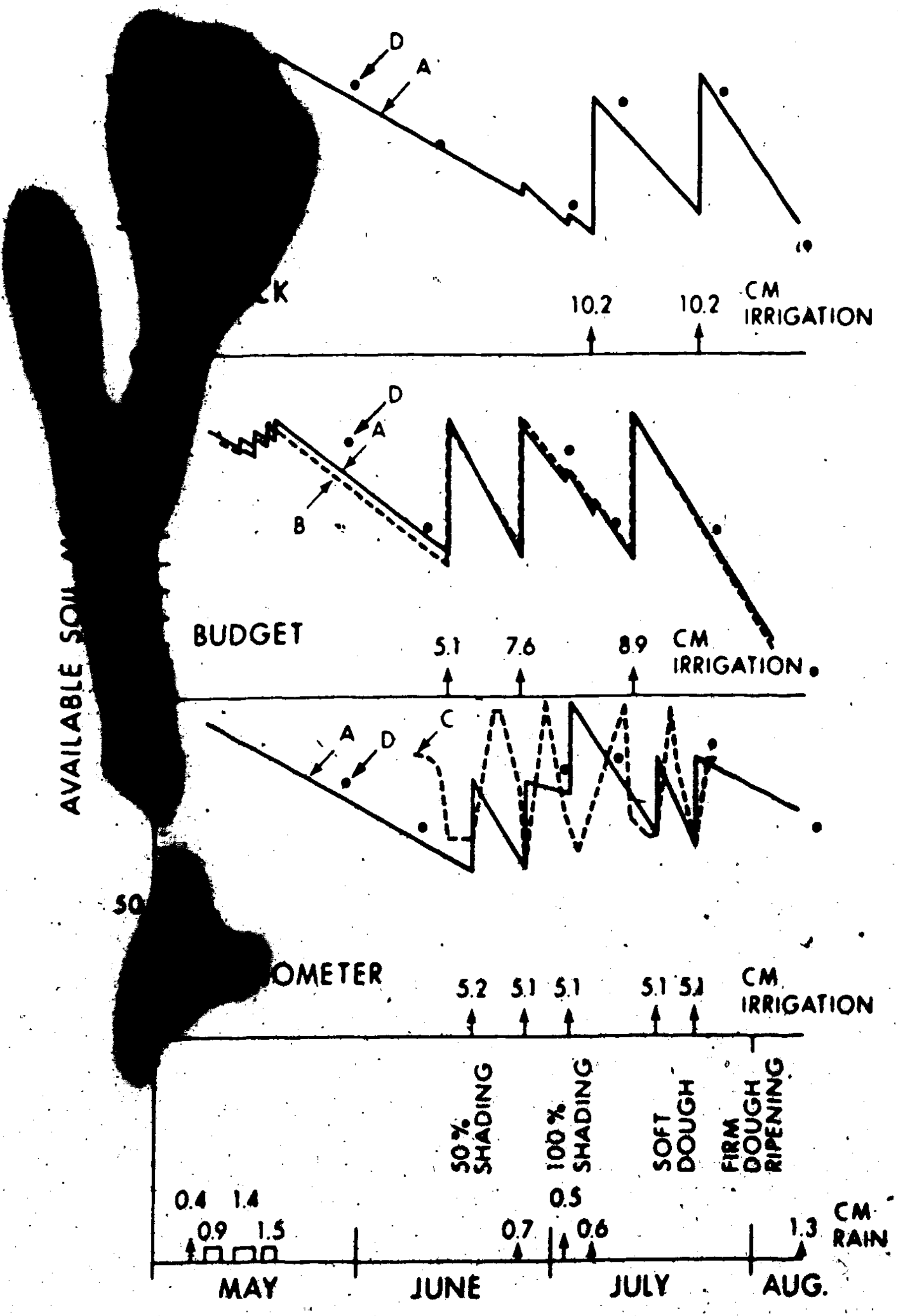

Figure 4.1. Calculated percentages of available moisture at 120 cm depth. A - based on gravimetric sampling; B - based on soil moisture budget (where irrigations were scheduled by the budget method); C - based on soil moisture suction at the 30 cm depth (where irrigations were scheduled by tensiometers); D - based on neutron moisture measurement

TABLE 4.2: MEASUREMENT OF THE DEPTH OF WATER TABLE AT VAUXHALL, ALBERTA, 1974.

Date	Observation Wells	Depth of Water Table (m)			
		OW1	OW2	OW3	OW4
June 29		1.4	1.9	2.3	1.8
July 8		1.6	2.0	2.1	1.8
July 15		1.6	2.0	2.0	1.8

from soil moisture characteristic curves instead of choosing figures based on judgement and experience within the area, varied from 5.5 to 6.4 cm. These figures compare favourably with the figures used by Dubetz and Krogman (14). However, this approach is better because it has more transfer value.

4.3 Crop Root Study.

The data from the crop root zone study (Figure 4.2) shows that barley roots actually go deeper than 120 cm. However, the dense concentration of the fine secondary root system barely extended beyond the 90 cm zone. A careful examination of soil moisture content from each quarter layer of the crop root zone profile showed very little change in the fourth zone throughout the season. Thus the high concentration of roots with their large total surface area in the top quarter to three quarters of the profile, possibly provided the major portal through which most of the plants moisture needs were satisfied.

4.4 Soil Moisture, Irrigation and Evapotranspiration.

The three methods of scheduling irrigations influenced the date of the first irrigation, the irrigation interval and the total amount of

TABLE 4.3: IRRIGATION AMOUNTS FOR THE THREE IRRIGATION SCHEDULING METHODS TESTED IN VAUXHALL, ALBERTA, 1974.

Plot No.	Irrigation Amount (cm) at	
	120 cm Root Zone	90 cm Root Zone
Check		
4	10.2	
5	10.2	
8	10.2	
13	10.2	
15	10.2	
18	10.2	
Budget		
2	6.2	5.1
3	6.2	5.1
6	9.4	7.6
7	8.5	6.4
10	8.8	7.6
17	10.2	7.6
Tensiometer		
1	5.5	
9	5.5	
11	5.5	
12	6.4	
14	5.5	
16	5.5	

