EFFICIENCY IN IRRIGATION WATER USE
A CASE STUDY IN THE OKANAGAN VALLEY, BRITISH COLUMBIA

by

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ABSTRACT

Increasing costs associated with the construction of new water supplies support the need to examine alternative measures for solving water supply problems in semi-arid environments. Because irrigation consumes a very large proportion of water supplies in such regions, it has the greatest potential for water saving through more efficient management. Research based on an analysis of the physical processes controlling the movement of water through the soil-plant-atmosphere system leads to the development of an irrigation control model, which could improve the productivity of irrigation water in the Okanagan Valley, B. C. Data from experiments with irrigated alfalfa conducted on the Summerland Research Station are used to test three hypotheses concerning the optimum timing and quantity of irrigation applications.

Using the Bowen Ratio approach to examine the fluxes of water and energy to and away from the alfalfa surface during different weather periods, alfalfa crop water requirements (ET) are found to be a function of the latent evaporation from Bellani plate atmometers (E), the maturity of the crop (M) and the prevailing weather type (W).

$$ET = f(E, M, W)$$

Three different weather types significantly influence the relationship between E and ET -- cool and cloudy, partly clear and hot and dry (advective) conditions. The frequency distribution of these weather types is shown to follow a first-order Markov chain model.

The optimum timing of irrigations occurs when the soil water content reaches turgor loss point (θ_K). Using the water balance model and from an examination of the alfalfa rooting distribution, θ_K is found to be a function of the level of atmospheric demand (ET) and soil water content in the upper two feet of soil (θ_U)

$$\theta_K = f(ET, \theta_U)$$

Decision rules controlling the depth of irrigation are developed from an analysis of the drainage component (D), which is related to soil water content in the lower root zone before irrigation (θ_{LI}) and the depth of irrigation (I).

$$D = f(\theta_{LI}, I)$$

The set of decision rules prescribing the timing and quantity of irrigation applications are then incorporated into a "model" irrigation treatment, which is verified to be a more efficient user of irrigation water than present methods used in the Okanagan Valley. Under the conditions of the experiment, savings of at least 20 per cent of present water applications could be achieved without reducing crop yields.

The theory of inventory control is used to construct the framework for an irrigation control model (based on the decision rules developed for the "model" treatment), that could be employed to areal units in the study area. The procedure for using Monte Carlo simulation to generate outputs of seasonal crop water use is demonstrated and consequences of these generated outputs on irrigation water allocation both on a regional scale and on the individual farm are discussed.

The final chapter examines various implications of the irrigation control model on present Provincial water policy and agricultural economic systems in the Okanagan, with the conclusion that implementation of the efficient control model would require a change in the present attitude and capabilities of the irrigator. This change could be induced by the inclusion of incentives in Provincial water policy and law, such as pricing schedules based on incremental costs, monitoring of water applications, and by a reorganization of existing farm units and irrigation districts.

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NOTATION

a	albedo
B	bulk density of soil
c_p	specific heat of air
c_v	heat capacity of soil per unit volume
D	drainage loss per unit time
D_I	drainage loss following an irrigation
D_i	daily drainage loss
E	latent evaporation (Bellani plate atmometers)
e	vapour pressure
e_s	saturation vapour pressure
F	variance ratio
G	ground heat flux
H	sensible heat flux
Ha	sum of vertical and sensible heat fluxes (advective conditions)
I	depth of irrigation
K_e	eddy diffusivity for water vapour
K_T	eddy diffusivity for heat
K_W	hydraulic conductivity of soil
L	latent heat of vapourization
LE	latent heat flux
L_s	length of plant roots per unit volume of soil
M	number of days following an irrigation
m	number of days with drainage following an irrigation
N	number of possible hours of bright sunshine
n	actual number of hours of bright sunshine
P	precipitation
Q	total amount of water removed from soil root zone by plants during unit time

q	water uptake per unit volume of soil during unit time
R, R^2	(multiple) regression correlation coefficient, and coefficient of determination
R_b	terrestial radiation
R_n	net radiation
R_s	solar radiation
R_v	surface runoff
r_i	reorder point (time to irrigate)
S	water stress day
T	potential temperature
t	unit of time
ti	irrigation interval
t_m	mean daily air temperature
U	horizontal wind speed
V	vertical flux of soil water
v(t)	control input vector
x, z	Cartesian co-ordinates, indicating horizontal and vertical directions respectively
x(t)	uncontrolled input vector
Y	loss in yield
y(t)	output vector
z	effective rooting depth
α	Stephan - Boltzman constant
β	Bowen Ratio (H/LE)
$\triangle$	increment
ρ	air density
ϕ_p, ϕ_s	water potential in plant and soil respectively
Θi	soil water content at i^{th} depth
Θ_U, Θ_L	soil water content in upper and lower root zones respectively

Θ_{UI}, Θ_{LI}	soil water content in upper and lower root zones on day of irrigation
Θ_{K}, Θ_{LK}	turgor loss point in upper and lower root zones respectively

ABBREVIATIONS

AE	actual evapotranspiration
ET	evapotranspiration
I. D.	irrigation district
DPD	diffusion pressure deficit
PSP	physiological saturation deficit
SPAS	soil-plant-atmosphere system
in., ft.	inches, feet
cm., m.	centimeters, meters
c. f. s.	cubic feet per second
c. c.	cubic centimetres
cals.	calories
ac. ft.	acre feet
g. p. m.	gallons per min.
sec., min., hr.	second, minute, hour
lbs.	pounds
ly.	langley

CHAPTER 1
INTRODUCTION

Scientific and technological advance and the changing character of water demand underline the desirability of a dynamic approach to water management. Fundamental to this dynamic approach is the idea of enlarging the range of choice in water management and use to include both constructional and managerial alternatives. However, most water resources agencies still only consider and plan constructional solutions to water problems, which, because the more readily accessible water supplies have already been utilized, results in a large social cost in terms of other resources foregone. Furthermore, proposed inter-regional diversions, which are now included in the structural approach could set in motion a number of irreversible and ultimately undesirable changes in the environment. Thus, it is now of crucial importance to explore short-term managerial (non-structural) measures, which may be practical substitutes for long-term constructional measures in order to preserve flexibility in future planning (Hirschleifer et al., 1960).

The objective of this dissertation is to examine one managerial alternative, namely, the possibility of increasing the productivity of irrigation water use in the Okanagan Valley, a semi-arid region in southern British Columbia. The more efficient the use of water (defined in terms of the amount of water required per unit of agricultural production), the smaller will be the amount of water required to produce a unit of agricultural output. In other words, under more efficient management, the existing water supply should be able to irrigate more land.

Detailed studies into the system of irrigation water management must be undertaken before the water use efficiency alternative can be implemented. Already, water productivity in certain important water uses is being improved by efficient management as demonstrated by recirculation techniques in industrial water use (Bower, 1966) and purification of municipal effluent for water quality management (Kneese and Bower, 1968). Although some important progress has been made in recent years in the development of more efficient management of irrigation water supplies in Canada and elsewhere, irrigation, which accounts for more than 90 per cent of the gross abstraction of water resources in Western North America, still remains the most inefficient use of water supplies. Thus far, few water resources agencies in Canada have shown willingness to incorporate the efficiency in use alternative in their decision-making matrix. Three reasons are suggested for their failure to examine this alternative more thoroughly.

Firstly, an irrigation control model prescribing the optimum application of irrigation water has yet to be devised, since little is known about the real values of incremental quantities of irrigation water as they vary in both time and place during the irrigation season. The economic models presently used only consider a fixed annual application of irrigation water (Moore, 1961), yet physical models describing crop water use demonstrate that this demand is a stochastic process dependent upon soil, plant and atmospheric variables (Baier, 1967b; Penman, 1963; Veihmeyer, 1964).

Secondly, attempts to apply the physical models mentioned above in the field usually resort to a large amount of empiricism, either because the necessary climatic, edaphic and plant data are not available, or because the investigators have failed to grasp a complete understanding of the soil-plant-atmosphere system. Furthermore, because most of the research has been undertaken by specialists such as plant or soil scientists, there has been little attempt to integrate these findings into a regional context. Therefore, there is both an academic and practical need for the development of a geographical methodology that will improve the efficiency of water use in irrigation and that can be included in the decision-making framework of a water resources manager.[1]

Thirdly, because most water resources planners in Canada have an engineering training, they are biased towards the constructional

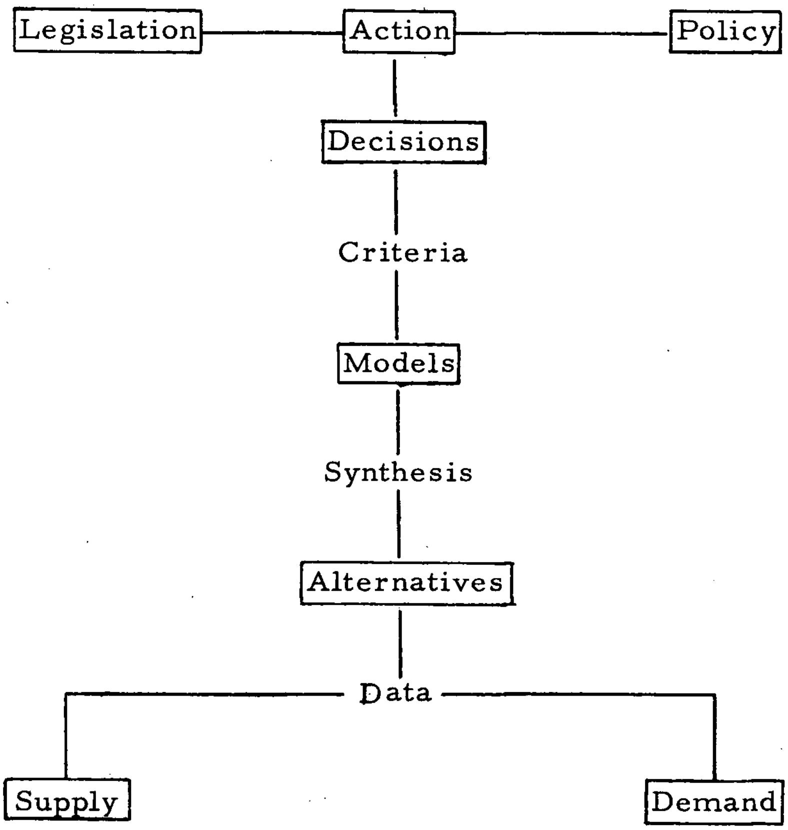
1 This term refers to a person or agency which is responsible for the development and allocation of regional water resources.

approach and are therefore unaccustomed to thinking in terms of non-structural (managerial) alternatives for solving water supply problems. Yet, the real cost of developing new water supplies by constructional alternatives has tended to increase through time, because of the large size of projects now necessary to satisfy the multiple demands of modern society and the increasing inaccessibility of untapped water resources. Thus, reassessment of the present attitudes of planners would seem desirable so that both structural and non-structural alternatives are included in the range of choice of possible policy decisions (National Academy of Sciences, 1968).

It is recognized that the final policy decision concerning the future development of the Okanagan water resources should be made from the examination of a wide array of constructional and non-structural measures according to some economic rational criteria, such as benefit-cost analysis (Prest and Turvey, 1965; Sewell et. al., 1961). Hopefully, this study will make water resources policy makers more aware of the efficiency in use approach so that it may be included amongst the various possible alternatives for solving the region's water supply problems.

Thus, the dissertation is conceived as part of the systems approach to regional water resources development (figure 1.1). Basically, this approach analyses the balance between supply and demand for water resources within a region and then proposes several alternative solutions to equate supply with demand (Hufschmidt, 1965). Each of these policy alternatives are synthesized as models (Maass et al., 1962; Dorfman, 1965), which are then assessed according to decision criteria established by the decision-making agencies. The more alternatives that are considered, the broader will be the range of choice available to the decision maker and the better will be his final decision on how to develop and manage regional water resources (National Academy of Sciences, 1966).

Figure 1.1 The Systems Approach to Water Resources Management



Statement of the Problem

Objectives

The principal objective of the dissertation is to design an irrigation control model for improving the productivity of water used in irrigated agriculture. More specifically, the research is orientated towards determining decision rules that will control the timing and amount of water to be applied at each irrigation. The details of the above objective are given below:

(1) To identify and assess the principal physical processes controlling the movement of water within the soil-plant-atmosphere system (S. P. A. S.)

(2) To identify and control the amount of water that is not directly or indirectly utilized by crops.

(3) To construct an irrigation control model based on the above physical understanding of the S.P.A.S., which will increase the productivity of irrigation water with minimum annual irrigation costs.

The main emphasis in the research necessary to develop this irrigation model is directed towards explaining the physical inter-relationships between the water lost and water supplied to the S.P.A.S., the pertinent economic conditions and constraints being assumed. However, it will be noted that the model has many economic implications. It is hoped that an understanding of the model will enable the water resources manager to maximize the productivity of irrigation water supplies, i.e. to supply the minimum amount of water necessary to maintain optimum crop production with minimum total annual irrigation costs.

Scope of the Dissertation

Within the frame of reference stated above, the dissertation examines a number of techniques which will improve the productivity of irrigation water use by controlling the timing and quantity of irrigation applications. To be applicable on the regional scale, the proposed irrigation control model should take into account the spatial and temporal variations in the S.P.A.S. within the study area. Because of the multiplicity of exogenous variables and the complexity of the inter-relationships acting within the operating characteristics of the model, testing the model on a regional scale would be a monumental task beyond the scope of this research. Consequently, the actual testing of a series of hypotheses concerning the movement of water within the S.P.A.S. is restricted to data obtained from experimental plots, and the results are used to provide the framework for a more general irrigation control model.

As a further control, the soil and plant factors in the experiments are standardized by examining the water balance of a specific crop (alfalfa) on a homogenous soil (silt loam) on a number of experimental plots on the Canada Department of Agriculture Research Station at Summerland. A randomized experimental plot design is established consisting of three irrigation treatments and four replications. In sum, the physical model used to test the set of hypotheses contains a number of controlled status variables (crop type, rooting system, soil type), one controlled exogenous variable (irrigation application) and a number of uncontrolled exogenous variables (atmospheric energy demand, rainfall). Although the quantitative effects of the spatial variation in the status variables will not be specifically tested, the areal variation in some of the climatic parameters controlling atmospheric energy demand and rainfall in the study area has already been analyzed (O'Riordan, 1966) and can be incorporated into a decision-theory model to find the optimum irrigation schedule in various parts of the Okanagan.

Normally, the performance of a control model is tested by comparing the model's output (amount of irrigation water used by crops) with measured outputs, according to a stipulated performance criterion (Sworder, 1966). Because there are no existing data in the Okanagan Valley which specify the quantity of irrigation water used each year, the model cannot be solved analytically at present. Thus, the dissertation approaches the problem from a different angle, by determining an efficient irrigation application schedule through experimentally formulating a set of decision rules controlling the timing and quantity of irrigation applications, and thereby ensuring that the model's output approaches the optimum.

Choice of Study Area

There are three reasons why the Okanagan Valley was chosen as the research area. Firstly, it is a semi-arid region in which there is an increasing demand for a limited stored water supply, almost all of which is used by irrigation (North and South Okanagan Reports, 1966). To meet this crisis, the Water Resources Investigation Branch of the Provincial Government's Water Resources Service has produced a report (1966), describing an engineering project to increase the existing water supply. Not only does this report fail to justify the project in economic terms, but it also fails to consider possible alternative methods for increasing the water supply. This deficiency is due to the fact that technical and economic information that might increase the present productivity of water used in agriculture is not available.

Secondly, the original distribution network of canals and flumes which led stored water to the farms is or will be replaced by a rehabilitated system. The cost of renovation will more than double the present tax paid by the irrigation farmer, who will therefore be more willing to accept methods for conserving water and increasing his output.