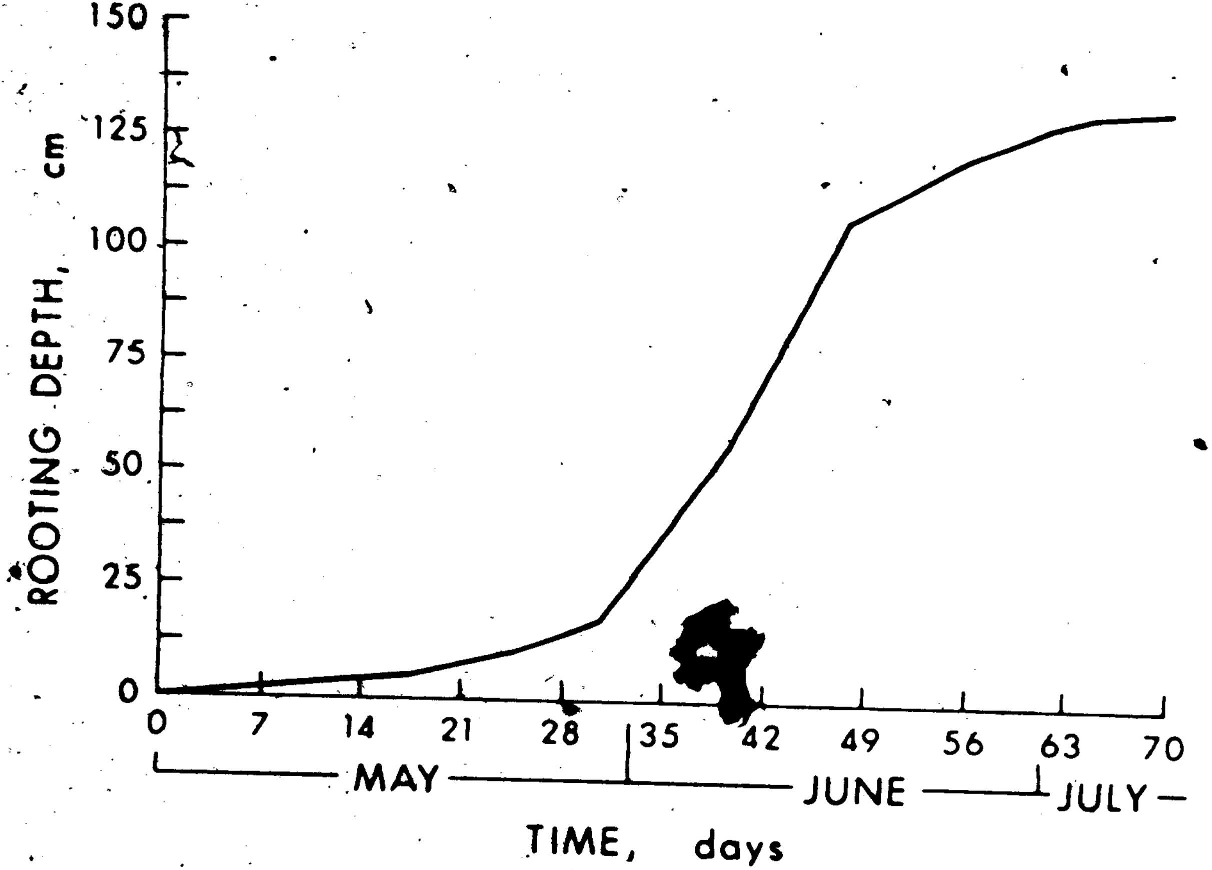

Figure 4.2. Measurement of the extent of rooting depth of barley at Vauxhall, Alberta, 1974.

water applied (Table 4.4). The budget method plots were the first to receive the irrigation water. By comparison, the tensiometer and the check method plots received the first irrigations four and 18 days afterwards respectively. The tensiometer method plots had the highest number of applications scheduled with the shortest irrigation intervals while the opposite was true for the check plots. The budget plots were in an intermediate position. No significant (P = 0.05) difference existed among the mean storage losses of the plots. Hence there is no real advantage in choosing one scheduling method over the other with a view of minimizing storage losses.

On June 25, the soil moisture content (gravimetric) to the 120-cm depth on the tensiometer plot was depleted to a seasonal minimum of 61 percent of the available moisture range (Figure 4.1). This was slightly lower than the seasonal average minimum of 74 percent. The June 25 and the seasonal average minima, as determined from the tensiometer readings at the 30-cm depth, were 66 and 70 respectively. At the time that the tensiometer registered the 66 percent available moisture, gravimetric sampling at the bottom half of the root zone showed a 90 percent available moisture. The second irrigation, which was scheduled on July 3, was early and gravimetric sampling to the 120-cm zone indicated that the soil moisture content was over the 100 percent available moisture level.

The soil matric potential dropped with time as the crop used up moisture and developed (Figure 4.3, a,b,c). A drop in matric potential was permitted until the tensiometer reading was about -500 mb and then the potential was restored by application of the irrigation water. The rise in matric potential above -300 mb seemingly suggests deep percolation losses. However, considering the whole root zone and

TABLE 4.4: IRRIGATION DATA FOR THREE METHODS OF IRRIGATION SCHEDULING CONDUCTED AT VAUXHALL, ALBERTA, 1974.

Plot No. & treatments	First irrigation	Mean interval (days)	No. of Irrigations	Initial soil moisture (cm)	Irrigation amount (cm)	Storage losses (cm)	CU* (cm)
Check							
4	July 5	-	2	31.8	20.3	19.6	29.5
5	July 5	17	1	34.0	10.2	21.8	39.6
8	July 4	18	2	30.0	20.3	18.0	39.4
13	July 4	12	2	31.0	20.3	24.6	35.1
15	July 4	12	2	32.5	20.3	22.6	37.6
18	July 5	-	1	32.0	10.2	23.6	26.4
Mean			1.7	32.0	17.0	21.6	34.5
Budget							
2	June 14	10.3	4	30.7	24.1	21.1	40.9
3	June 14	10.6	4	29.0	24.1	19.8	40.4
6	June 14	11.5	3	29.0	21.6	19.3	38.4
7	June 14	14	3	33.5	22.1	20.1	42.7
10	June 13	13.5	3	27.4	21.6	13.5	42.4
17	June 14	16	3	33.8	22.9	25.4	38.4
Mean	June 14		3.3	30.5	22.9	19.8	40.6
Tensiometer							
1	June 18	-	-	27.2	10.2	19.8	25.9
9	June 17	7.6	6	32.5	20.5	19.1	39.4
11	June 17	8.5	5	27.7	25.4	20.8	39.4
12	June 17	10.3	4	34.5	25.4	23.9	43.2
14	June 17	10.3	4	31.5	20.3	19.6	40.4
16	June 17	8.5	5	32.0	25.4	25.9	38.6
Mean			4.8	31.8	25.4	21.8	40.1

* CU - consumptive use.

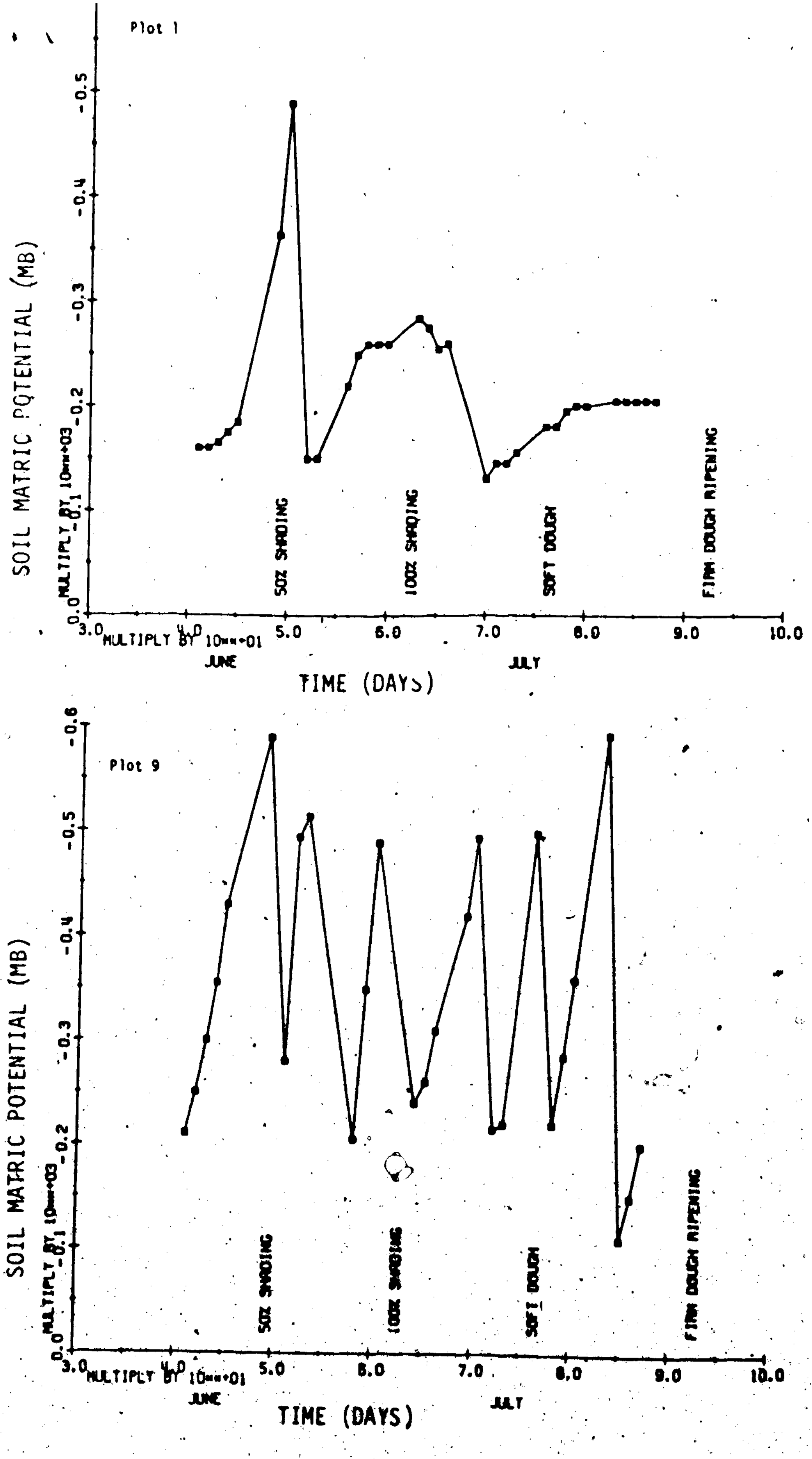

Figure 4.3a. Tensiometer measurements at a depth of 30 cm at Vauxhall, Alberta, 1974.

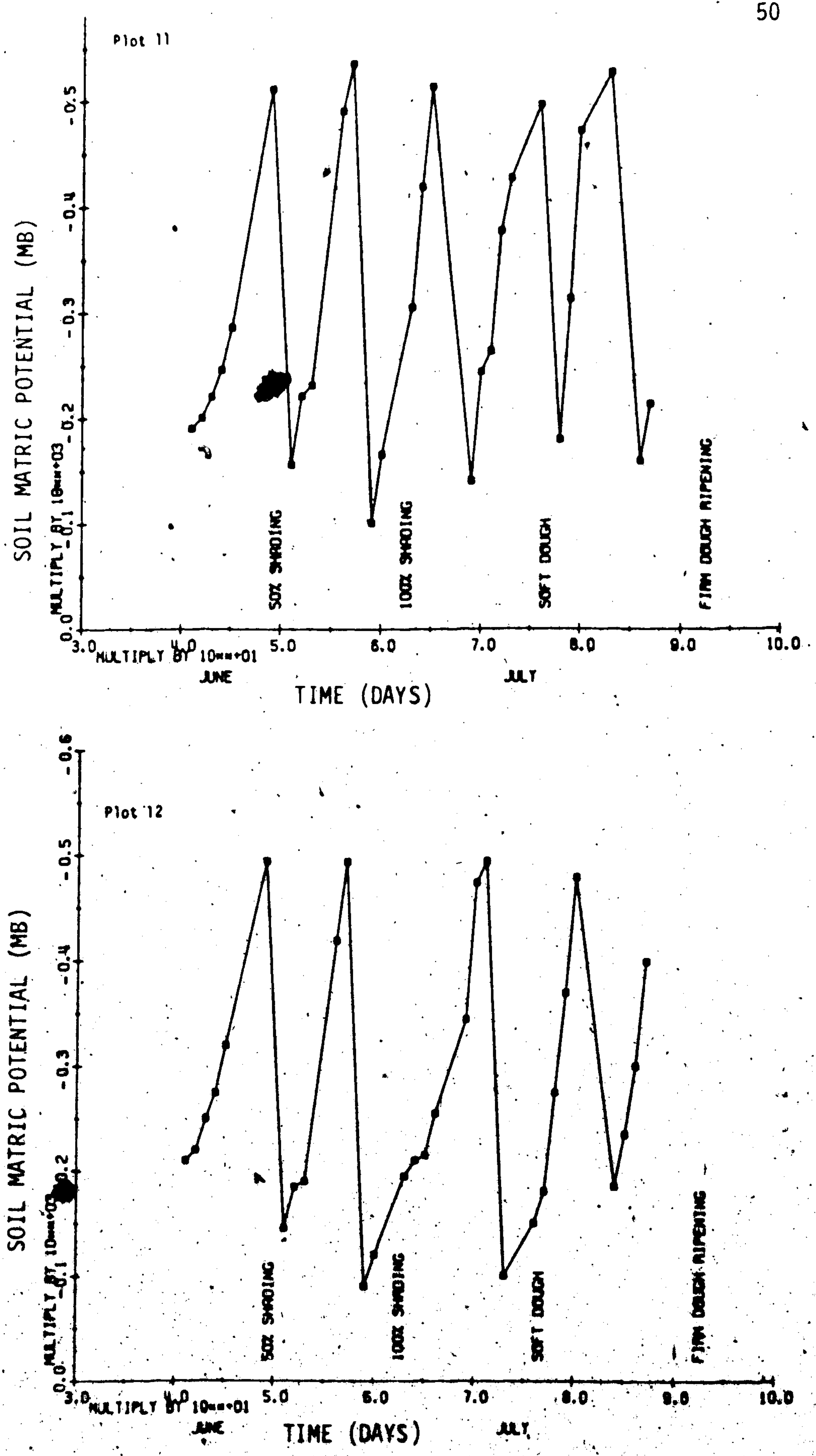

Figure 4.3b: Tensiometer measurements at a depth of 30 cm at Vauxhall, Alberta, 1974.

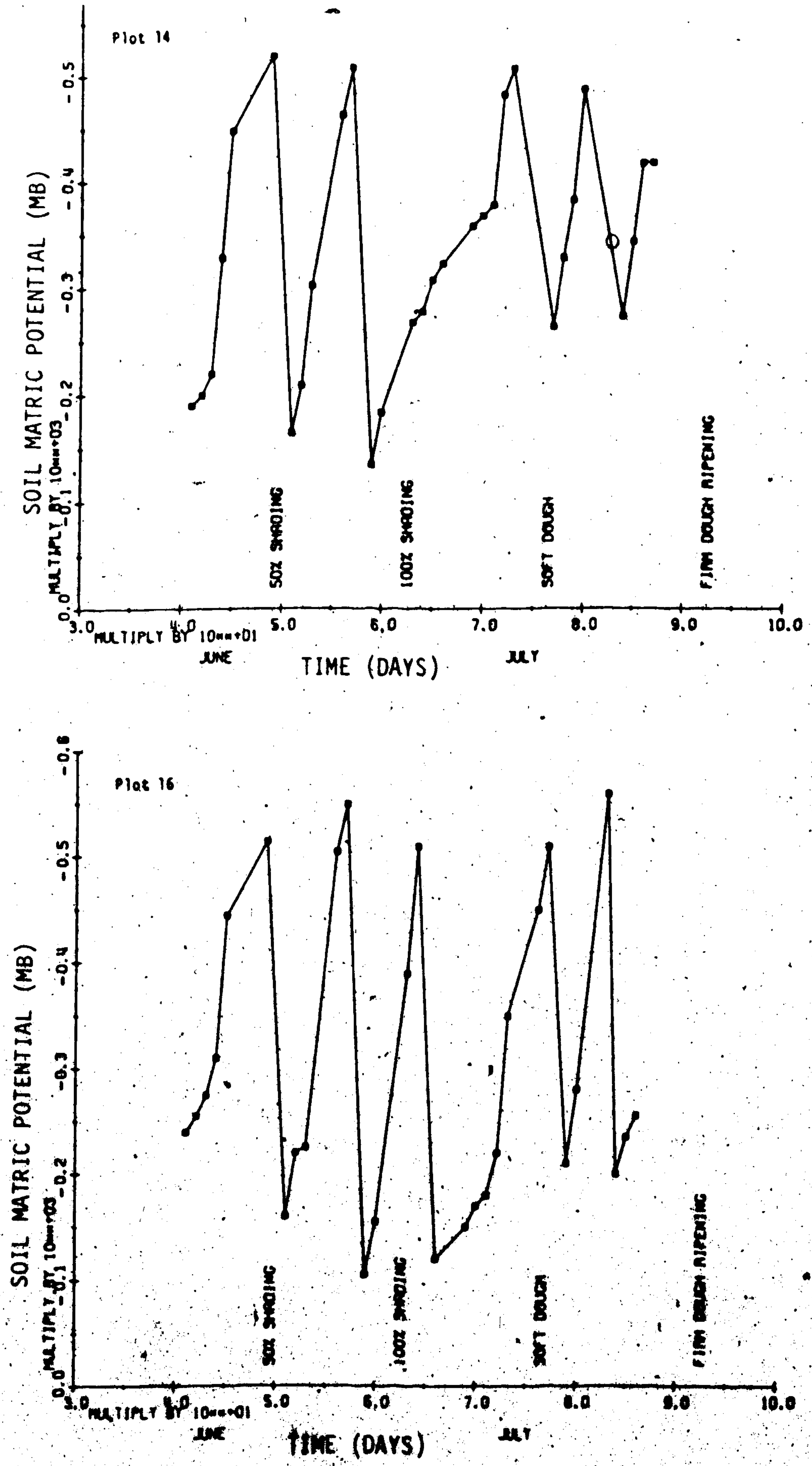

Figure 4.3c. Tensiometer measurements at a depth of 30 cm at Vauxhall, Alberta, 1974.