Thirdly, the irrigation scheduling studies undertaken by Wilcox and others (Wilcox, 1962; Wilcox and Korven, 1964) applied empirical coefficients to atmometer readings to obtain estimates of crop water use. While this approach is a considerable improvement on the rule-of-thumb scheduling by the farmer, it lacks a sound physical framework and fails to take into account the stochastic nature of the climate and soil-plant water relationships. Thus, much of the physical research in this dissertation is directed towards improving the operational characteristics of the Wilcox model through a more complete analysis of the movement of water within the S.P.A.S.

Outline of the Dissertation

This study examines procedures for improving the scheduling of irrigation in the Okanagan Valley. Chapter 2 provides a description of the present irrigation water supply system in the Okanagan Valley. The chapter also contains a discussion of the current federal and Provincial approaches to improving the efficiency of irrigation water use, both by structural and managerial measures, and indicates how the system still remains suboptimal. Chapters 3 to 5 outline and test various hypotheses that form the basis of the two decision rules controlling the efficient application of water, namely, when to irrigate and how much water to apply. Chapter 3 examines the demand for water in the S.P.A.S., noting the importance of advection of warm air over irrigated alfalfa in middle and late summer. Chapter 4 relates this demand function with the supply function to determine the first decision rule controlling the timing of irrigations. The amount to apply at each irrigation is specified in Chapter 5 after a detailed examination of the drainage loss function. The two decision rules are then combined into an irrigation scheduling model, and the results of this irrigation treatment in terms of water used and alfalfa crop yield are compared with two other irrigation treatments. Using the theory of inventory control as a framework, Chapter 6 constructs an irrigation control model, which, because it employs the two controls already described, should maximize the productivity of irrigation water use. Finally, Chapter 7 discusses implications of the control model on policy formulation.

CHAPTER 2

IRRIGATION WATER MANAGEMENT IN THE OKANAGAN VALLEY

The Okanagan Valley is a broad, irregular rift-valley, extending from latitude 49° north to latitude 50° 43' north with an average longitude of 119° 30' west (figure 2. 1). The study area is confined to the valley bottom and adjacent bench lands, extending approximately 120 miles in length and varying between two and six miles in width at its southern end to 12 miles in width at its northern end near Armstrong.

The Pleistocene glaciation left the valley bottom U-shaped, parts of which are terraced with glacio-lacustrine clays or alluvial silts and fine sands, while other portions are occupied by lakes (Kelley and Spilsbury, 1949). At several points tributary streams have carved channels through the river and glacial lake terraces and spread their fans out onto the valley floor. A large proportion of the presently irrigated acreage lies on these fertile colluvial deposits.

Climatically, the region lies in the "rain shadow" of the Coast Mountains (Kerr, 1950; Chapman, 1952). The prevailing westerly air flow is modified in two ways as it crosses this mountain barrier. Firstly, much of its moisture is precipitated on the western flank of the Coast Mountains, and, secondly, while descending their leeward slopes, the air masses are warmed adiabatically and consequently assume more stable air mass characteristics. Both of the orographic modifications favour a semi-arid climate in the region, since the warmer and drier air masses promote higher rates of evaporation, while the occurrence of precipitation is reduced.

The annual precipitation ranges from an average of 10 inches in the southern part of the Valley to 15 inches in the north, though most of the region experiences a coefficient of variation of 25 to 30 per cent (B. C. Department of Agriculture, 1967c). The higher elevations of the watershed receive over 20 inches annually, a large proportion of which falls as snow during the winter months and serves to supply most of the available water for irrigation.

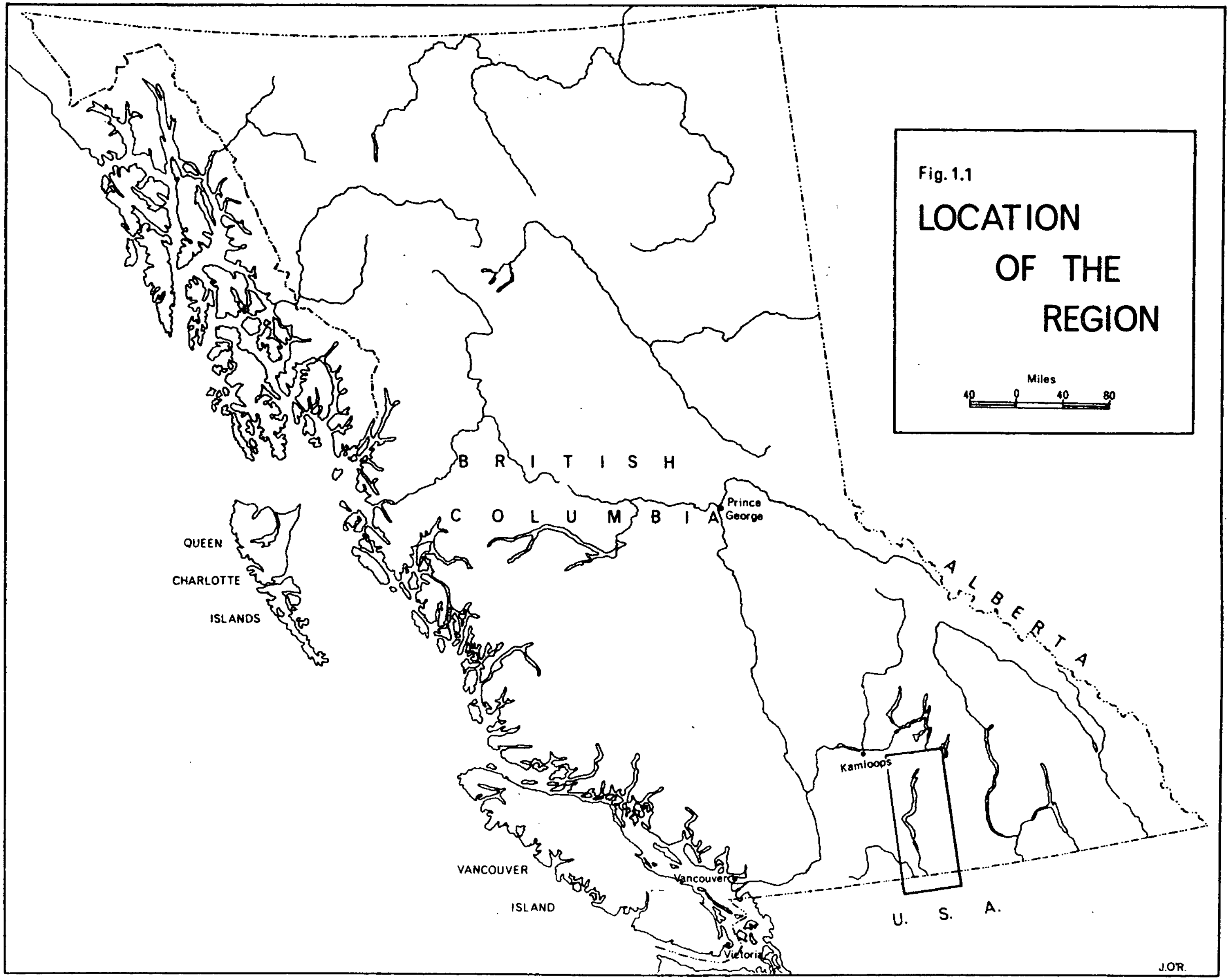


Fig. 1.1 LOCATION OF THE REGION

Temperatures also reflect the importance of terrain. Generally, average temperatures drop with increasing altitude, thus the sheltered valley floor experiences average summer temperatures ranging between 65 and 75°F, while the exposed uplands are 10 to 15° cooler. Several other factors, such as proximity to large water bodies and the steepness and aspect of slope, also influence the temperature patterns.

Irrigation Water Supply and Demand

The Supply of Irrigation Water

All current irrigation water requirements are met by surface water supplies. Annual runoff from the tributary watersheds into Okanagan Lake, discounting diversions and storages for irrigation purposes averages 360,000 acre feet, with a range from 80,000 to 630,000 (figure 2.2). As these figures represent estimates of the amount of water flowing into Okanagan Lake during the spring snow-melt season from April 1 to July 31, they do not include losses due to evaporation from the lake surface, or a major fraction of the Okanagan Lake tributary run-off, which is stored in catchment reservoirs above the lake or diverted directly onto irrigated farms (figure 2.3).

The Okanagan Lake surface covers 84,200 acres. The lake level is controlled by a concrete dam at the southern outlet near Penticton over a range of 4 feet or approximately 340,000 acre feet (Raudsepp, 1967). The lake level can be lowered an extra foot in an emergency to supply a total storage capacity of 421,000 acre feet. Skaha Lake is likewise regulated by a dam at Okanagan Falls over a 2 foot range to produce a controlled storage capacity of 9420 acre feet. At present both of these storage supplies are mainly used for flood control and navigation purposes and domestic and municipal use (DeBeck, 1967), very little being directly used for irrigation because of the large cost of pumping water onto the irrigated farm lands.

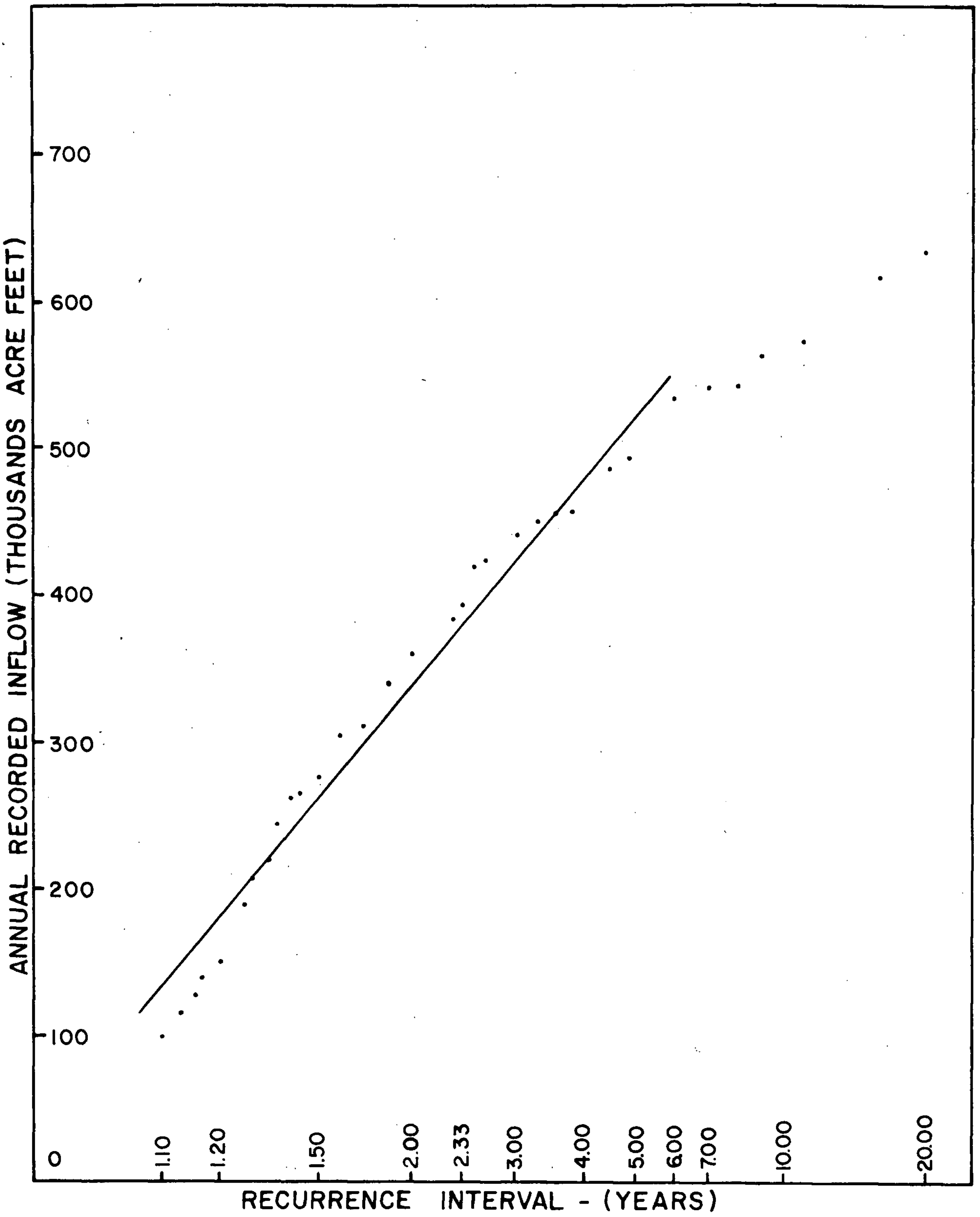
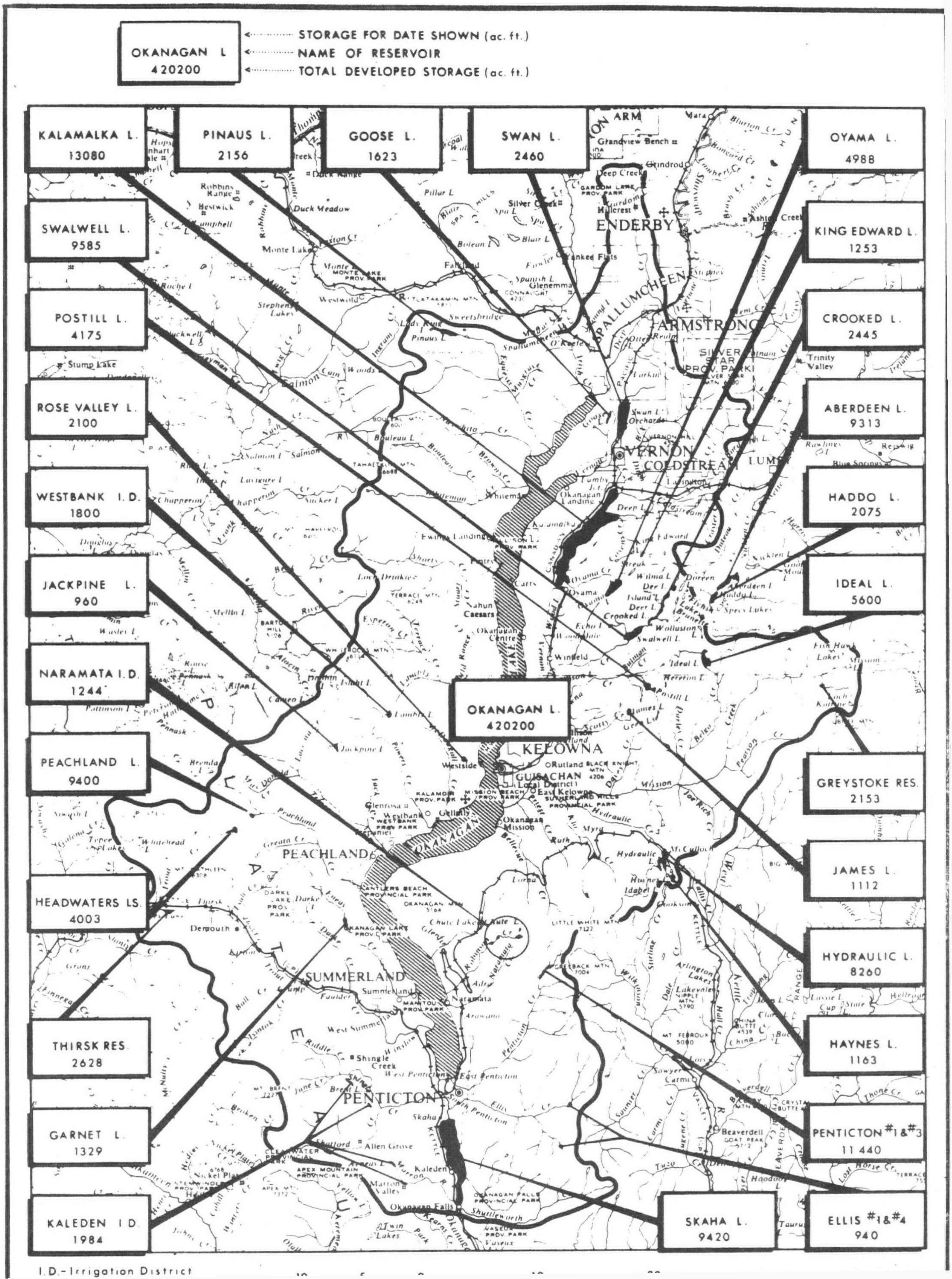


Figure 2.2 Annual Inflow Frequency Curve for Okanagan Lake, 1922-1963.
(Reproduced with kind permission of B. C. Water Investigations Branch, Victoria, B. C.)