TABLE 4.5. GRAIN YIELD AND QUALITY DATA OF BARLEY FOR T REE METHODS OF IRRIGATION SCHEDULING AT VAUXHALL, ALBERTA, 1974.

Plot No. & Treatments	Yield (t/ha)	Grain/ Total Yield (%)	Protein Content (%)	P Content (%)	Ca Content (%)	Moisture Content (%)	Hectolitre Weight (kg)	WUE* (t/ha-cm x 100)	Returns/ Application ($/ha)	Returns/ Hectare ($)
Check										
4	3.81	63	13.0	0.30	0.5	7.2	55.1	19	734.80	734.80
5	3.88	52	12.7	0.38	0.50	7.6	59.1	38	400.78	801.55
8	2.67	50	12.4	0.38	0.5	7.6	51.1	13	246.73	493.47
13	1.63	32	15.7	0.41	0.8	7.0	39.5	8	148.78	297.56
15	1.40	32	17.1	0.43	0.6	6.5	31.3	7	129.37	258.75
18	4.32	46	17.6	0.42	0.6	7.1	42.7	42	416.58	833.16
Mean	2.95 a	46a	14.1a	0.39a	0.6a	7.2a	46.5a[1]	21.2a	346.17 a	565.88a
Budget										
2	5.38	56	12.6	0.34	0.5	7.5	62.0	22	270.20	1080.79
3	5.73	61	11.7	0.34	0.5	7.1	60.0	24	288.78	1155.12
6	3.71	61	13.8	0.38	0.5	7.3	58.0	17	248.43	745.30
7	5.47	59	12.4	0.32	0.5	7.5	60.8	25	366.29	1098.87
10	4.42	65	12.3	0.32	0.5	7.3	56.4	20	284.15	852.44
17	3.01	52	15.4	0.40	0.5	6.7	57.8	13	201.56	604.68
Mean	4.62b	59b	13.0a	0.35a	0.5a	7.2a	59.2b	20.2a	276.57a	922.86b
Tensiometer										
1	5.12	65	13.9	0.34	0.5	7.3	60.4	-	-	-
9	5.79	61	11.1	0.33	0.5	7.5	61.0	28	193.86	1163.15
11	5.60	66	12.0	0.36	0.5	7.5	56.4	22	216.00	1080.02
12	5.73	62	12.2	0.37	0.5	7.2	59.8	23	287.77	1151.10
14	5.48	63	11.5	0.32	0.5	6.8	53.3	27	264.22	1056.87
16	5.19	50	13.4	0.35	0.5	6.6	57.8	20	208.52	1042.82
Mean	5.49 b	60b	12.4a	0.35a	0.5a	7.2a	58.1b	24.0a	234.07a	1098.76b

* WUE - water use efficiency

1. Any two means, within a subgroup, followed by the same letter are not significantly (P = 0.05) different.

the fact that tensiometer porous cups were 30 cm below ground surface, this apparent absurdity can be explained. The calculation of the irrigation amount was based on a 120 cm root zone, hence there must be some deep percolation from the top quarter of the root zone to the second, third and fourth zones to effect complete recharging. Examination of graph A of the tensiometer (Figure 4.1) method indicates that the soil moisture content of the entire root zone seldom exceeds 100 percent of the available range. Thus deep percolation losses, if any, were minimal.

The matric potential graph for plot 1 was particularly different from the others (Figure 4.3a). This atypical result was caused by the leakage from the subterranean lateral line. The sub-irrigation from this leakage maintained the soil matric potential above -500 mb during most of the growing season.

A unique property of tensiometer scheduling is illustrated by the above unfortunate problem. The sub-irrigation from the leakage was sensed by the tensiometer and hence fewer irrigations were scheduled. This unique property can be a disadvantage on large farms. A set of tensiometers that are located around a local leakage will schedule fewer irrigations than normal for the entire field and hence cause reduced yields.

Considering the extent of the dynamic root zone in the scheduling procedure for the budget method reduced over-estimation of the soil moisture by at least 2.5 cm. The timeliness of the change (from 90 cm to 120 cm after the first six weeks) in the calculations is supported by the shape of the graph (Figure 4.2). The highest rate of root development that extended beyond the second half of the root zone coincided with the change in root zone depth. By June 13 and July 12 soil moisture to the 120 cm depth on the budget method plots was depleted to 49 percent according to the budget procedure (Figure 4.1). The values of 52 and 48 percent that were determined gravimetrically on these respective dates agree closely with the budget calculations. In comparison with the tensiometer method calculations, soil moisture to the 30 cm depth on the days that the soil moisture content was minimal was 15 percent and zero percent respectively. The crop did not develop signs of wilting at this time because the soil moisture content in the second half of the root zone on these respective dates was 82 and 71 percent. This confirms the suppositions of Dubetz and Krogman (14). It appears, therefore, that to maintain the soil moisture content in the top half of the root zone above a minimum allowable of 50 percent, then the average minimum allowable of the entire root zone must be above 50 percent.

From June 28 to July 5, the soil moisture content on the check plots was depleted from about 50 percent to 42 percent available moisture. Stress to the crop was more severe than was apparent because at this time, the soil moisture content in the top half of the root zone was depleted from nine percent to zero percent. This period coincided with the booting stage of the crop.

4.5 Crop Yield and Quality.

There was no significant difference (P = 0.05) between yields that were obtained from the two different sets of samples taken during the harvest. The means of crop yields from the budget and the tensiometer plots were significantly higher (P = 0.05) than those of the check plots by 1.67 t and 2.54 t per hectare respectively.

(Table 4.5). Also, there was no correlation between the total irrigation amounts and the corresponding crop yields. Hence the difference in yield have been brought about mainly by the timing of each application.

The relatively lower yields that were obtained from the check plots was caused by the soil moisture conditions, discussed under section 4.2. The significantly lower ($P = 0.05$) ratios between the grain yield and total yield above ground surface that were obtained from these same plots point to the fact that with improper irrigation timing, grain yield is impaired more than straw yield and vice versa. The relatively low yield from Plot 17 has been caused by high soil moisture stresses. The soil of the Vauxhall substation is quite heterogeneous. Samples that were obtained for characterization within a 0.13 ha area indicated a sandy clay for plot 6 and loam for plot 17 while over 50 percent of the entire sample lot was sandy loam (Table 4.1). Plots 11 (SL), 16 (SL) and 18 (SL) which were adjacent to the north, west, and east respectively of Plot 17 had available moisture values of 15.2, 15.7 and 15.5 cm respectively. By comparison the available moisture value of 20.4 cm obtained from Plot 17 was quite high. Overestimation of available moisture lowered the effective minimum allowable moisture as compared to the budget calculation and hence the undesirable plant stress and the attendant poor yield.

The lack of significant differences in the means of the grain's chemical analyses (Table 4.5) justifies the choice of grain bushel weight as the main criterion for determining the marketability of feed barley (personal communication with grain elevator agents). Though slight differences existed among the means of the grains protein content, the differences were not significantly high enough to justify the choice of any one particular batch of grain over the others with a view of saving on protein supplements during feed compounding. The means of the grain grade groups from the plots that were irrigated by the budget method and the tensiometer scheduling were No. 1 and their hectolitre weight means were significantly higher ($P = 0.05$) than those from the check plots; the mean grade group of the latter being No. 2.