Figure 2.3 Selected storages on Okanagan Lake Tributary Streams. (Reproduced with kind permission of B. C. Water Investigations Branch, Victoria, B. C.)



The Demand for Irrigation Water

The presently irrigated area within the region totals approximately 60,000 acres[1], most of which lies on a series of lacustrine benches surrounding Okanagan Lake and Okanagan River (figure 2.4). Total annual gross irrigation diversion requirements are estimated to be approximately 190,000 acre feet. In comparison, the total annual domestic, municipal and industrial water demand is approximately 44,500 acre feet, giving a total annual water demand of some 234,500 acre feet. Thus, irrigation water requirements consume 81% of the total gross abstraction of water resources in the Okanagan Valley (table 2.1).

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1 A large proportion of this irrigated acreage is devoted to fruit growing, mainly apples in the northern part of the Valley and soft fruits and grapes in addition to apples in the south (McPhee, 1958). The irrigated alfalfa acreage occupies a relatively small part of the irrigated acreage, but plays a vital role in the development of important beef production in the Valley. Since most of the natural range land is at present being used to capacity, further development of the beef cattle industry will be dependent upon irrigated alfalfa production to provide both summer and winter feed.

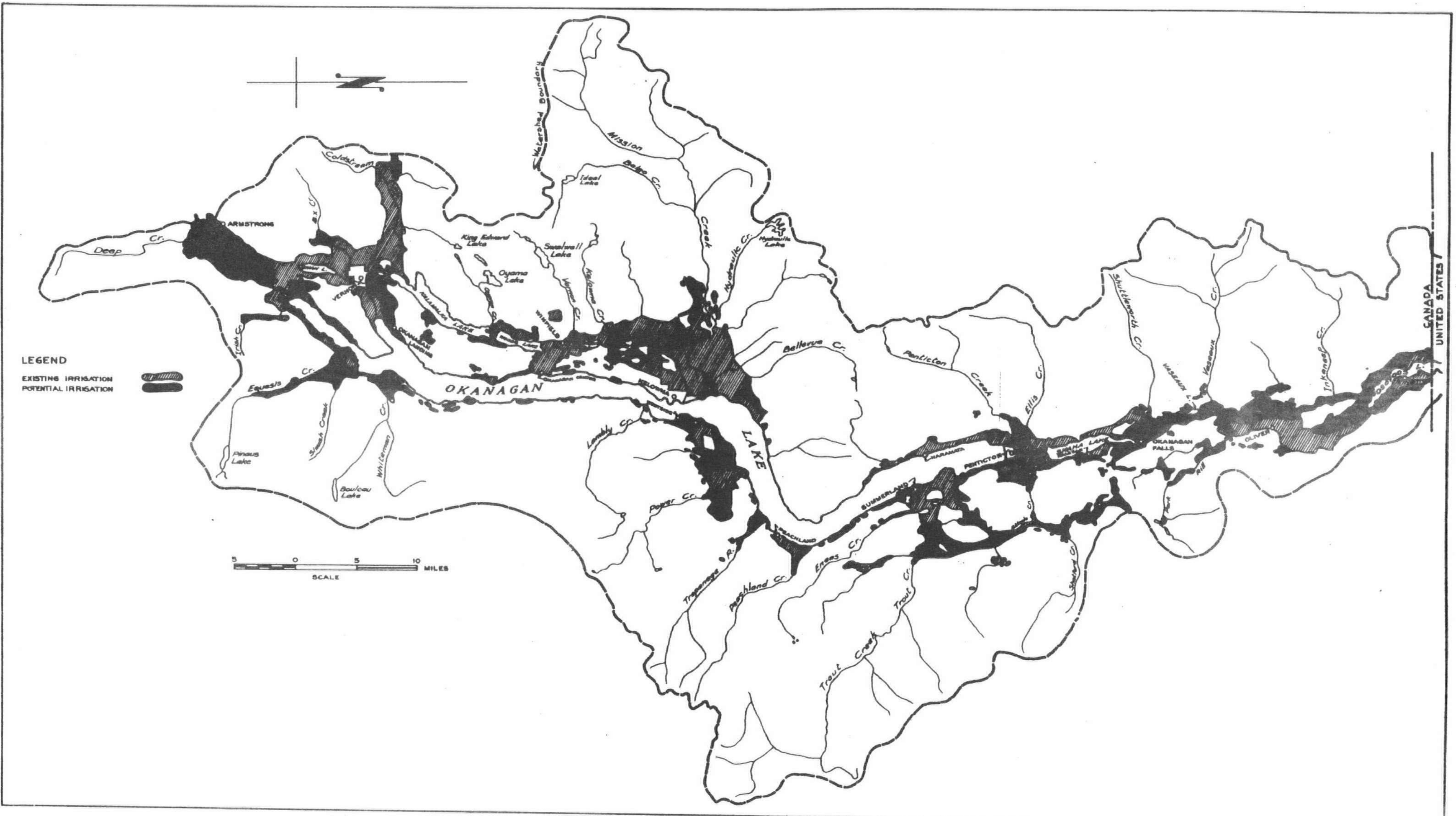

Figure 2.4 Irrigated Acreage in the Okanagan Watershed
(Source: Water Resources of the Columbia River Basin, Appendix IV, 1955)

TABLE 2.1

PRESENT USE OF OKANAGAN WATER SUPPLY

Source of Supply	Irrigation			Domestic, Industrial Municipal	
	Acreage	Div. Duty of water[1] in inches	Gross water need; acre ft.	Population	Gross water need; acre ft.
Okanagan River	9,935	4.55	45,204		
Okanagan Lake	592	2.97	1,758	65,000	27,300
Okanagan River Tributaries	1,567	4.55	7,130		
Okanagan Lake Tributaries	43,701	2.97	129,792	15,000	13,200
North Okanagan	4,277	1.40	5,988	4,000	4,150
Totals	60,072		189,872	84,000	44,650

Source: Shuswap River - Okanagan Lake Water Supply Canal Report (1966). Table 3:1.

The above statistics do not provide a comprehensive representation of the relationship between supply and demand throughout the region. The average net inflow of 360,000 acre feet is, in fact, only the total available irrigation water supply for the area south of Penticton, totalling 12,000 acres, or 20%, of the entire irrigated acreage. To evaluate the patterns of supply and demand in the remainder of the watershed, it is necessary to examine in detail the present system of irrigation water management in the Okanagan.

1 Duty of Water: The above water requirements have been estimated by using farm irrigation duties of water of 3.50, 2.25 and 1.25 acre feet per acre for the Okanagan River (area south of Penticton), Okanagan Lake and North Okanagan (area north of Vernon) regions respectively. To obtain the diversion duty of water, the farm duties of water have been increased by a variable amount to account for distribution losses. These duties are recommended in the B. C. Department of Agriculture Reclamation Briefs and B. C. Water Resources Service Reports.

Irrigation Water Management Programme

A brief review of the history of the present system of irrigation water management in the Okanagan shows that there has been a gradual increase in the level of governmental participation as the costs for providing sufficient water supplies to serve the growing irrigated acreage have multiplied[1]. The first irrigation farms were built and financed by private citizens and companies at the turn of the century. Due to the irregular topography, these schemes amounted to no more than a few thousand acres and used crude earth ditches and leaking wooden flumes to direct water from tributary streams onto the land.

The First World War shattered the dreams of these early speculative ventures, and forced most of them out of business. Consequently, the Provincial Government initiated a Conservation Fund in 1918 (Morton and May, 1965) to make interest-free loans to areas which formed public irrigation districts for the renewal of the old irrigation systems. There are at present 24 such irrigation districts in operation, managing a total irrigated area of some 39,000 acres, or 65 per cent of the total irrigated area. They range in size from 8,200 acres in the Vernon Irrigation District to 180 acres in the Black Sage Irrigation District near Osoyoos. The remaining acreage is managed by private individuals or groups, who have constructed their own irrigation works.

As the irrigation districts had access to both Provincial funds and engineering experience, they soon began to develop a more elaborate water supply system than the old diversion flumes built by the pioneers. The annual hydrograph for BX Creek[2] near Vernon (figure 2.5) indicates that the

1 This is only partly a response to the increasing cost of supplying water for irrigation. It is also due to a combination of social, political and economic forces that seem to be stimulating large-scale development projects in the Province, e.g. the enormous programme of hydro-electric development (Fox, 1966b).

2 This example was specifically chosen, since the gauging station lies above all diversion control structures.

only significant period of run-off occurs during the snow-melt months of April, May and June. Consequently, most of the irrigation districts have constructed a series of catchment reservoirs or they have controlled the lake levels in the tributary valleys to provide a more dependable supply of water in the later summer months when crop water demand is at a maximum.

There are at present 89 control structures on the tributary watershed of Okanagan Lake, serving the irrigated bench lands between Penticton and Vernon, and 29 reservoirs on tributaries to the Okanagan River serving the area to the south of Penticton. Their combined developed storage totals 98,719 acre feet, ranging from 9700 acre feet in Aberdeen Lake near Vernon to many small structures containing less than 100 acre feet. Many of these reservoirs fill to capacity by the end of the snow-melt run-off season (table 2.2), and are gradually drawn down during the remainder of the irrigation season in preparation for next year's run-off.

The developed storage capacity is sufficient to supply the annual irrigation demand for most of the irrigation districts, though a few supplement this source with direct diversion control structures on the tributary streams during the freshet season (table 2.3). Since these diversion data are not available and the stipulated duty of water does not represent the actual use of water by irrigators with any degree of accuracy, it is difficult to assess the present patterns of supply and demand for each irrigation district. However, only Naramata Irrigation District experienced a shortage during the unusually hot summer of 1967, which suggests that the present system can adequately supply the needs of the presently irrigated acreage in most irrigation districts.

Although there is now a well developed system of supply reservoirs, until recently many irrigation districts were still using the original metal and wooden flumes to distribute the water from the reservoirs into the irrigated fields. Since many of these distribution systems had not been maintained, a large proportion of the irrigation water is lost through leakage and evaporation or contaminated by algae. To reduce this loss,

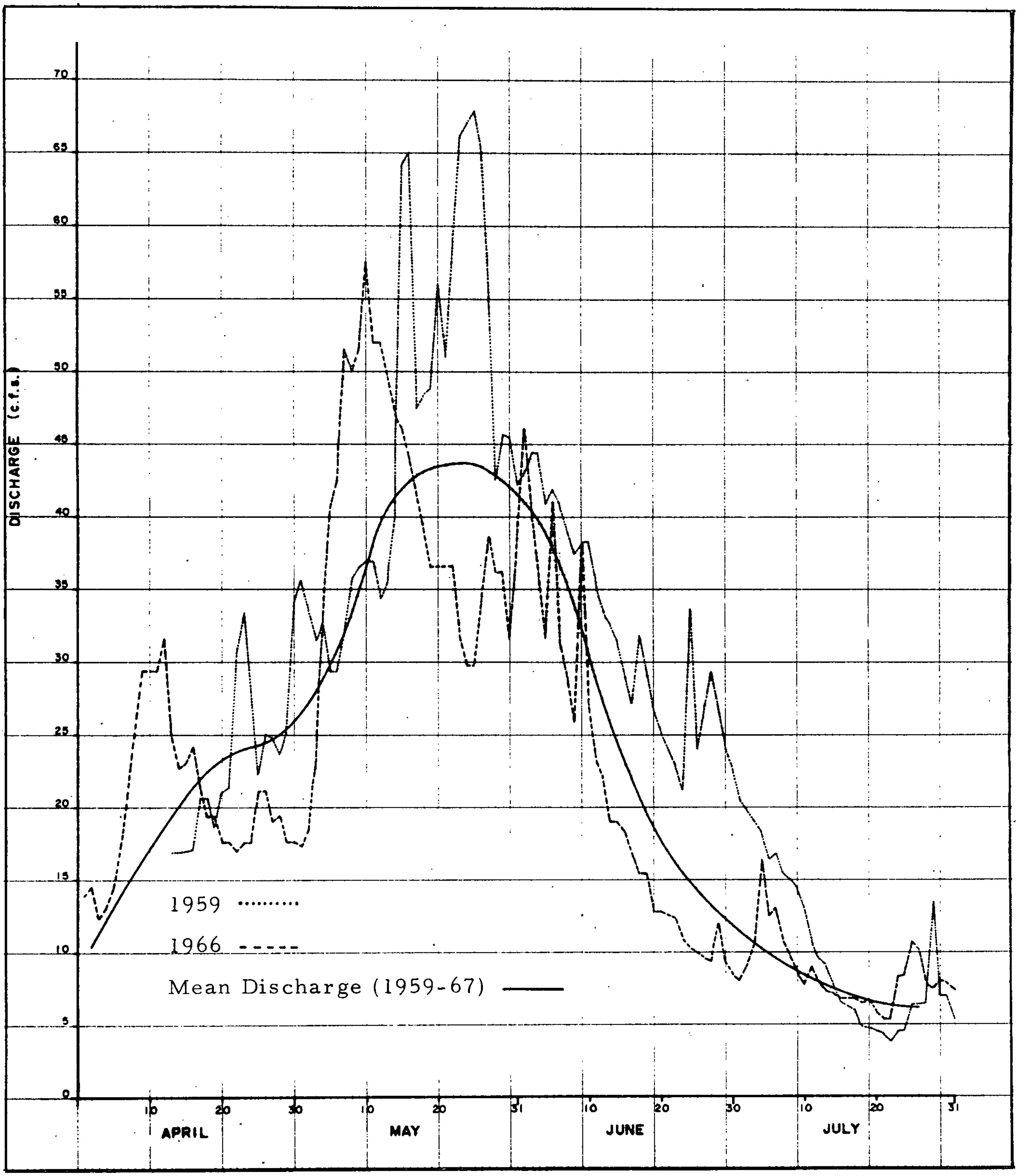

Figure 2.5 Annual Hydrograph for BX Creek near Vernon, 1959-1967.
(Reproduced with kind permission of B. C. Water Investigations Branch, Victoria, B. C.

TABLE 2.2

STORAGE IN SELECTED OKANAGAN LAKE TRIBUTARY RESERVOIRS ON JUNE 1ST IN ACRE FEET

Reservoir	Capacity	1963	1964	1965	1966	1967	1968
Kalamalka	13,080	13,080	10,464	13,080	11,080	11,725	12,626
Swalnell	9,585	6,150	9,110	7,240	8,850	9,585	7,946
Posthill	4,175	3,020	2,743	4,175	4,175	4,175	3,843
Rose Valley	2,100	2,100	1,900	1,790	1,520	1,490	1,820
Westbank	1,505	-	-	-	-	950	1,505
Jack Pine	960	-	-	-	-	960	960
Naramata	950	940	800	702	665	590	950
Headwaters	4,003	2,600	2,968	2,840	2,400	3,000	3,900
Thirsk	2,628	2,628	812	2,628	2,628	2,628	2,628
Garnet	1,329	1,200	1,200	1,329	1,235	1,000	1,329
Penticton	2,000	1,695	500	215	1,500	185	1,258
Haynes	1,163	1,022	1,100	1,080	815	1,100	1,163
Hydraulic	8,260	8,131	7,430	7,340	8,200	7,800	8,043
James	1,112	-	-	-	1,112	800	1,000
Greystoke	2,153	-	1,057	745	1,125	250	745
Ideal	5,600	5,480	4,686	5,600	5,600	5,600	5,600
Haddo	2,075	2,090	1,960	1,995	2,075	1,710	2,075
Aberdeen	9,313	6,700	7,838	5,761	9,313	8,050	3,733
Crooked	2,445	2,500	2,445	2,445	2,445	2,445	2,445
King Edward	1,253	-	-	-	1,000	1,050	1,172
Oyama	3,717	3,200	3,200	3,717	3,717	3,200	3,717
Swan	2,460	1,195	1,308	1,308	2,725	1,760	2,357
Goose	1,623	1,105	1,105	1,014	1,060	890	574
Pinaus	2,156	1,500	1,200	2,000	2,000	2,000	2,000
Storage to Date	86,503	66,336	63,826	67,004	75,240	72,943	73,388
% Capacity		83.1	78.1	82.1	89.5	84.3	84.8

Source: B. C. Water Resources Service, Hydrology Division.

TABLE 2.3

WATER STORAGE AND WATER REQUIREMENTS OF IRRIGATION DISTRICTS IN THE OKANAGAN WATERSHED

Irrigation District	Dev. Storage Acre Feet	Irrigated Acreage	Duty of Water Feet	Requirements Acre Ft.	Per Cent Dev. Storage
Vernon	15,034	8,200	1.50	12,300	122.2
Winfield - Okanagan Centre	11,774	1,900	1.50	2,850	413.1
Oyama	1,930	292	1.75	511	377.6
Woods Lake	3,717	870	2.50	2,175	170.8
Black Mountain	7,753	3,300	2.50	8,250	93.9
Ellison-Glenmore	4,575	2,900	2.50	7,250	63.1
S. E. Kelowna	11,288	2,600	2.50	6,500	173.6
Scotty Creek	812	750	2.50	1,875	43.3
Okanagan Mission OK. Lake		350	2.50	875	-
Lakeview	2,100	1,125	2.50	2,812	74.6
Westbank	2,376	828	2.50	2,070	114.7
Peachland	1,042	3,192	2.50	7,980	13.2
Summerland	9,206	3,340	2.50	8,350	110.2
Penticton	3,310	1,900	2.50	5,225	63.3
Naramata	1,403	915	2.75	2,516	55.7
Kaleden	2,030	643	2.75	1,929	105.2
Okanagan Falls Skaha Lake		150	3.00	450	-
S.O.L.I.D. Okanagan River		4,800	3.00	16,800	-
Osoyoos Osoyoos Lake		203	3.50	711	-
Black Sage Osoyoos Lake		180	3.50	630	-
West Bench Okanagan River		305	3.50	1,068	-
Totals	78,350	38,743		93,034	

Source: B. C. Department of Lands, Forests and Water Resources, Water Investigations Branch, Irrigation District Rehabilitation Reports.

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there is at present in progress a complete rehabilitation of all existing supply systems in all the irrigation districts in the Valley carried out in accordance with the Agricultural Rehabilitation and Development Act (A.R.D.A.) provisions. The total cost of $21 million[1] (or $350 per irrigated acre) is being shared equally by the federal and Provincial governments and the irrigation districts. This face-lift, to be completed by 1970, includes the construction of underground pressurized pipes, which will replace the old open-flume systems, rebuilding and heightening reservoir dams and the installation of pumping equipment. Not only will the conveyance losses be reduced by an estimated 30 per cent[2], but the system will also be able to serve domestic water needs in addition to irrigation water requirements within the irrigation district.

Despite the considerable capital cost of reconstructing the irrigation supply systems, the Provincial government believe that any future expansion of irrigated acreage in the Valley will require additional supplies of water. Since almost all the potential storage capacity of the tributary watersheds has already been developed, the Provincial water engineers, in response to a request from several irrigation districts, are seeking supplies from outside the regional watershed. In 1966, the Water Resources Service undertook an engineering and feasibility study of a proposed Shuswap River-Okanagan Lake diversion canal, (B. C. Water Resources Investigations Branch, 1966) which would divert water from the Shuswap River in the Thompson watershed into the Okanagan Lake in the vicinity of Vernon. The cost of this scheme is estimated to be between 12 and 16 million dollars. At the time of writing, no firm decision has been made concerning the implementation of this project, but it has generated considerable discussion throughout the province.

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1 Personal communication with Mr. V. Raudsepp, Chief Engineer, B. C. Water Resources Service.

2 Personal Communication with Mr. R. J. Talbot, Kelowna District Engineer

However, much of this discussion has centred around such aspects of the scheme as hydrology, ecology, pollution and administration. Few have questioned whether there is a real need at this time to add 12 - 16 million dollars to the present considerable capital costs of supplying water to the farmer. Already the cost of supplying water for irrigation purposes has increased out of all proportion to the economic returns from agricultural production, with the result that the irrigation districts are no longer self-supporting but now rely on federal and Provincial capital.

The present planning approach of the water resources decision-makers in British Columbia epitomizes the criticisms outlined in Chapter 1. Until now, the Provincial Water Resources Service has developed a formal, administrative approach for solving the Okanagan Valley's irrigation water supply problems, based on constructional measures at a large and increasing cost. It is now time that the decision-makers include the water use efficiency alternative in their decision matrix.

How efficient are the present irrigation water use systems in the Okanagan? What is being done to improve them? The answers to these questions require an examination of the conservation aspects of the present irrigation water management programme in the Valley.

The Control of Inefficient Water Use

It is difficult to assess the present efficiency of irrigation water use in the region, since there is no record of the seasonal amounts of water used by the irrigation farmers except in the Vernon I. D., where the water supply is metered. However, there is little doubt that a considerable amount of over-irrigation occurs throughout the Valley, as indicated by soil erosion, nutrient leaching and drainage problems. In 1966, S.O.L.I.D.[1] spent $26,000 on a drainage programme as a result of over-irrigation. Furthermore, Wilcox has estimated that 52 per cent of the water applied by the farmer is not utilized by the crops, but drains through the soil profile and

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1 Southern Okanagan Lands Irrigation District.

re-enters the ground-water system (B. C. Water Resources Investigation Branch, 1966, Appendix 4). Although some drainage is necessary for soil leaching purposes, much of the present return flow is simply the result of inefficient irrigation scheduling.

The three management agencies at the federal, Provincial and local levels of government have made some attempts to control this waste. Their efforts can be divided into two categories (a) structural and (b) non-structural.

Structural Controls In line with the improvement of the supply systems that lead water from the reservoirs to the irrigation field, there has been a gradual modernization in the techniques of irrigation application on the farm itself. At the end of the Second World War, furrow irrigation methods were universal in the Valley, but in 1944, improvements in the sprinkler irrigation equipment enabled this more efficient irrigation system to become available to most farmers, with the result that by 1965 over 90% of all irrigated land in the Okanagan used sprinkler irrigation techniques. Wilcox (1955) estimated that growers who had changed from furrow to sprinkler irrigation systems were saving as much as 40 per cent of their water.

The increased water pressures obtained by using the sprinkler system provided some irrigators with more water than others, who operated further down the distribution system. Consequently, there were water shortages, lack of adequate water pressures and low pump capacities in some parts of an irrigation district, which forced the district managers to tighten their regulations on water use. Firstly, they controlled the flow capacity of the distribution system so that most irrigators received the same supply of water. This capacity varies from district to district according to the prevailing soil and climatic conditions, ranging from two to six Imperial gallons per minute per acre. Secondly, they limited the number of sprinkler heads per acre and controlled their nozzle size according to the stipulated flow capacity. Thirdly, they requested that flow control valves be placed under every sprinkler head to compensate for the variation in water pressure which occurs in a gravity-flow system. Each of these conservation measures restricts the amount of water a farmer can apply during each irrigation but they do not restrict his frequency of irrigation. This problem has been tackled by the Provincial and federal Governments.

Non-Structural Controls The two basic questions facing the irrigation manager are how much water do crops require throughout the irrigation season and how often should they be irrigated. Most of the research into these two decision criteria has been undertaken by Dr. J. C. Wilcox at the federal Government's Research Station at Summerland.

Wilcox uses empirical techniques to obtain his estimates of seasonal crop water requirements. He discovered that there was a statistically significant correlation between evaporation from Bellani plate atmometers and evapotranspiration (ET) from orchards and hay crops (Korven and Wilcox, 1965). Thus, he used a simple conversion factor to transform latent evaporation data into ET from cropped surfaces. He also recognized the fact that the amount of irrigation water required by the farmer would be greater than this theoretical crop water requirement due to surface evaporation, deep percolation and application losses and developed an I/E ratio (Wilcox, 1963), which is the ratio of the irrigation requirement (I) to the theoretical crop water demand (E). Generally speaking, the more frequent the irrigations, the higher is the I/E ratio. He further developed the concept of the "safe interval" (Wilcox, 1960b) which, like the I/E ratio, depends upon the soil and climatic conditions. It represents the length of time in days between irrigations during the hottest part of the summer and is found by dividing the readily available soil water content (estimated at 50 per cent of the total available soil water supply) by the maximum rates of ET experienced in a district. He uses this parameter to estimate peak flow requirements for irrigating various soil types in the Valley (table 2.4) and to estimate the annual irrigation requirements (table 2.5).

TABLE 2.4

PEAK FLOW REQUIREMENTS OF WATER FOR SPRINKLER IRRIGATION OF MATURE ORCHARDS IN THE OKANAGAN VALLEY

Soil Texture	Safe Interval	Flow per acre Imp. gallons	Amount per Irrigation	Amount per Month
	Days	g.p.m.	Inches	Inches
Sand, gravel	5	5.67	1.80	10.79
Loamy sand	7	5.09	2.26	9.68
Sandy loam	10	4.49	2.85	8.54
Sandy loam	15	3.79	3.60	7.21
Loam	20	3.30	4.18	6.27
Silt loam	25	2.90	4.60	5.51
Clay loam, clay	30	2.60	4.94	4.94

Source: Proceeding of B. C. Reclamation Committee, Brief 38, Kelowna, B. C., (1953).

TABLE 2.5

ESTIMATES OF MAXIMUM ANNUAL IRRIGATION WATER REQUIREMENTS FOR VARIOUS PARTS OF THE OKANAGAN VALLEY[1]

District	Length of Safe Interval			
	5 days	10 days	20 days	30 days
Osoyoos	49.8	39.0	28.6	22.2
Oliver	44.6	34.5	24.7	18.8
Summerland	43.4	34.1	25.0	20.0
E. Kelowna	42.0	32.9	23.9	18.4
Vernon	33.9	25.3	16.9	12.0
Armstrong	29.2	21.7	13.9	10.0

Source: J. C. Wilcox, "Evaporimeter records in Southern B. C.", Unpublished manuscript (1963).

1 The above figures are only rough estimates of the actual irrigation requirements, since they are based on only 4 years of record. They are presently being revised in several districts as a result of the extremely hot summer of 1967.

The important task of disseminating this information among the irrigation district managers is undertaken by the Provincial Government. The B. C. Reclamation Committee, which consists of members of both the Department of Agriculture and Lands, Forests and Water Resources, as well as local representatives, estimates the seasonal irrigation water requirements for each irrigation district from the basis of a detailed soil survey. More specific information on the irrigation equipment design and standards for all parts of the farmer's irrigation system have been published by the B. C. Department of Agriculture (1967a, 1967b).

Having calculated how much water a grower should require during the irrigation season, Wilcox has subsequently attempted to estimate the frequency of irrigations in various parts of the Valley. He devised a simple scheduling model (Wilcox and Korven, 1964) based on the "balance sheet" technique, in which credits are represented by irrigation applications and natural rainfall (Wilcox 1967b) and the debits by the daily ET rates estimated from Bellani plate atmometers. The irrigator must determine how much available water his soil can hold throughout the effective rooting depth of the crop, and is asked to resume irrigations only when the balance sheet indicates that 50 per cent of the available soil water has been removed.

Assessment of the Management Programme

There is no doubt that engineers have constructed a very efficient system for storing irrigation water and distributing it to the head-gate of the farmer. In theory, there would also seem to be an effective control on the use of this water once it has been received by the farmer, but in practice there is still a considerable wastage.

This inefficiency is a result of two factors. Firstly, there is no economic incentive to encourage the irrigator to conserve water. Each farmer in an irrigation district pays a land tax[1] to cover the annual

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1 The average tax is at present $25 per acre per annum. This is likely to increase considerably as a result of the A. R. D. A. rehabilitation programme.

operational costs of the district. However, this tax is assessed on the size of his irrigated acreage alone, and not on the amount of water he uses. Consequently, the irrigator can use all the water available to him at no extra cost, i.e., the marginal cost of his water supply is zero.

Secondly, although most irrigators are abiding by the technical constraints imposed by the irrigation districts, few are attempting to employ any type of scheduling procedure. Therefore, the great majority have not developed any criteria to decide when they should irrigate and how much they should apply. Consequently, they take no risks of running short and irrigate almost constantly from early May until September, using all the water they are allowed.

The duty of water as specified by the B. C. Reclamation Committee (see tables 2.4 and 2.5) represents the maximum amount of water required by crops during the hottest summer on record. It does not represent the average seasonal crop water requirements, which will be significantly lower due to the variability in ET from season to season. Accordingly, most irrigators are unable to control their application schedules in accordance with the stochastic nature of the prevailing climate. As a result, although these maximum duties of water statistically should only be applied approximately once in 20 years, rough estimates of seasonal water use for some irrigation districts from storage and diversion records suggest that even in a normal year these "maximum" amounts are surpassed by as much as 15 - 20 per cent.

To generate more efficient use, the irrigator must employ, or be encouraged to employ, some type of scheduling technique which would allow him to withhold his irrigation applications during periods of cool, wet weather. In a region such as the Okanagan where the crop water requirements vary significantly from year to year (O'Riordan, 1966) this technique can save considerable water and operating time. Wilcox (1967a) estimated by indirect methods the amount of water saved by using his scheduling model from four years of scheduling sprinkler irrigation on a wide variety of soil textures in Summerland, Oliver and Osoyoos. As compared with steady irrigation, scheduling saved between 25 and 54 per cent of the water used, depending on the year and measurement criteria.

However, it is contended that his model can be improved. Almost the entire construction of the model is based upon empirical relationships that fail to integrate the complex inter-relationships of the various input variables in the soil-plant-atmosphere system (S. P. A. S.). Because the model is not based upon a complete physical understanding of the various processes affecting the S. P. A. S. , it cannot explain local variations over space or time. Furthermore, the empirical relationships developed in the model are only applicable to the Okanagan region, and therefore may not necessarily be applicable in other regions, where irrigation scheduling is required. Scheduling of irrigation water will have to become universal to all irrigating areas if the efficiency with which the irrigator uses his water is to match up with the costs entailed in providing him with his water. There is a need to construct a regional scheduling model, soundly based on physical theory so that it may be applied in any region and yet can also be incorporated into the decision-making framework of regional water resource management. This is the principal objective of this thesis.

CHAPTER 3

THE INFLUENCE OF ADVECTIVE ENERGY ON EVAPOTRANSPIRATION

The development of a model for improving the efficiency of irrigation water use must first be concerned with the total crop water requirements during the irrigation season. Such a calculation is necessary to enable the water resources planner to estimate the total irrigation storage requirement. The irrigation farmer is also interested in determining the peak water requirements that may be expected to occur during the irrigation season to enable him to design his irrigation system. Accurate assessment of this information can best be obtained from a critical examination of the atmospheric component of the S. P. A. S., since it contains the major exogenous variables controlling the demand function for water. This demand function has been termed "potential evapotranspiration" by Thornthwaite (1948), but, for reasons explained at the conclusion of this chapter, will be referred to here as evapotranspiration[1] (ET).