Although the hectolitre weights obtained from this experiment were within the range that is officially recognized for the Vauxhall area (43), their means were slightly lower than the official value. Possibly this difference is due to the barley variety used in the experiment. The mean chemical values of the grain compare favourably with the official values. The mean yield of grain from plots that were irrigated by the budget method were comparable to what was observed by Hobbs and Krogman (27). A similar pattern of yields of these three scheduling treatments on potatoes was observed by Dubetz and Krogman (14) but the treatments did not affect the specific gravity of tubers. A reason for the superiority of the tensiometer over the other two methods has been discussed earlier (Chapter 2).

4.6 Efficiency Measures - Water Use Efficiency, Returns per Hectare* and Returns per Application*.

The treatments did not affect the water use efficiency and the returns per application (Table 4.5). However, the total dollar returns per application from the tensiometer and the budget plots exceeded that of

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* Appendix 5

the check plots by $532.88 and $356.98 per hectare respectively. These values differed at the five percent level of significance (P = 0.05).

The relative levels of water application and the total dollar returns per application follows the total product curve (39,42, Figure 4.4a). The relative variation of the mean values of the number of applications and the returns per application seem to follow the law of diminishing returns (Figure 4.4b). However, the lack of significant differences among the mean values of the returns per application does not permit the proof of this law using the data from this experiment. The decreases in marginal returns (the dollar returns, \$/ha-cm) with increasing variable input (number of irrigations) indicate that at least the plots that were irrigated by the budget and the tensiometer methods were utilizing the irrigation applications within stage II of the total product curve. Here the total product is represented by the total dollar returns per hectare. The stage of business operation on the check plots is uncertain but the two possible positions are either in stage I or the lower part of stage II.

Frequently, the economists have shown that the region of the total product curve for the best business operation is in stage II. Stage II is defined to include the range of the variable input from the point at which the average product of the variable input (the number of applications) is maximum to the point at which the marginal product (returns per application, \$/ha) is zero. Thus the plots that used the budget and the tensiometer methods were more profitable with irrigation than the plots that used the check method.

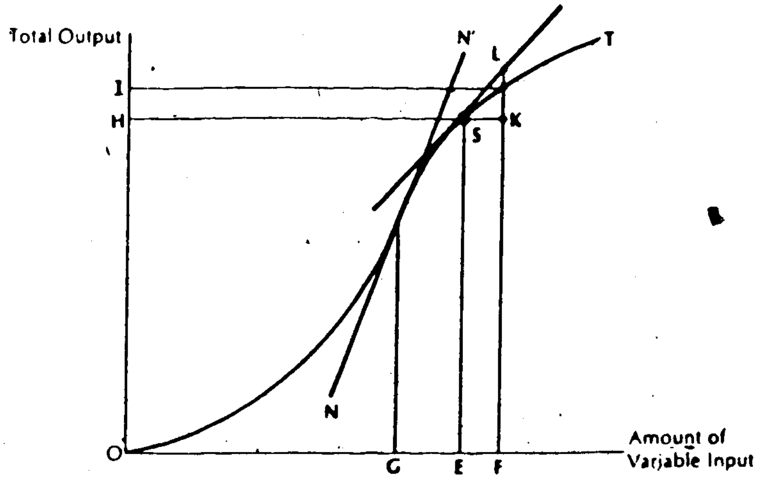

Figure 4.4b. The total output curve (after Mansfield, 1970).

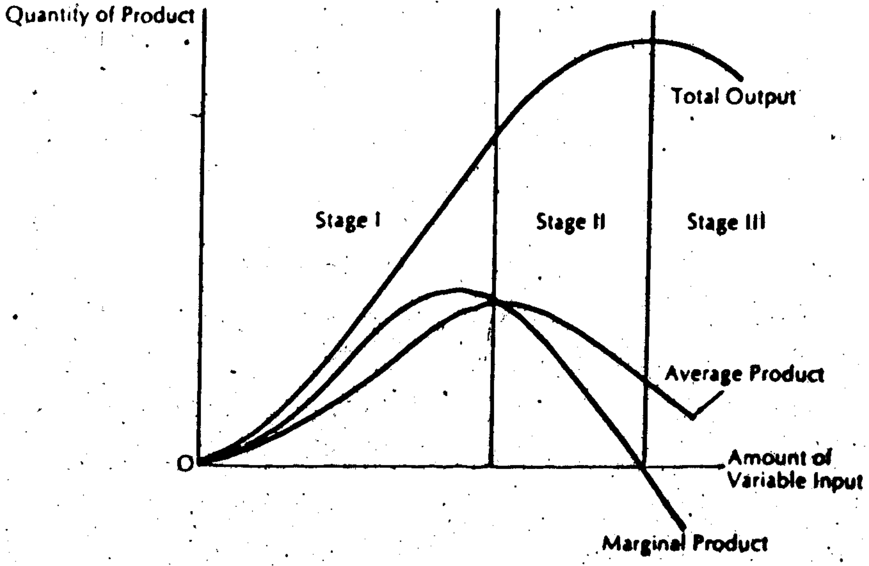

Figure 4.4a. The three stages of business operation (after Mansfield, 1970).

4.7 Judgement of Scheduling Methods.

The relatively low yield and hectolitre weight that were obtained from the check plots were caused by improper timing and poor judgement of the irrigation amount. Though this method produced the highest returns per application (not significant at P = 0.05), economic analysis indicated that the operation of the plots as simulated farm business units at this level of water application were not economical from the application of irrigation. The grain quality (No. 2 feed barley) and water use efficiency were poor and the total dollar returns were quite low ($565.88/ha). This method is the least desirable in order of merits.

There was no significant difference (P = 0.05) between the yields from the budget and the tensiometer plots. However, the mean yield differences that were significant at the one percent level of significance (P = 0.01) calls for a re-examination of the data and comparisons with the data of other investigators. The results of experiments by Dubetz and Krogman (14) had shown that the tensiometer scheduling method was superior to the budget method for irrigating potatoes. The mean yield differences were significant at the five percent level of significance (P = 0.05). They also reported that in using the tensiometer scheduling the minimum allowable moisture was never below about 60 percent of the available range. Calculations from the present investigations also indicated that the minimum allowable moisture in the tensiometer plots had an average value of 72 percent.

Hobbs et al (24) had shown that there was a strong tendency for no yield benefits to be derived from the maintenance of soil moisture at levels higher than 50 percent of the available moisture. However, they explained that the growth of potatoes was better at 75 percent minimum allowable moisture. This agrees with the findings of other investigators (44,52). Further investigations by the same team (27), using data collected over eight years, indicated no significant difference ($P = 0.05$) between yields of barley irrigated at 50 percent and 75 percent minimum allowable moisture.

A Student-t test performed on the yields obtained from the application of the budget method with 75 percent minimum allowable moisture and by tensiometer scheduling (Table 4.6) did not yield any significant difference for both potatoes ($P = 0.4$) and barley ($P = 0.1$). These findings strongly suggest that the increment in crop yield that were obtained by tensiometer scheduling had been brought about by the use of a high minimum allowable moisture and not necessarily due to better sensing of the irrigation needs by tensiometers. This is different from the explanation given by Dubetz and Krogman (14). The budget method is capable of performing as well as the tensiometer method if the minimum allowable moisture is fixed at the same level at which the tensiometer operates. Possibly the yields from the tensiometer plots would be identical to those of the budget plots if both methods were operated with the same minimum allowable moisture levels. This fact can be substantiated by further research at various levels of minimum allowable moisture. Difficulties in measuring soil matric potential at the low moisture levels are foreseen. However, in such situations, resistance methods may be used.

TABLE 4.6: COMPARISON OF YIELDS USING BUDGET AND TENSIOMETER SCHEDULING.