Several investigators (Baier and Robertson, 1965; Davenport, 1967; Pelton, 1964; Wilcox, 1963) have used multiple regression techniques to examine the relative importance of various climatic elements that influence the rate of evaporation and ET. The most important of these variables is solar radiation since it is the only direct source of energy which converts water into water vapour[2]. The other significant variables were found to be air temperature, saturation vapour pressure deficit[3] and wind speed, the latter two factors enabling the atmosphere to absorb and transport the

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1 ET is defined as the combined evaporative loss of water from soil and plant surfaces.

2 This process requires approximately 585 cals. $gm^{-1}\ {}^{o}C^{-1}$ at normal temperatures and pressures.

3 Saturation vapour pressure deficit is defined as the difference between the actual and maximum pressure that water vapour can exert at a given temperature.

evaporated moisture away from the evaporating surface. However, although all these investigators found highly significant correlations between these four climatic variables and evaporation from evaporimeters, they failed to produce as significant results using measured ET from lysimeters.

A possible reason for this is that these studies only considered the vertical exchange of heat and water vapour fluxes over an evaporating surface. Recent studies using the energy balance approach (Abdel-Aziz et al., 1964; Miller, 1964) have demonstrated the importance of horizontal advection of both heat and water vapour fluxes over evaporating surfaces, particularly in semi-arid environments. Philip (1959) defines advection as "the exchange of energy, moisture and momentum due to horizontal heterogeneity". This heterogeneity of heat and moisture fluxes between adjacent land surfaces is often present when a finite area of land is irrigated, a situation which occurs in the Okanagan Valley, where much of the irrigated bench land lies immediately adjacent to the dry, unirrigated valley sides.

The objective of this chapter is to analyse and evaluate the advective energy component over an irrigated alfalfa crop at Summerland by means of the energy balance approach. It is hoped that the inclusion of this term in the atmospheric energy demand function will lead to a more realistic methodology for estimating the seasonal crop water requirements than that presently used in the Okanagan Valley.

Theory

The advection process attempts to level out the difference in the micro-climatic energy balance, which occur as a result of a differential availability of water for evaporation between two adjacent land surfaces. The energy balance partitions the net radiation flux[1] (R_n) into three major component fluxes - latent heat of vaporization (LE); sensible heat (H) and

1 See Appendix III for details of measurement.

ground heat (G) (Tanner, 1960).

$$R_n = H + G + LE \qquad (3.1)$$

Over a dry, unirrigated area, where the latent evaporation flux is small or negligible due to a lack of available water for evaporation, the net radiation flux[1] will only be partitioned into two component fluxes, viz. the sensible heat flux and the ground heat flux (equation 3.2)

$$R_n = H + G \qquad (3.2)$$

Although the heat flux into the ground in the dry area will be somewhat larger than its counterpart in the irrigated area, the difference is far too small to compensate for the lack of latent evaporation heat loss. Thus, the air overlying the unirrigated area will become warmer and drier than the air overlying the irrigated surface. The resultant horizontal temperature and water vapour gradients will advect warm, dry air from an unirrigated surface and raise the air temperature and vapour pressure deficit of the air above an adjacent cooler, transpiring cropped surface downwind (Davenport and Hudson, 1967). In addition to this horizontal heat flux, energy is also transmitted to the crop by a downward convective heat flux from the over-riding warm air, i.e. under advective conditions

$$R_n + H_a = LE + G \qquad (3.3)$$

where H_a is the sum of both vertical and horizontal sensible heat fluxes.

Quantitatively, the horizontal advection of heat and moisture (Rider et al., 1963) may be expressed as:

$$U \frac{dT}{dx} = \frac{d}{dz} \quad K_T \frac{dT}{dz} \qquad (3.4)$$

$$U \frac{de}{dx} = \frac{d}{dz} \quad K_e \frac{de}{dz} \qquad (3.5)$$

---

1 Rn will be slightly reduced over the desert compared with an irrigated area as a result of both higher surface albedo and higher temperatures of its radiating surface (Munn, 1961).

where x and z are the horizontal and vertical planes respectively.

U is the horizontal wind speed (cm. sec.$^{-1}$)

K_T is the eddy diffusivity for heat (cm. sec.$^{-1}$)

K_e is the eddy diffusivity for water vapour (cm. sec.$^{-1}$)

T is potential temperature (^oC)

e is vapour pressure (mbs.)

and

$$H = - \rho C_p K_T \frac{dT}{dz} \qquad (3.6)$$

$$LE = - L K_e \frac{de}{dz} \qquad (3.7)$$

where ρ is the air density (gm. cm.$^{-3}$)

C_p is the specific heat of air (cal. gm.$^{-1}$ $^oC^{-1}$)

L is the latent heat of vaporization (cal. gm.$^{-1}$)

The above equations indicate that the amount of advected energy transfer depends upon two factors: (1) the rate of horizontal air movement U and (2) the magnitude of the sensible heat and water vapour gradients between two adjoining surfaces. Expressed symbolically:

$$\text{Advection} = f\left(U, \frac{dT}{dx}, \frac{de}{dx}\right) \qquad (3.8)$$

In consideration of the above functional relationship, it is hypothesized that the amount of advected energy over irrigated crop surfaces in the Okanagan will increase during the irrigation season. The available soil water content of the unirrigated valley sides is on average sufficient to maintain potential rates of ET during May and June because of the spring snow-melt, the relatively low rates of ET experienced during these months and the high probability of moist weather in June (O'Riordan, 1966). However, soil water deficits quickly accumulate in the unirrigated valley soils during July and August, reducing the rates of ET and establishing the necessary heterogeneity in the energy balances between the irrigated and unirrigated land which promotes advection.

Experimental Procedure

The Bowen Ratio Approach

The above hypothesis was tested by estimating the energy balance of an irrigated alfalfa crop at Summerland. Due to the fact that accurate instrumental measurement of the latent energy and sensible heat fluxes is a very complicated and expensive procedure (Lettau and Davidson, 1957), these fluxes were determined indirectly by the Bowen Ratio method (Bowen, 1926). This experimental procedure was developed under two assumptions:

(i) Eddy diffusivities for water vapour (K_e) and sensible heat (K_T) are equal.

(ii) Divergence of the vertical fluxes of water vapour and heat in the air layer above the crop is negligible.

The first condition, known as the Principle of Similarity, is based on the assumption that the turbulent transfer process for heat and water vapour must be similar since they are influenced by the same eddy transfer process (Sellars, 1965). Available evidence (Pasquill, 1949; Brooks *et al.*, 1966; Rider and Philip, 1960) indicates that the Principle of Similarity is approximately true under most atmospheric conditions, except large lapse rates which are seldom found over irrigated surfaces in summer. The second condition can also be justified if the two vertical levels for recording temperature and vapour pressure are carefully chosen.[1]

Assuming $K_T = K_e$ and using equations 3.6 and 3.7

$$\text{Bowen Ratio} \quad \beta = \frac{H}{LE} = \frac{Cp \frac{dT}{dz}}{L \frac{de}{dz}} = \frac{Cp\,(T_2 - T_1)}{L\,(e_2 - e_1)} \qquad (3.9)$$

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1 In this experiment, temperature and vapour pressure gradients were recorded between the heights of 0.8 m. and 1.6 m. (Fritschen, 1965). (See Appendix I).

Rearranging equation 3.1 and using equation 3.9

$$LE = \frac{-(Rn + G)}{1 + \frac{Cp(T2 - T1)}{L\ (e_2 - e_1)}}$$

$$= \frac{- Rn + G}{1 + \beta} \qquad (3.10)$$

Details of the measurement of the various parameters of equation 3.10 are given in Appendix I.

The Bowen Ratio approach is a relatively simple and accurate technique well suited to estimating daily rates of ET. Several investigators (Brooks et al., 1966; Mukammal and Bruce, 1960; Fritschen and van Bavel, 1963) have verified that this ratio provides better estimates of daily ET than either the aerodynamic approach or the eddy correlation technique.

The LE/R_n Ratio

Because the heat flux (G) into the ground is small compared with the other component fluxes in the energy balance of cropped surfaces, the incoming net radiation is essentially divided into latent and sensible heat fluxes (equations 3.11a and 3.11b).

$$R_n \simeq LE + H$$

or $$LE \simeq R_n - H \text{ (non-advective conditions)} \qquad (3.11a)$$

and $$LE \simeq R_n + Ha \text{ (advective conditions)} \qquad (3.11b)$$

Many investigators (Tanner, 1960; Bahrani and Taylor, 1961; Stern, 1967) have used the ratio of evaporative loss to net radiation (LE/R_n) as a criterion for determining the occurrence of advection. This ratio is less than unity during non-advective conditions when there is a sensible heat loss from the crop surface, but is greater than unity under advective conditions when the crop is extracting heat from the air above it.

Analysis of Results

The relationship between estimated net radiation and ET[1] over a mature alfalfa crop[2] for several days during the experimental periods in 1967 and 1968 are shown in figure 3. 1. Most of the points recorded in June (solid dots) fall to the left of the 1:1 line, indicating that there was no advective influence during the early part of the irrigation season. The large number of points recorded in July and August (open dots) which fall to the right of the 1:1 line testify that the advective influence becomes more important later in the irrigation season.

The amount by which the LE/R_n ratio exceeds unity provides some indication of the amount of advected energy that is intercepted by the crop. Table 3. 1 shows that this ratio gradually increased during the growing season from 0. 83 in June to 1. 24 in August. While these figures are perhaps not representative of the average situation, since August 1967 was exceptionally warm and dry, it is believed that the rapid increase in ET rates during July is a direct result of the increasing influence of advection.

TABLE 3. 1

AVERAGE RATIO OF LE/R_n OVER A MATURE ALFALFA CROP FOR THREE SUMMER MONTHS AT SUMMERLAND, B. C.

Year	Month	LE/R_n
1968	June	0. 83
1967	July	1. 15
1967	August	1. 24

1 ET is assumed to equal the latent energy flux when the alfalfa crop is not under water stress (See Chapter 4).

2 The alfalfa crop was considered to be mature when its leaf surface covered the soil surface. This factor is important, as will be shown later in the chapter.

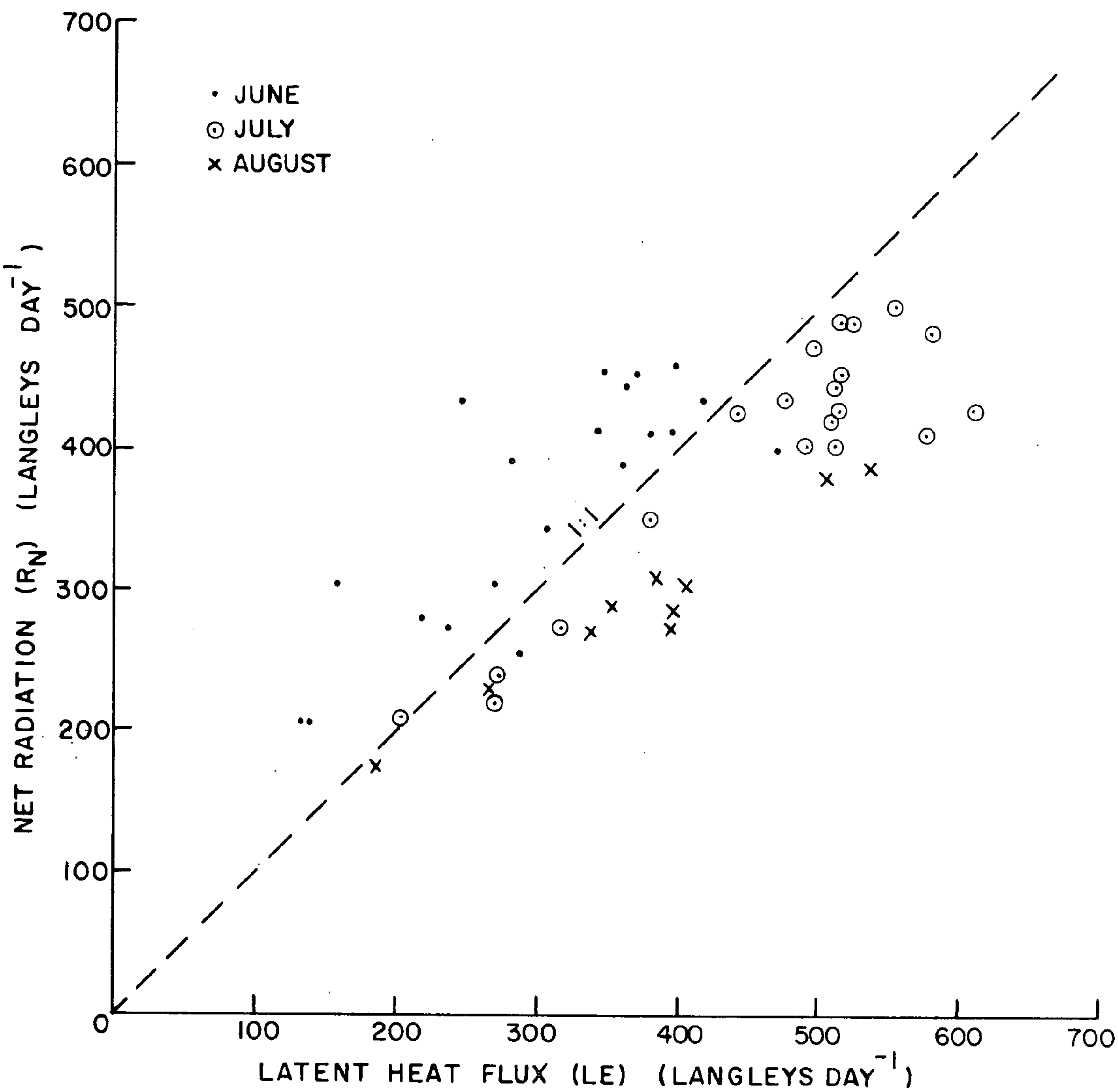

Figure 3.1 Relationship between Latent Heat Flux (LE) and Net Radiation (R_n) over Irrigated Alfalfa at Summerland, B. C., 1967-1968.

However, the influence of advection is not completely determined by the time of year. Figure 3.2 traces the trend in the Bowen Ratio measured over a mature alfalfa crop during late June and early July, 1968. Negative values indicate advection of warm air over the crop. This figure points out the stochastic nature of the advective influence, especially in June, by suggesting it is related to the occurrence of warm spells which can dry out the surrounding unirrigated land sufficiently to restrict potential rates of ET. It should be noted that the Bowen Ratio becomes positive (indicating non-advective conditions) immediately following two periods of cool, damp weather.

It would appear that the occurrence of advection over an irrigated crop is a function of time following a heavy rainfall. Lemon et al. (1957) also noted this fact in experiments with irrigated cotton in Texas. It is possible that a heavy rainfall could supply enough water to an unirrigated soil water reservoir to equalize the energy balance over both an irrigated and non-irrigated surface and consequently remove the advective influence. A return to dry weather following such a wet spell would be accompanied by a gradual increase in the LE/R_n ratio (decrease in the Bowen Ratio - see figure 3.2). Unfortunately, no such rainfall occurred during the experimental period, though such rainfalls are not uncommon in the Okanagan. However, several non-advection days were recorded during cool, cloudy periods and the importance of this fact will be considered in a later section.