Yield of Potato (t/ha)

75% M.A.M.[*]	Tensiometer[+] (Equivalent to over 60 percent M.A.M.)
35.34	37.28
44.95	39.09
52.16	40.44
$\bar{X}_1$ 44.15	$\bar{X}_2$ 38.94

$\bar{X}$'s not different at P = 0.4 significance

Yield of Barley (t/ha)

75% M.A.M.[**]	Tensiometer[Ø] (Equivalent to 72 percent average of available range)
4.95	5.12
5.26	5.79
4.38	5.60
3.97	5.73
4.57	5.48
3.83	5.19
4.28	
4.33	
$\bar{X}_1$ 4.45	$\bar{X}_2$ = 5.49

$\bar{X}$'s not different at P = 0.1 significance

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[*] Hobbs and Krogman 1965

[+] Dubetz and Krogman 1973

[**] Hobbs and Krogman 1970

[Ø] Present investigation

CHAPTER 5

SUMMARY AND CONCLUSIONS

A comparative study of three methods of scheduling irrigations for barley was conducted at the Canada Department of Agriculture Irrigation Research Substation, Vauxhall, Alberta. The experiment was conducted during the summer of 1974, and the treatments were:

(a) irrigate when plants displayed the first visual stress symptoms (check method),

(b) soil moisture budgeting or 'Irrigation Gauge' (budget method),

(c) irrigate when soil tensiometer readings were -400 to -500 mb (tensiometer method).

The following inferences and conclusions were drawn.

1. The treatments did not affect the moisture storage losses and water use efficiencies (no significant differences at P = 0.05). The mean values of the storage losses were 21.6, 19.8 and 21.8 cm for the check, budget and tensiometer methods respectively. The respective values of water use efficiencies were 21.1, 20.2 and 24.0 t/ha-cm x 100.

2. The mean consumptive use values of the budget (40.6 cm) and the tensiometer (40.1 cm) methods were significantly higher (P = 0.05) than those of the check method by 6.1 and 5.6 cm respectively. The mean consumptive use value of the check method (34.5 cm) was lower than the potential value. This value (34.5 cm) was lower than the evapotranspiration estimates

as calculated from the Gen atmometer (42.9 cm, Appendix 6) and the 10-year average of 40.1 cm reported by Sonmor (58).

3. By using the tensiometer method, the minimum allowable moisture was equivalent to about 72 percent of the available moisture range.

4. The use of soil moisture characteristic curves to determine the irrigation amount of the tensiometer method was satisfactory. Also the timeliness in the change of the extent of root zone (from 90 to 120 cm) in the budget method was satisfactory.

5. The mean total irrigation amount applied by the budget (22.7 cm) and the tensiometer (25.4 cm) methods were significantly higher (P = 0.05) than that of the check method by 5.7 cm and 8.4 cm respectively. Also, there was no correlation between the irrigation amount and the yield of grain.

6. The mean number of applications of the budget (3.3) and the tensiometer (4.8) methods were significantly higher (P = 0.05) than that of the check method by 1.6 and 3.5 respectively.

7. The mean grain yield per hectare of the budget (4.62 t/ha) and the tensiometer (5.49 t/ha) methods were significantly higher (P = 0.05) than that of the check method by 1.27 and 2.54 t/ha respectively. Also, the mean ratios of grain to total yield above ground of the budget (59 percent) and the tensiometer (60 percent) methods were significantly higher (P = 0.05) than those of the check method by 13 and 14 percent respectively. This indicates that the check method produced more straw yield in relation to grain yield. The

budget and the tensiometer methods have been shown to perform equally well when they are operated at the same level of minimum allowable moisture.

8. The budget and the tensiometer methods produced better quality grain (hectolitre weight means were 59.2 and 58.1 kg respectively - No. 1 feed barley) than the check method (mean hectolitre weight was 46.5 kg - No. 2 feed barley). However, the treatments did not affect the calcium, phosphorus and protein content of the grains.

9. The treatments did not affect the mean values of the returns per applications; the mean values were $346.17, $276.57 and $234.07 per hectare for the check, budget and the tensiometer methods respectively. However, the total returns per hectare of the budget ($922.86) and the tensiometer ($1098.76) methods were significantly higher (P = 0.05) than that of the check method by $356.98 and $532.88 respectively.

10. Micro-economic analysis of the returns from water application indicate that the budget and the tensiometer methods were more profitable from the application of irrigation than the check method.

The following recommendations are proposed for further work:

1. A comparative test of the tensiometer and the budget methods may be conducted to compare their performance at various equivalent levels of minimum available moisture.

2. The test to prove the law of diminishing returns by compiling data of number of water applications and the total dollar returns per hectare.

CHAPTER 6

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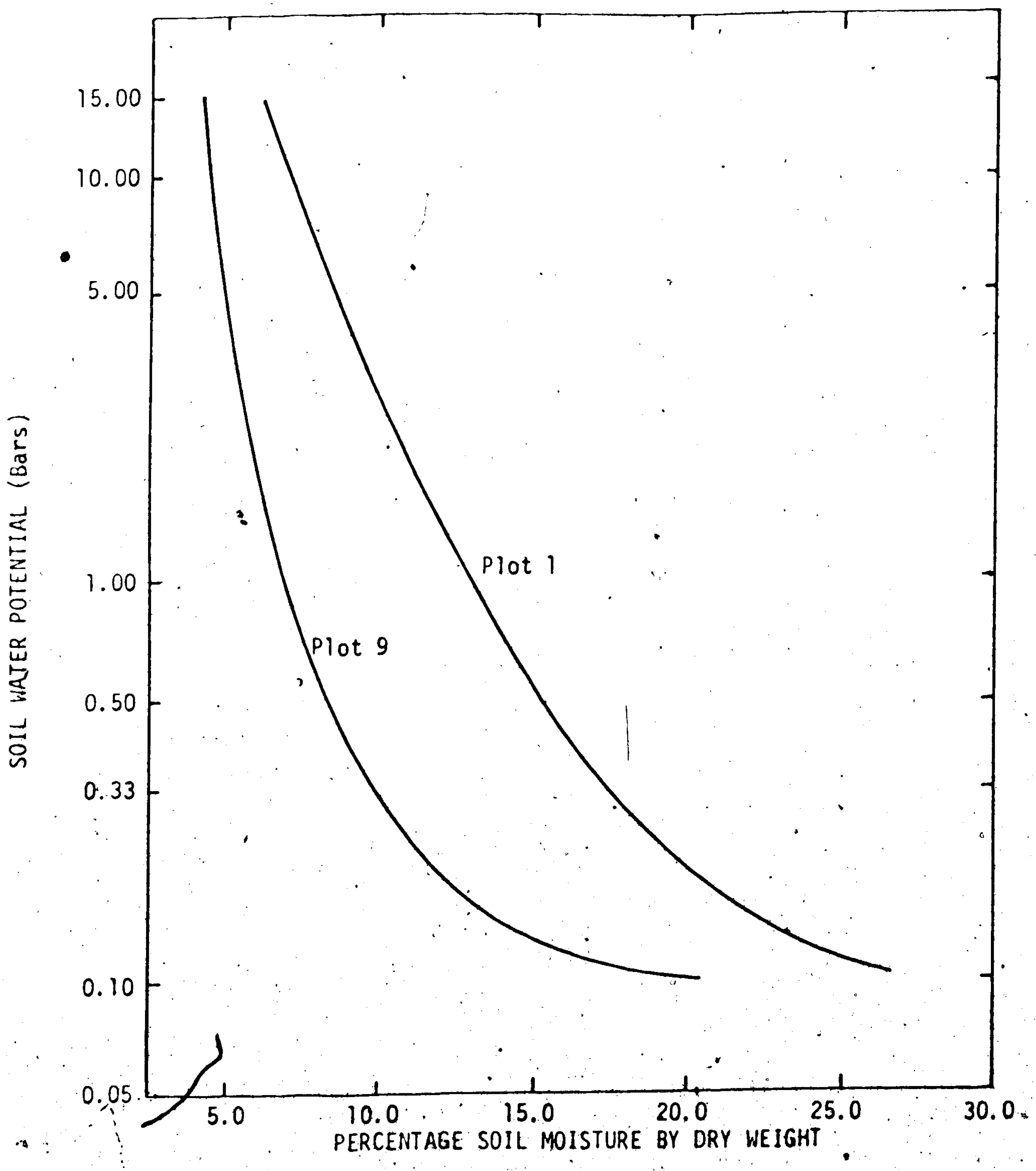
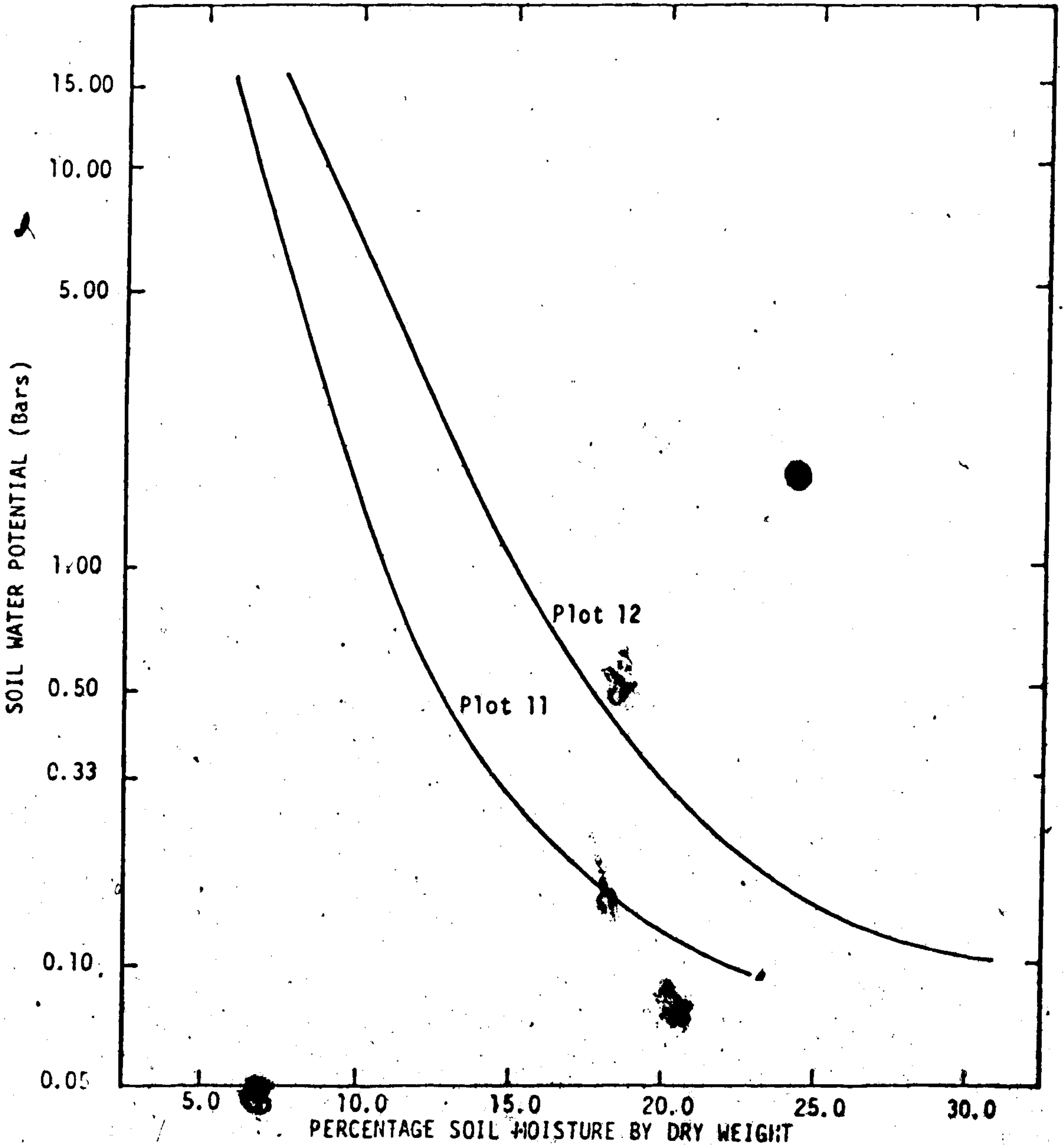
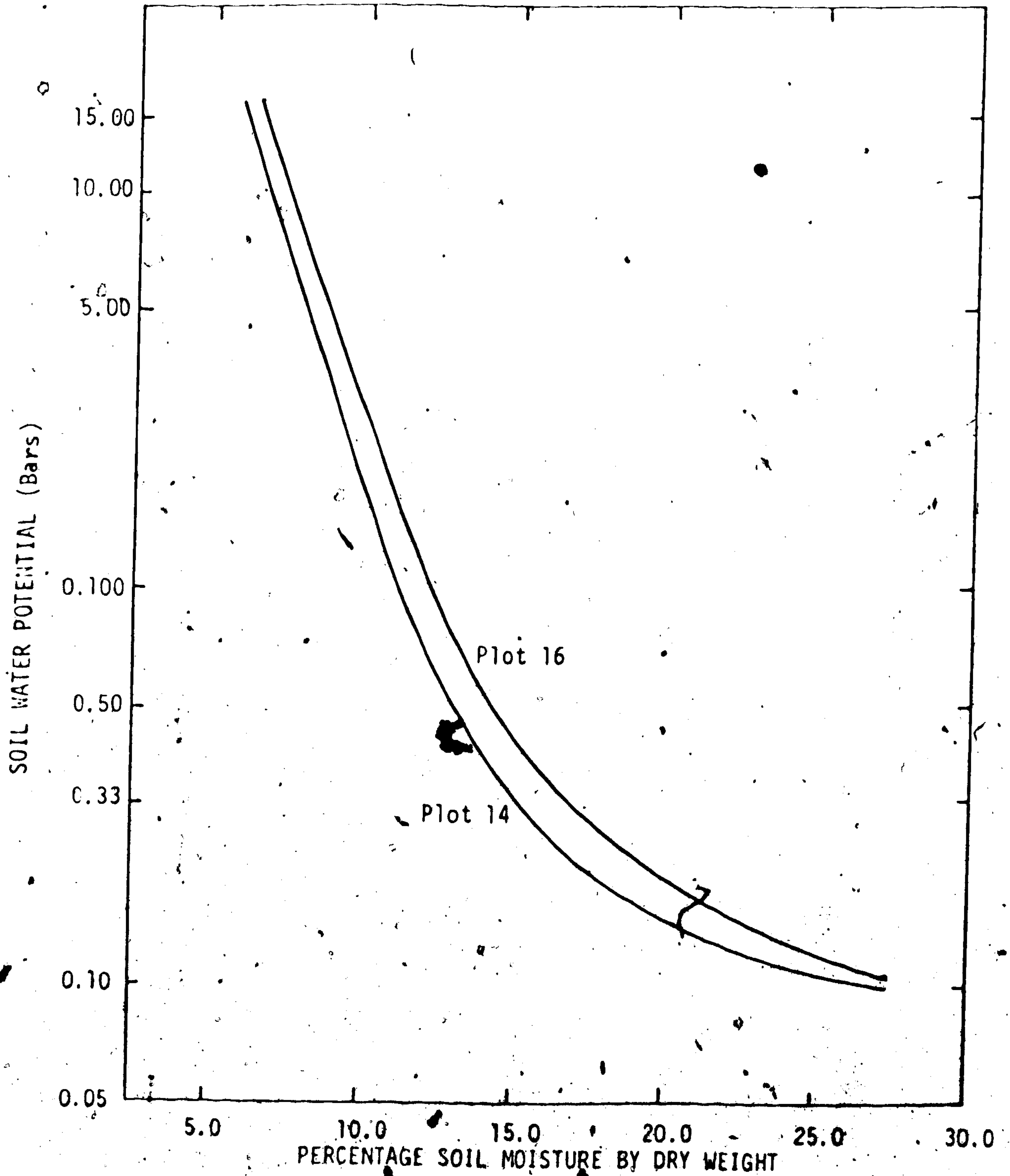
APPENDICES



APPENDIX 1: MEASURED SOIL WATER POTENTIAL AND PERCENTAGE SOIL MOISTURE CONTENT BY DRY WEIGHT AT VAUXHALL, ALBERTA, 1974.