The Roughness Factor

Thus far, the discussion has centred around the micro-climatic conditions that favour the occurrence of advection. However, the amount of the advected energy supply that can be effectively utilized by a surface depends upon the roughness coefficient of that surface. The roughness coefficient is defined as the constant of integration of the wind profile above a crop surface (Slayter, 1963), and will be zero for a completely smooth surface, increasing in proportion to the size of the protruberances above the surface. An increase in the roughness of a crop surface coefficient is accompanied by a proportional increase in the eddy diffusivities of heat

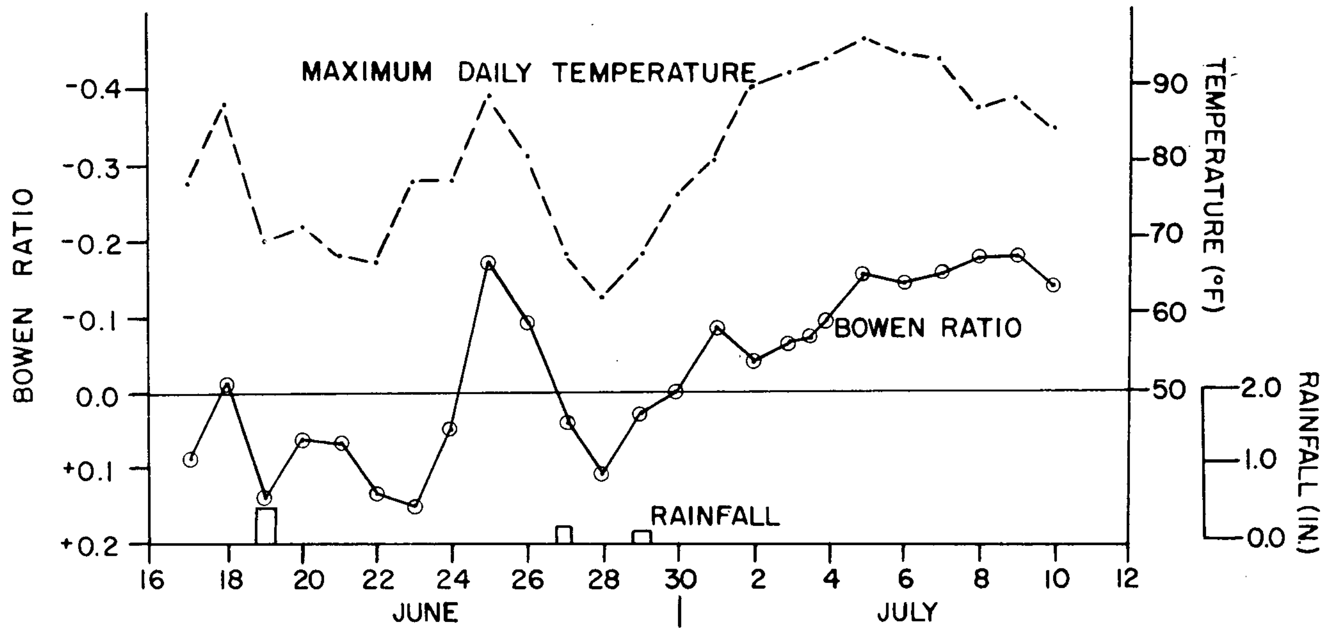

Figure 3.2 Trends in Bowen Ratio and Temperature over Irrigated Alfalfa during June and July, 1967.

and water vapour over the crop which, in turn, increases the amount of advected energy that can be absorbed by the crop (Rider et al., 1963 -- see equations 3.4 and 3.5).

The roughness factor must be taken into consideration when determining the crop water demand function for an annual crop such as alfalfa[1]. The roughness coefficient for alfalfa increases during its regular growth cycle from values close to zero immediately after cutting to approximately 4.0 cms (Tanner and Pelton, 1960). It has also been pointed out that ET from a rough crop surface can exceed that from a smoother surface during periods of advection (Tanner and Pelton, 1960). In consideration of these factors, it is hypothesized that the LE/R_n ratio and consequently ET itself will be a function of the stage of growth in the alfalfa growth cycle. It is also hypothesized that, even though conditions favouring the occurrence of advection are established, the alfalfa crop will not be able to absorb this energy supply until it has reached a height at which its roughness coefficient is sufficiently large enough to disturb the aerodynamic turbulence in the atmosphere above it.

Figure 3.3 verifies these hypotheses. Fortunately, this entire growth cycle took place during a prolonged spell of warm, dry weather which reduced the climatically controlled variation in the LE/R_n ratio to a minimum. The low rate of ET at the beginning of the growth cycle is due to the small leaf-surface area exposed for transpiration. As this leaf-surface area increases, during the maturation of the alfalfa crop, so will the potential rates of ET, but superimposed upon this process is the increasing ability of the crop to extract advected heat from the air above. Although the entire growth cycle took place under strongly advective conditions, the

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1 In the case of tree fruits, the roughness coefficient is assumed to be approximately constant throughout the irrigation season. Therefore, only climatic variables will influence the amount of advected energy absorbed by the crop.

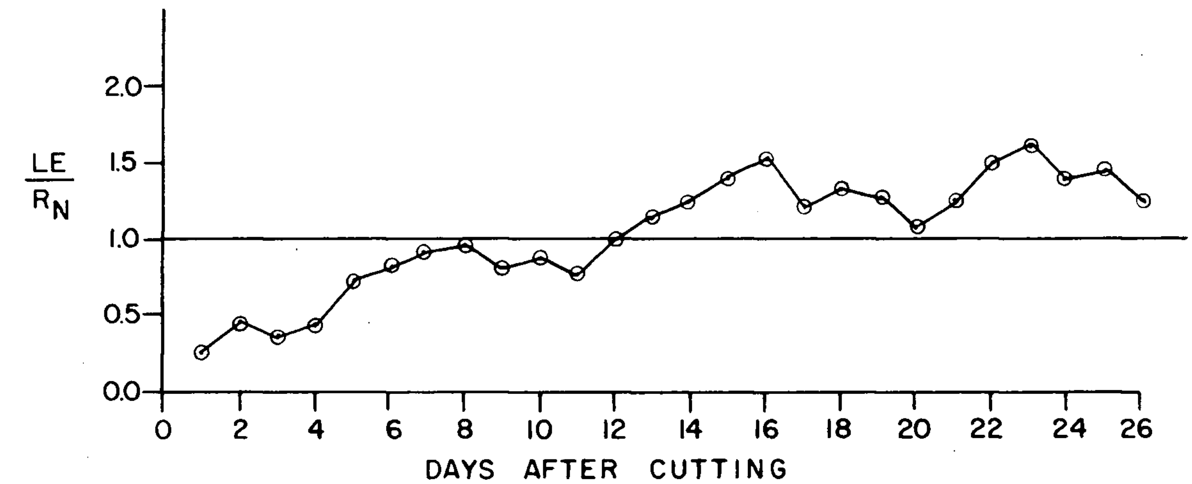

Figure 3.3 Trend in LE/R_n Ratio over Irrigated Alfalfa During its Growth Cycle, July-August, 1967.

alfalfa crop was unable to utilize this additional source of energy for ET until approximately 12 days after harvesting, or when its plant surface covered the soil. Furthermore, the figure suggests that the amount of advective energy absorbed by the crop tended to increase as the crop continued to gain height, i.e. as its roughness coefficient increased. The point is further emphasized in table 3.2.

TABLE 3.2

THE RATIO OF LE/R_n DURING VARIOUS STAGES OF ALFALFA CROP GROWTH AT SUMMERLAND, B. C., JULY - AUGUST, 1967

Dates	Stage of Growth	LE/R_n
July 13-18	Bare soil	0.54
July 19-23	Emerging	0.67
July 24-28	Ground covered	0.93
July 29-August 14	Fully mature	1.25

In order to eliminate any variation in the LE/R_n ratio caused by climatic controls, the energy balance over alfalfa was examined during various stages of its growth cycles on three days that were climatologically similar (figure 3.4). When the crop was emerging (figure 3.4a) there was a net convective heat loss from the surface and consequently LE was less than R_n. A small advection effect was established during the late afternoon and evening as R_n decreased rapidly, yet a warm wind remained to become the more important source of energy for ET.

The energy balance of an alfalfa crop, which was just covering the soil surface, is shown in figure 3.4b. The air at 1.6 meters was approximately 1°C cooler than the air at 0.8 meters during the morning, resulting in a convective heat flux away from the surface during the afternoon to produce a definite temperature inversion above the crop throughout the remainder of the day. In this case, the additional heat gained from the atmosphere was less than the heat given up by the crop during the morning, resulting in a daily LE/R_n ratio of 0.95.

Figure 3.4c shows the energy balance situation over a fully mature alfalfa crop under similar highly advective conditions. An inversion appears over the crop by mid-morning and temperature gradients of 3°C between the recording levels at 0.8 and 1.6 m. were observed during the afternoon. The resultant LE/R_n ratio was 1.10.

Superimposed upon the deterministic functional relationship between LE/R_n ratio and stage of growth are the stochastic variations imposed by the prevailing climatic conditions (see figure 3.2). The resulting relationship becomes rather more complicated, but the same trends appear, as may be seen from an examination of table 3.3 in which the energy balance over alfalfa at various stages of growth during different weather periods is analysed (see later section). Convective heat flux (H) represents a fairly large loss of energy during the early stages of growth under most climatic conditions but it decreases as the crop matures and becomes a heat gain under advective conditions for a fully mature crop. Conversely, the latent energy flux accounts for an increasing proportion of the radiative energy during the course of the alfalfa growth cycle and can become very large under highly advective conditions.

TABLE 3.3

THE ENERGY BALANCE OF AN ALFALFA CROP AT VARIOUS STAGES OF GROWTH UNDER VARYING CLIMATIC CONDITIONS[1]

Date	Stage of Growth	R_s lys.	R_n lys.	G lys.	LE lys.	H lys.	LE/Rn
12 June '68	stubble	468.5	+305.0	+14.6	-157.1	-133.8	0.52
19 July '68	stubble	347.0	+207.8	+13.2	-132.0	- 62.6	0.63
19 June '68	low growth	423.9	+283.4	+ 4.7	-217.4	- 61.8	0.77
24 June '68	low growth	565.1	+392.3	+11.6	-360.5	- 43.3	0.92
25 June '68	low growth	580.5	+400.0	+13.3	-470.7	+ 57.4	1.18
10 July '68	mature	598.0	+425.6	+ 2.8	-512.2	+ 83.8	1.20
11 July '68	mature	357.9	+275.5	+ 3.5	-316.3	- 37.3	0.90
25 July '67	mature	614.9	+411.3	-	-575.2	+163.9	1.40

1 Positive sign indicated energy received by the surface and negative sign indicates energy lost from the surface.

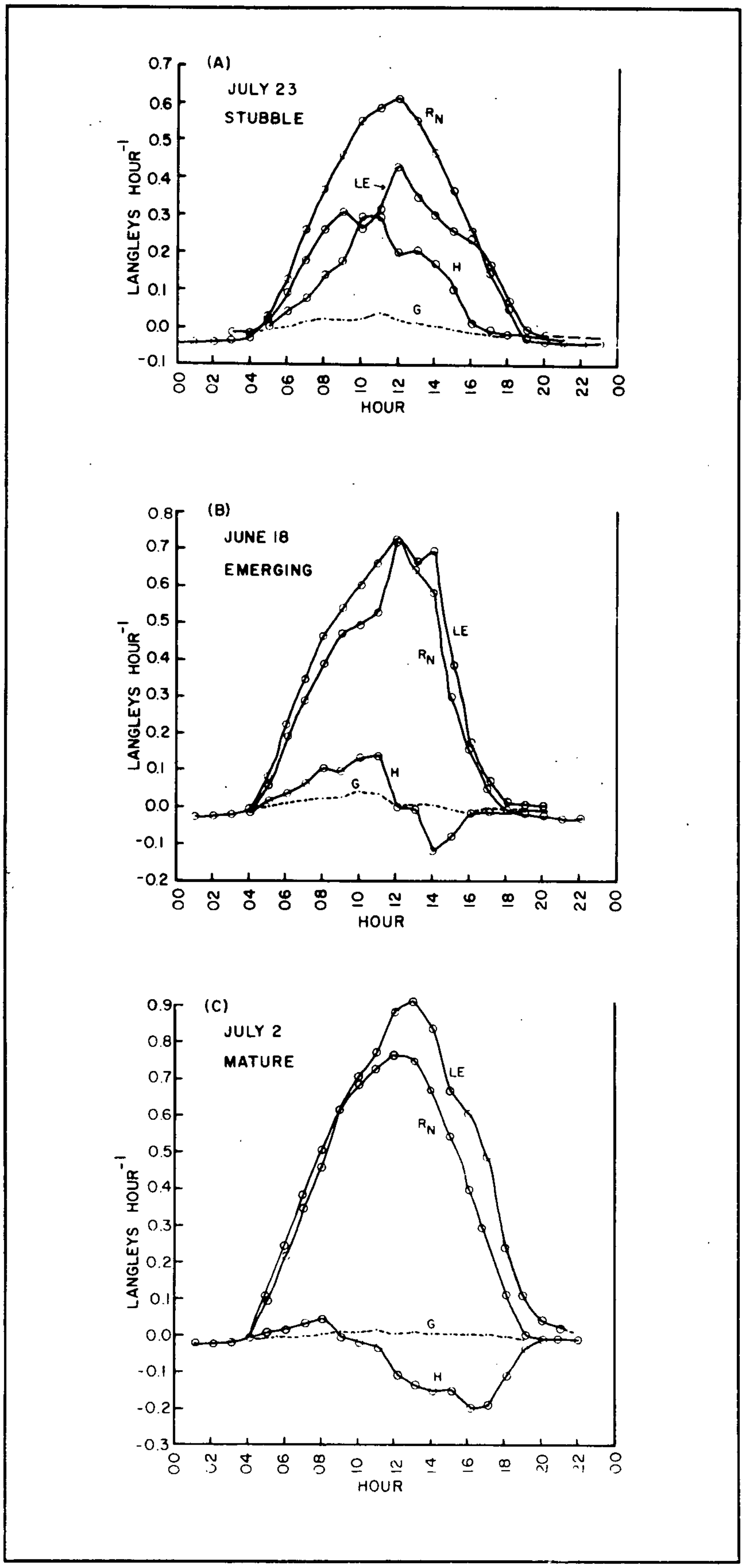

Figure 3.4 Daily Variation in Components of the Surface Energy Balance over Irrigated Alfalfa at Summerland, B. C.

Advection and Estimation of ET in the Okanagan

There can be no doubt that the advection of sensible heat over rough cropped surfaces supplies an important source of energy for ET. It should be noted here that this advection effect is not conceived as a local "oasis effect" existing at the edges of small irrigated fields. As described in Appendix I measurements of the energy balance were taken at the centre of a large alfalfa field at least 800 yards from the nearest large area of unirrigated land. McIlroy and Angus (1964) noted similar advection effects over irrigated pasture in South Australia and considered it to be a regional phenomenon associated with the prevailing synoptic weather patterns and Lemon et al. (1957) measured the influence of advection over a cotton field 11 km. distant from the nearest unirrigated land.

How well do the empirical models presently used in the Okanagan for estimating daily crop water demand take account of this advective influence? How can they be improved?

The two empirical models that have been used in the Okanagan are the Wilcox model, based on Bellani Plate evaporation (see Chapter 2) and the Penman model used in a theoretical study by O'Riordan (1966). Statistically, both models show a significant relationship with measured rates of ET[1] (figures 3.5 and 3.6), but their regression coefficients differ significantly from unity. On closer examination, however, both display a relatively close agreement with measured ET on non-advective days (solid dots), but generally underestimate ET during periods of advection (open dots). Because the Penman model in its original form does not include an advection factor at all, it should only be used during periods when LE/R_n is less than unity. Certain adjustments to account for advection, such as a roughness coefficient and an improved wind function (Tanner and Pelton, 1960) would be necessary if this model is to be used to estimate crop water requirements under advective conditions.