APPENDIX 2: MEASURED SOIL WATER POTENTIAL AND PERCENTAGE SOIL MOISTURE CONTENT BY DRY WEIGHT AT VAUXHALL, ALBERTA, 1974.



APPENDIX 3: MEASURED SOIL WATER POTENTIAL AND PERCENTAGE SOIL MOISTURE CONTENT BY DRY WEIGHT AT VAUXHALL, ALBERTA, 1974.

APPENDIX 4: CALCULATION OF THE IRRIGATION AMOUNT FROM THE SOIL MOISTURE CHARACTERISTIC CURVE OF PLOT 11.

Percentage soil moisture at -300 mb = 14.5%

Percentage soil moisture at -500 mb = 11.5%

Irrigation amount, $d = \frac{PAD}{100}$

where P is the percentage soil moisture difference at -300 mb and -500 mb; A is the apparent specific gravity (= 1.5) and D is the depth of crop root zone (= 120 cm)

$$d = \frac{(3)(1.5)(120)}{100} = 5.5 \text{ cm.}$$

APPENDIX 5: CALCULATION OF THE RETURNS PER HECTARE AND RETURNS PER APPLICATION.

The price of the various grades of feed barley as given by some of the grain elevator companies in the Edmonton area (during January 1975) are:

Hectolitre Weight* (kg)	Grade	Price/Tonne* ($/t)
56.3 and above	1	200.89
Below 56.3 to 53.8	2	192.86
Below 53.8	3	184.82

$$\text{Returns per hectare} = (\text{tons/ha})(\text{grade price/ton})$$

$$= (5.38\ \text{t/ha})(200.89\ \$/\text{t})$$

$$= \$1080.79/\text{ha}.$$

$$\text{Returns per application} = \frac{\text{Returns per hectare}}{\text{No. of applications}}$$

$$= \frac{(\$1080/\text{ha})}{4}$$

$$= \$270.20/\text{ha}.$$

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* Original figures converted to metric.

APPENDIX 6: EVAPORATION AND PRECIPITATION DATA AT VAUXHALL, ALBERTA, 1974.

Date	Evaporation (E) From Gen Atmometer (cm)	Precipitation Record (cm)		Calculated Evapotranspiration (ET, cm)		
		Daily	Cumulative	Daily EK	Cumulative KE(Ei)	Net Deficit
May 1	20	0.08*		0.08	0.08	0.08
2	32	Tr.		0.13	0.21	0.13
3	58			0.23	0.44	0.44
4	56			0.20	0.64	0.64
5	97			0.38	1.02	1.02
6	19		0.38	0.08	1.10	0.72
7	98			0.38	1.48	1.10
8	50	0.56	0.94	0.20	1.68	0.74
9	54	0.28	1.22	0.20	1.88	0.66
10	38	0.18*		0.15	2.03	0.81
11	30			0.13	2.16	0.94
12	42	Tr.		0.15	2.31	1.09
13	0	0.38	1.60	0.00	2.31	0.71
14	32	Tr.		0.13	2.44	0.84
15	36	1.02	2.62	0.13	2.57	0.05
16	20	0.10*		0.08	2.65	0.03
17	29	1.12	3.74	0.10	2.75	0.99
18	6	0.36	4.10	0.03	2.78	1.32
19	21			0.08	2.86	1.24
20	26	Tr.		0.10	2.96	1.14
21	35			0.13	3.09	1.01
22	54			0.20	3.29	0.81
23	78			0.30	3.59	0.51
24	80			0.30	3.89	0.21
25	104			0.41	4.30	0.20
26	126			0.48	4.78	0.68
27	44	Tr.		0.15	4.93	0.83
28	38	Tr.		0.15	5.08	0.98
29	20	0.15*		0.08	5.16	1.06
30	30	0.08*		0.13	5.29	1.19
31	50			0.20	5.49	1.39

* Considered as trace

Tr. Trace

APPENDIX 6: Continued

Date	Evaporation (E) From Gen Atmometer (cm)	Precipitation Record (cm)		Calculated Evapotranspiration(ET,cm)		
		Daily	Cumulative	Daily EK	Cumulative KE(Ei)	Net Deficit
June 1	114			0.43	5.92	1.82
2	132			0.76	6.68	2.58
3	114	0.03*		0.66	7.34	3.24
4	92			0.53	7.87	3.77
5	76			0.43	8.30	7.20
6	52	0.23*		0.30	8.60	4.50
7	10	0.08*		0.05	8.65	4.55
8	90			0.53	9.18	5.08
9	71			0.41	9.59	5.49
10	72			0.43	10.02	5.92
11	81			0.48	10.54	6.44
12	88			0.51	11.01	6.91
13	80			0.46	11.47	7.37
14	88			0.51	11.98	7.88
15	135			0.79	12.77	8.67
16	100			0.58	13.35	9.25
17	98			0.58	13.93	9.83
18	110	0.05*		0.64	14.57	10.47
19	116			0.69	15.26	11.16
20	67			0.38	15.64	11.54
21	70			0.41	16.05	11.95
22	105			0.61	16.66	12.56
23	134			0.79	17.45	13.35
24	128			0.74	18.19	14.08
25	68	0.71	4.81	0.48	18.67	13.86
26	100			0.71	19.38	14.57
27	130			0.91	20.29	15.48
28	105			0.74	21.03	16.22
29	115			0.81	21.84	17.03
30	130	0.05*		0.91	22.75	17.94

* Original figures have been coverted to metric.

APPENDIX.6: Continued

Date	Evaporation (E) From Gen Atmometer (cm)	Precipitation Record (cm)		Calculated Evapotranspiration (ER, cm)		
		Daily	Cumulative	Daily EK	Cumulative KE(Ei)	Net Deficit
July 1	28	0.46	5.27	0.20	22.95	17.68
2	42	0.03*		0.30	23.25	17.98
3	100			0.71	23.96	18.69
4	106			0.76	24.72	19.45
5	38	0.56	5.83	0.28	25.00	19.17
6	35	0.03*		0.25	25.25	19.42
7	20	0.15*		0.15	25.40	19.57
8	43			0.31	25.70	19.87
9	100	0.10*		0.71	26.41	20.58
10	55			0.38	26.79	20.96
11	152			1.09	27.88	22.05
12	145			1.04	28.92	23.09
13	95			0.69	29.61	23.78
14				0.94	30.55	24.72
15	94			0.66	31.21	25.38
16	139			0.99	32.20	26.37
17	128			0.91	33.11	27.28
18	104			0.74	33.85	28.02
19	132			0.94	34.79	28.96
20	118			0.84	35.63	29.80
21	66			0.46	36.09	30.26
22	103			0.74	36.83	31.00
23	71			0.51	37.34	31.51
24	117			0.84	38.18	32.35
25	70			0.51	38.69	32.86
26	87			0.61	39.30	33.47
27	91			0.64	39.94	34.11
28	97			0.69	40.63	34.80
29	106			0.76	41.39	35.56
30	86			0.61	42.00	36.17
31	77			0.36	42.36	36.53
Aug. 1	64			0.30	42.66	36.83
2	84			0.46	43.12	37.29
3	75			0.36	43.48	37.65
4	76			0.36	43.84	38.01
5	153			0.71	44.55	38.72
6	44	0.02*		0.20	44.75	38.92
7	37	1.30	7.13	0.18	44.93	37.80
8	30			0.13	45.06	37.93

Original figures have been converted to metric.