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1 Estimated from the Bowen Ratio technique over mature alfalfa.

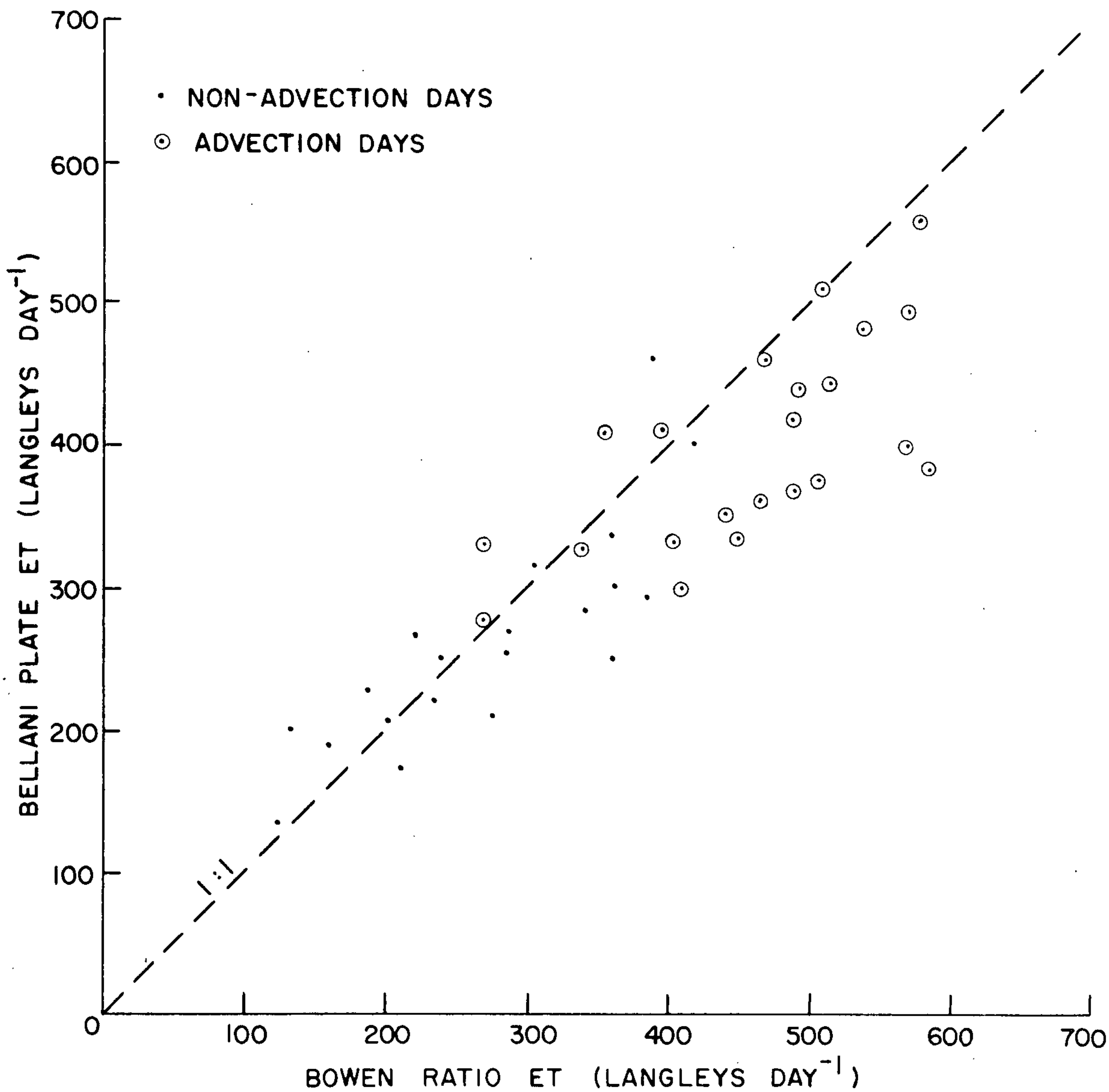

Figure 3.5 Relationship between ET estimated from Bellani Plates and Measured ET from an Irrigated Alfalfa Plot, Summerland, B. C.

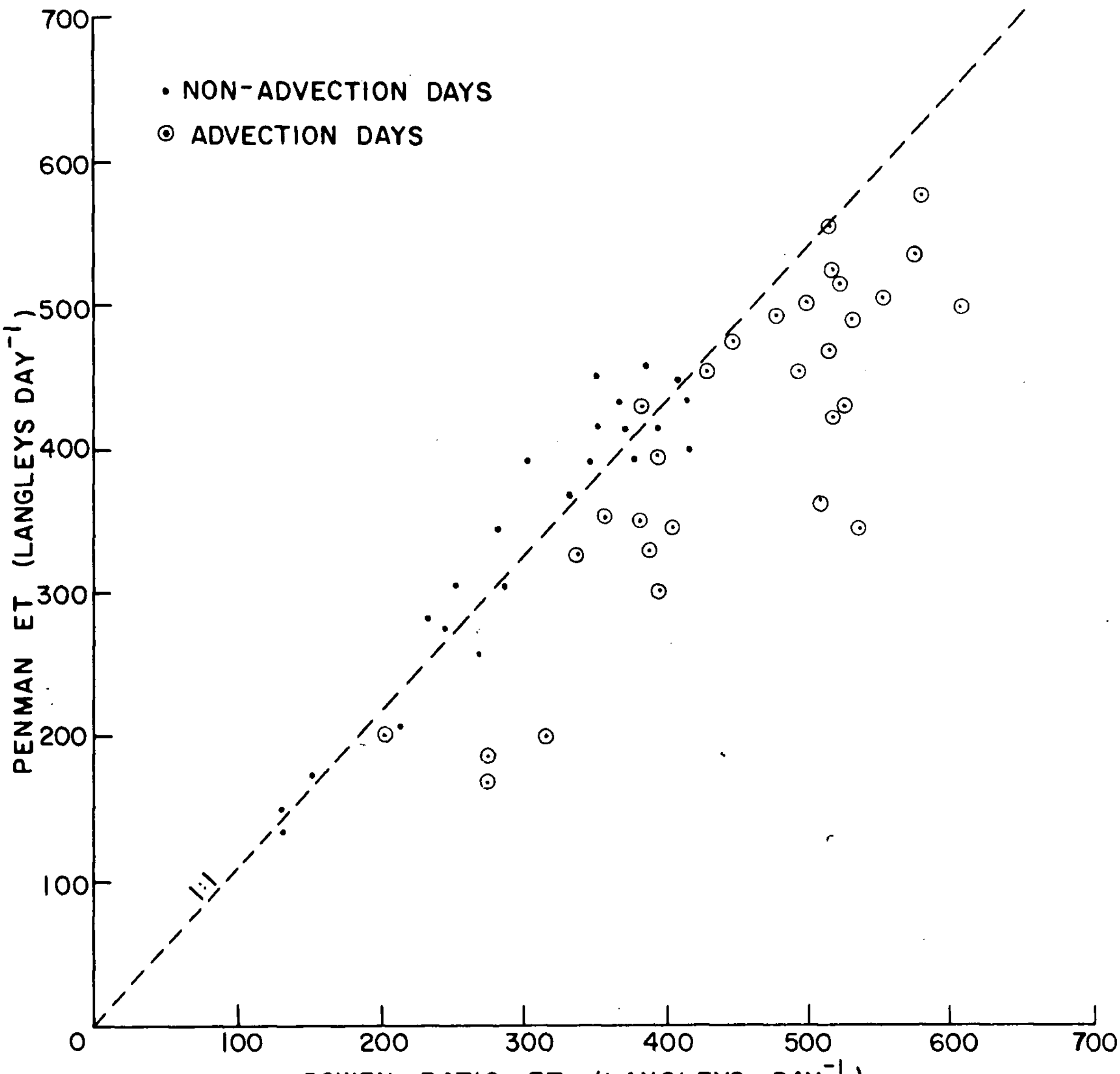

Figure 3.6 Relationship between ET estimated by the Penman Model and ET measured from an Irrigated Alfalfa Crop, Summerland, B. C.

Generally speaking, the Wilcox model provides better estimates of ET than the Penman model, since the Bellani plate atmometer does integrate the advective effects to some degree (Mukammel and Bruce, 1963). However, Wilcox failed to realize that the relationship between Bellani plate evaporation and ET is not a constant, and that varying rates of R_n, associated with different weather periods, affect ET in varying proportions, thereby increasing the scatter about the regression line. In other words, it is hypothesized that there is not one unique regression coefficient relating Bellani plate evaporation with ET, but several, each associated with a different natural weather period or (in the case of annual crops such as alfalfa), a different stage in growth.

Natural Weather Periods

As was mentioned earlier, the rate of ET is dependent upon the amount of net radiation, the turbulent transfer process and the difference in water vapour pressure between the evaporating surface and the air above[1]. During cool, cloudy weather, when the vertical water vapour gradient is small, thus limiting the rate of ET, one would expect that only a relatively small proportion of the radiant energy would be used to evaporate moisture (LE) and a relatively large proportion would be used to heat the air (H). In other words, the LE/R_n ratio would be less than unity.

Under drying conditions there will be an increase in R_n and in the vapour pressure gradient above the crop, which permits higher rates of ET. It is postulated that relatively more of this increased R_n will therefore be used to evaporate moisture and relatively less will be used to heat the air. This combination of events will tend to increase the LE/R_n ratio toward unity (see table 3.2). A continued drying trend will eventually promote advective conditions and a LE/Rn ratio greater than unity.

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1 The following analysis assumes that ET is from a mature alfalfa crop.

Statistical Analysis

The LE/Rn ratio over mature alfalfa was found to vary from 0.45 on cool, damp days to 1.5 on hot, sunny days. Accordingly, four weather periods were arbitrarily chosen from this range of values (table 3.4).

TABLE 3.4

DESIGNATION OF NATURAL WEATHER PERIODS ACCORDING TO LE/Rn RATIO[1]

Weather Period	LE/Rn
1. Wet	0.4 - 0.6
2. Cool and Cloudy	0.6 - 0.8
3. Partly sunny	0.8 - 1.0
4. Hot and dry	1.0 - 1.5

A series of statistical tests were performed on the experimental data to see whether there were any significant differences in the effect of each of four significant climatic variables[2] on ET during each of these four weather periods. Table 3.5 shows the results of a simple correlation analysis.

1 The same system of classification and statistical methodology could be used to assess the variation of stage of growth on daily ET.

2 The four chosen were mean daily temperature t_m (°F); daily wind speed U (miles per day); vapour pressure deficit $e-e_s$ (mbs) and solar radiation R_s (langleys) -- see introduction to this chapter.

TABLE 3.5

SIMPLE CORRELATION ANALYSIS BETWEEN ET AND FOUR METEOROLOGICAL VARIABLES DURING FOUR WEATHER PERIODS

Period/Variable	t_m	U	$(e - e_s)$	R_s	No. Obs.
1	0.667 **	0.162	0.474 **	0.498 **	33
2	0.643 **	0.145	0.454 **	0.525 **	30
3	0.363 *	-0.172	0.172	0.785 **	38
4	0.270	0.312 *	0.245	0.749 **	38
All periods	0.767 **	0.364 **	0.764 **	0.714 **	140

* indicates R significant at 0.05 level

** indicates R significant at 0.01 level

The most obvious result of this test is that, with the exception of radiation, the climatic variables are not as significantly correlated with ET during each period as they are for all weather periods combined. Radiation becomes more highly correlated and vapour pressure deficit less highly correlated with ET as the weather dries out, indicating that, as theorized, the vapour pressure deficit is a more important control on daily ET during cool weather than in drier weather periods, while the opposite is true for radiation.

More significant results were obtained when the standard normal regression coefficients (Steel and Torrie, 1960, p. 280) were calculated (table 3.6). These coefficients indicate the relative effect of each independent weather variable on the rate of ET. During cool periods temperature and vapour pressure deficit explain relatively more of the variation in ET rates and radiation relatively less, than in the drier and warmer periods. One other important result is that the wind variable, which is barely significant during periods 1, 2 and 3, becomes very important during the hot, dry spells when advection is an important source of energy (see equation 3.8). In fact, it becomes almost as important as the solar radiation variable under such conditions.

TABLE 3.6

STANDARD NORMAL REGRESSION COEFFICIENTS OF FOUR METEOROLOGICAL VARIABLES ON ET DURING FOUR WEATHER PERIODS

Period/Variable	t_m	U	$(e - e_s)$	R_s	R	R^2
1	0.35	0.17	0.28	0.20	0.659	0.432 **
2	0.33	0.19	0.30	0.18	0.680	0.462 **
3	0.10	0.13	0.20	0.56	0.822	0.676 **
4	0.10	0.34	0.20	0.36	0.786	0.619 **
All periods	0.13	0.12	0.34	0.41	0.863	0.745 **

** indicates R^2 significant at 0.01 level.

Multiple Covariance Analysis

Analysis of covariance is a statistical technique which partitions the sums of products of X (independent variables) and Y (dependent variables) into various components (Li, 1964). This is achieved by incorporating both the analysis of variance and regression analysis into the same statistical model. It has already been shown that a significant amount of the variation in the daily rates of ET can be explained by the variation of four climatic variables (table 3.6) and it has been hypothesized that there is an additional variation in these ET rates due to different prevailing weather periods. The multiple covariance technique can now be applied to test whether these weather periods do significantly affect the rates of ET. Firstly, the overall variation in ET due to variation of the four climatic variables is removed by adjusting the daily ET rates according to the all-period multiple regression equation.

$$ET = -0.154 + 0.0015t_m + 0.0006U + 0.0077(e-e_s) + 0.003R_s \qquad (3.12)$$

Secondly, an analysis of variance model is used to test for any significant differences between the means of the adjusted ET rates for each of the weather periods.

In this analysis of variance model, the "treatments" are designated as the four different weather periods presented in table 3.4. The analysis of covariance takes the form of a multiple regression analysis of Y (daily ET rates) on X_1, X_2, X_3, X_4 (the four climatic variables) and X_5, X_6, X_7, X_8 (the four weather periods). These weather periods can be quantified by assigning each of them a dummy constant (Li, 1964, Ch. 33). The results of the multiple covariance analysis are shown in table 3.7.

TABLE 3.7

MULTIPLE COVARIANCE ANALYSIS - TEST OF ADJUSTED MEANS

Source of Variation	d.f.		S.S.	M.S.	F.
Regression	7		1.122	0.1603	133.58
Weather Periods		3	0.1641	0.0547	43.90
Climatic Variables		4	0.9580	0.2395	199.58
Residual	132		0.1645	0.0012	
Total	139		1.2866		

The total regression with 7 degrees of freedom is the regression of both the four independent climatic variables and the four weather periods on daily rates of ET. The variance ratio of 133.58 with 7 and 132 degrees of freedom indicates that, as anticipated, this total regression removes a significant amount of variation in the independent variable. The component of variance designated "climatic variables" with 4 degrees of freedom represents the amount of variation attributed to the variation in the four climatic variables. The variance ratio of 199.58 with 4 and 132 degrees of freedom indicates that the adjustment of the daily ET rates to remove this source of variation was necessary. The component of variance designated "weather periods" with 3 degrees of freedom is the variation in ET due to the four different weather periods, after each "treatment" mean has been adjusted according to equation 3.12. The variance ratio of 43.90 with 3 and 132 degrees of freedom indicates that there is a significant difference between the adjusted mean rates of ET for these weather periods.

The New Duncan's Multiple Range Test (Steel and Torrie, 1969,

p. 107) was performed on the adjusted mean of each weather period to test for differences between the individual means (table 3.8).

TABLE 3.8

TEST FOR DIFFERENCES BETWEEN ADJUSTED MEANS

Weather Period	1	2	3	4
Adjusted Mean (in. day^{-1})	0.12	0.14	0.19	0.28

Any period adjusted mean not underscored by the same line is significantly different at the 0.01 level of significance. This suggests that there are no real differences between periods 1 and 2, which therefore can be amalgamated into one period - cool and damp.

Thus, there would appear to be three types of weather in the southern Okanagan Valley, which promote significantly different rates of ET. It is therefore believed that the Wilcox model for calculating ET could be greatly improved by distinguishing these three weather periods and calculating three separate regression coefficients to convert Bellani place evaporation into ET. Since there is already an established network of evaporation recording stations throughout the valley, the irrigation water resource manager could easily obtain information on the seasonal crop water requirements and the irrigator on peak water demand.

Summary and Conclusions

An examination of the LE/R_n ratio over a mature irrigated alfalfa crop at Summerland has indicated that during the middle and late summer the advection of warm air over an irrigated area from a non-irrigated area is an important supply of energy, in addition to net radiation for evaporating water from the crop. It was also shown that the amount of advected energy utilized by the crop depended upon its roughness coefficient, which in turn depended upon the stage of growth. This is an important variable in the case of alfalfa, though it is probably a constant in the case of tree fruits.

The empirical models presently used to estimate the annual duty of water for irrigated alfalfa in the Valley fail to take full account of this advection term and, therefore, underestimate ET during strong advection periods. The degree of this error is expected to vary according to crop type and climatic conditions and probably approaches a maximum under the experimental conditions at Summerland. The models fail to incorporate the variation in ET due to the stage in growth, a factor which may lead to considerable over-irrigation in the case of alfalfa, which is harvested several times during the irrigation season.

The Wilcox model can be improved by recognizing that the occurrence of different weather periods introduces a significant source of variation into the relationships between Bellani plate evaporation and measured rates of ET, in addition to the general variability of the climate. Statistical analysis of daily ET rates indicated that there are at least three significant weather periods distinguished by their LE/R_n ratios, which influence the rates of ET in the South Okanagan. It is possible to incorporate their effects into the Wilcox model and thereby improve the methodology for estimating ET from existing evaporation data.

Future models used to calculate ET in a semi-arid environment where advection is known to occur must take into consideration the roughness coefficient of the cropped surfaces. The results of this chapter suggest that under such conditions, when a crop canopy covers the ground and theoretically complies with the concept of potential ET, (Penman, 1948) certain factors such as surface roughness still affect the evaporative loss. Accordingly, the concept of potential ET loses some of its universality though not its usefulness.

This chapter has provided the irrigation water resource manager with a basic understanding of the processes which control the demand function of water in the S. P. A. S., and an improved methodology for estimating daily ET rates from alfalfa crops. This crop water demand is the major input variable within the S. P. A. S., the output of which is the removal of soil water. The relationship between the input and output functions depends upon the availability of soil water transpiration. An analysis of the processes which control this parameter is presented in the next chapter.

CHAPTER 4

FACTORS INFLUENCING THE AVAILABILITY OF SOIL WATER TO IRRIGATED ALFALFA

The preceding chapter developed an improved model, which will enable the irrigation water resource manager to estimate the daily loss of soil water due to ET. He must now formulate decision rules to inform the irrigator of the timing of irrigation applications. These decision rules should conform to the specified objectives of efficiency in water use, namely to use the minimum amount of water necessary to obtain optimum crop yields at minimum total cost. This chapter discusses the various factors which determine the optimum time to irrigate.

Theoretically, a farmer should irrigate when the water content of the soil reaches a critical level --Θ_K at which his crop begins to wilt. Although there has been much discussion concerning the percentage of total soil water availability[1] at which wilting begins (Veihmeyer and Hendrickson, 1955; Penman, 1963; Pierce, 1958; Lowry, 1959), many soil and plant scientists believe that this critical level is a deterministic variable[2] dependent only upon soil type. However, this assumption has neither satisfactorily explained the variation in crop yields (Fuehring et al., 1966), nor resulted in the most efficient use of irrigation water (Kramer, 1963).

Recently, several investigators (Makkink and van Heemst, 1956; Bahrani and Taylor, 1961; Closs, 1958; Marlatt, 1961) have enjoyed more success by considering this critical level to be a stochastic variable influenced by the level of atmospheric energy demand. Denmead and Shaw (1962) found that the ratio $\Theta_K | \Theta_{max}$[3] should increase as the rate of evaporation

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1 Soil water availability is defined here as the fraction of the total amount of water that a soil can hold against gravity that can be directly or indirectly utilized by a crop to maintain optimum growth rates.

2 Wilcox advocates that the irrigator should apply water when 50 per cent of the total available soil water has been removed.

3 Θmax is the total amount of water a soil can hold.

increases. In other words, on days with a small influx of evaporation energy (cool, cloudy weather-type 1), the crop should not begin to wilt until a large proportion of the total available water content had been removed; while on days with a large influx of evaporative energy (advection weather-type 3), the crop would begin to wilt when soil water content was considerably higher.

The objective of this chapter is to analyse and evaluate the various soil, plant and climatic factors that influence the availability of soil water to irrigated alfalfa at Summerland. It is hoped that the results of this investigation will provide the irrigator with the necessary decision rules to enable him to apply his water at the optimum time in accordance with the objectives of the regional water resource manager. The chapter is divided into two parts. The first part examines the various physical processes which determine the amount of soil water readily available to a crop and relevant hypotheses concerning the above functional relationship are formulated. The second part tests these hypotheses with data obtained from the irrigation experiments conducted on the Research Station at Summerland.

Theory

Plant growth is influenced by the internal water balance (or turgidity) of the plant itself (Vaadia *et al.*, 1961). This balance fluctuates according to the relationship between transpiration "expenditures" promoted by the external atmospheric energy demand, and water-absorption "income" supplied by the soil water reservoir. If transpiration exceeds absorption, an internal water deficit results which, in turn, reduces plant turgidity and plant growth rate. Thus the relationship between crop yield and soil water availability does not simply depend upon soil water content, but on all the factors that both create the demand for water and control its supply to the crop.

The plant water balance is maintained by a complete hydrostatic continuum, extending from the soil-water "reservoir" to the atmospheric "sink" (Slayter, 1960). The movement of water within this continuum is determined by the gradients of potential energy[1] of the water or water vapour in the various component parts of this S.P.A.S. In the atmosphere, the energy gradient or evaporative demand is termed the physiological saturation deficit (P.S.D. -- Skidmore and Stone, 1964), and is represented by the difference between the saturation vapour pressure of water at the ambient temperature of the leaf and the measured vapour pressure of the surrounding atmosphere. The water potential in the plant is known as the diffusion-pressure deficit (D.P.D.)[2], and for a vacuolated cell is measured as the difference between the internal cell osmotic pressure[3] and turgor pressure[4]. The soil water potential is composed of a matric potential due to the hydrostatic, gravitational and adsorptive forces acting on water attached to soil colloids, and on osmotic pressure dependent upon the salt concentration in the soil water solution (Taylor, 1965).

Water is absorbed by the plant in response to an increase in the D.P.D. gradient within the plant. This relation may be expressed quantitatively (Gardner, 1965):

$$q = \frac{L_s\ (\phi p - \phi s)}{I_s + I_p} \qquad (4.1)$$

$$Q = \int_o^z q\, dz \qquad (4.2)$$

where

q is the water uptake per unit volume of soil during unit time

L_s is the length of plant roots per unit volume of soil (cms.)

1 Potential energy is defined here as the amount of work that is necessary to transfer a unit quantity of free water from a free, pure water surface to a point in the system (Slayter, 1963).

2 Diffusion-pressure deficit expresses the difference between the diffusion-pressure of water in a cell or tissue and the diffusion-pressure of free water at the same temperature (Richards and Wadleigh, 1963).

3 Osmotic pressure is the pressure difference that must be exerted across a semi-permeable membrane to allow zero net transfer between water and a solution.

4 Turgor pressure is the hydrostatic pressure in a liquid system within a plant or plant cell.

$\emptyset p$	is the water potential of the plant (atmosphere)
$\emptyset s$	is the water potential of the soil (atmosphere)
I_s and I_p	are resistances to water movement in the soil and plant respectively.
z	is the total effective rooting depth and
Q	is the total amount of water removed from the soil during unit time

The atmosphere energy demand for water will promote ET from the crop surface at rates controlled by the atmospheric factors discussed in Chapter 3. This process decreases the water potential in the plant leaf, thus establishing a potential gradient between the plant and the soil (see equation 4.1), which is transmitted via the water continuum to the plant roots. Water will be absorbed by the root system as long as the potential gradient can overcome the resistances to water flow, both in the soil and at the root surface (Gardner and Ehlig, 1963).

Although the movement of water is dependent upon the energy gradients within the S.P.A.S., its actual rate is controlled by the resistances to flow, which occur in all three components of the S.P.A.S. The relative influence of these resistances depend upon the stage in the drying cycle. Immediately following an irrigation application or a heavy rainfall, water loss is limited only by the magnitude of the atmospheric energy demand and the resistance of the surrounding atmosphere to absorb and remove evaporated water vapour. But as the soil dries out, there is an increased resistance to water movement to supply the root zone, due to both an increase in the tension with which the soil water is held to the soil colloids and to a decrease in the hydraulic conductivity (K_w) which controls soil water movement (equation 4.3 -- Hanks and Gardner, 1965, Moltz *et al.*, 1968).

$$\frac{d\Theta}{dt} = \frac{d}{dz} \left[kw \left(\frac{d\emptyset}{dz}\right) \right] \qquad (4.3)$$

where

θ	= soil water content ($cm^3 . cm.^{-3}$)
t	= unit of time

z = effective rooting depth (cms.)

K_w = unsaturated hydraulic conductivity (cm. sec.$^{-1}$)

Θ = soil water potential (cms.)

There will also be an increased resistance to water movement at the root surface since the decreasing soil water content will increase the osmotic pressure of the soil water solution, which will, in turn, reduce the permeability of the root cortex (Kramer, 1949).

When a resistance to flow is encountered either in the soil or plant, a steeper potential gradient is required to maintain the same rates of water movement. Thus, if the combined resistances in the soil and roots are sufficiently large to prevent water being supplied to the roots at rates demanded by the plant, the internal water balance of the plant will be disturbed resulting in a loss of turgor, a reduction in ET and a decrease in the growth rate.

It seems reasonable to postulate, therefore, that on hot, advective days, when there is a large energy stress on the leaf surface, the soil will be unable to supply sufficient water to meet this demand unless its soil water tension is relatively low, i.e. soil water content is high. Conversely, on cooler days, when there is a low energy demand on the crop, the resistance to soil water movement could be considerably greater, i.e. the soil water content could be lower, and yet the soil could still maintain an adequate water supply to meet this smaller demand.

Effect of Root Distribution

The root distribution of most field crops, including alfalfa, are non-uniform and can usually be divided into two zones -- an upper root zone containing a high concentration of roots, and a lower zone which only contains a few roots. Equation 4.1 indicates that the rate of water loss from a given soil volume is proportional to the effective length of the roots contained in that volume. Therefore, under conditions of uniform potential gradient throughout the rooting system, the rate of uptake from the upper root zone will be proportionally greater than from the lower root zone (Taylor and Haddock, 1956).

The total rate of water removal (see equation 4.2) should vary with depth in the root zone according to the balance between water supply and demand during the drying cycle. Immediately following an irrigation, a large proportion of the total water loss should be removed from the upper root zones, which contain a high root density. Consequently, the soil water content in the upper root zones should decrease more rapidly than in the lower zones, resulting in an increased resistance to water movement because the hydraulic conductivity is a function of soil water tension. Therefore, as the upper soil dries out, an increasingly greater proportion of the total water loss should be removed from the lower root zones, where the soil water tensions are lower (Vasquez and Taylor, 1958; Stevenson, 1967). Because the root concentrations in these lower zones are small however, they are unlikely to supply sufficient water to satisfy high rates of atmospheric energy demand, though they may effectively prevent wilting on cooler days.

Experimental Procedure

From a consideration of the above theoretical discussions, two hypotheses concerning crop water availability are now proposed and are tested with experimental data obtained from irrigated alfalfa plots at Summerland. These hypotheses are that:

1. The rate of soil water extraction by a crop at any depth in the root zone is a function of root density.
2. Actual crop water use is a function of the amount of water held in the various root zones and the atmospheric energy demand.

Daily variations in the supply and demand for water for irrigated alfalfa were recorded on experimental plots (see Appendix I) and were analysed by means of the water balance model (Rose and Stern, 1965).

$$\Delta\Theta = P + I - \Delta R_v - D - ET \qquad (4.4)$$

where

$\Delta\Theta$ is the daily change in volumetric soil water content (inches day^{-1})

P	is rainfall (inches day^{-1})
I	is irrigation application (inches day^{-1})
ΔR_v	is net change in surface runoff -- outflow minus inflow (inches day^{-1})
D	is the drainage of water below the alfalfa root zone (inches day^{-1})
ET	is evapotranspiration water loss (inches day^{-1})

The experimental area consisted of 12 plots each 20 feet square and each containing four soil water recording stations. At each of these stations the daily change in soil water content was measured by means of electrical resistance blocks placed at four depths -- 6, 18, 30, and 42 inches.[1] A record of the amount of water supplied to each plot was kept by means of a recording rain gauge and two irrigation flow meters attached to the irrigation equipment. Surface runoff was assumed to be negligible because most of the water supplied to the crop was controlled by the irrigation application system so that it did not exceed the infiltration rate of the soil.

During the periods when the alfalfa was not subject to water stress, ET was measured by the Bowen Ratio method (see Chapter 3 and Appendix I), and the drainage term became the residual in equation 4.4. When the alfalfa was subjected to water stress, the drainage component was assumed to be zero and the actual rate of ET loss was estimated as the change in soil water content $-\Delta\Theta$. Thus, during a drying cycle:

$$\Delta \Theta = ET + D \qquad (4.5) \text{ when } ET = LE$$

$$\Delta \Theta = AE \qquad (4.6) \text{ when } ET < LE$$

where

AE is the actual rate of transpiration when the alfalfa crop is under water stress.

---

1 For details of soil water recording techniques and calibration of instruments, see Appendix I.

Analysis of Results

Influence of Rooting Distribution

The volumetric soil water content measured at four depths under one of the irrigated alfalfa plots was recorded on various days following an irrigation (figure 4.1). Over a 12-day period, the 6 inch dept lost 1.2 inches, the 19 inch dept lost 0.55 inches, while the 30 inch and 42 inch depths lost 0.38 inches and 0.35 inches respectively. This figure suggests that the high concentration of alfalfa roots in the upper two feet does result in significantly greater extraction rates from the upper root zones than from the lower zones when the entire root zone is subject to a low soil water tension.

It was further hypothesized that as the soil water tension increased in the upper root zones, relatively more water would be removed from the lower zones. Table 4.1 shows that the top two feet supplied 84 per cent of the total water removed from the alfalfa root zone five days after a plot was irrigated, but that this proportion dropped to 53 per cent after 15 days and only 22 per cent after 25 days as the soil water tension increased in the upper root zone. The table also indicates that the soil depth at which the relative water loss is greatest moves into progressively lower regions of the root zone as the soil profile dries out.

TABLE 4.1

RELATIVE RATES OF WATER LOSS FROM FOUR DEPTHS IN THE ROOT ZONE OF IRRIGATED ALFALFA AT SUMMERLAND, B. C., 1967-68

Depth	Days following an Irrigation				
Inches	5	10	15	20	25
6	53.5%	44.4%	27.9%	9.1%	7.1%
18	30.6	28.6	25.6	18.2	15.0
30	15.9	19.0	25.6	40.9	42.1
42	0.0	7.9	20.9	31.8	35.7

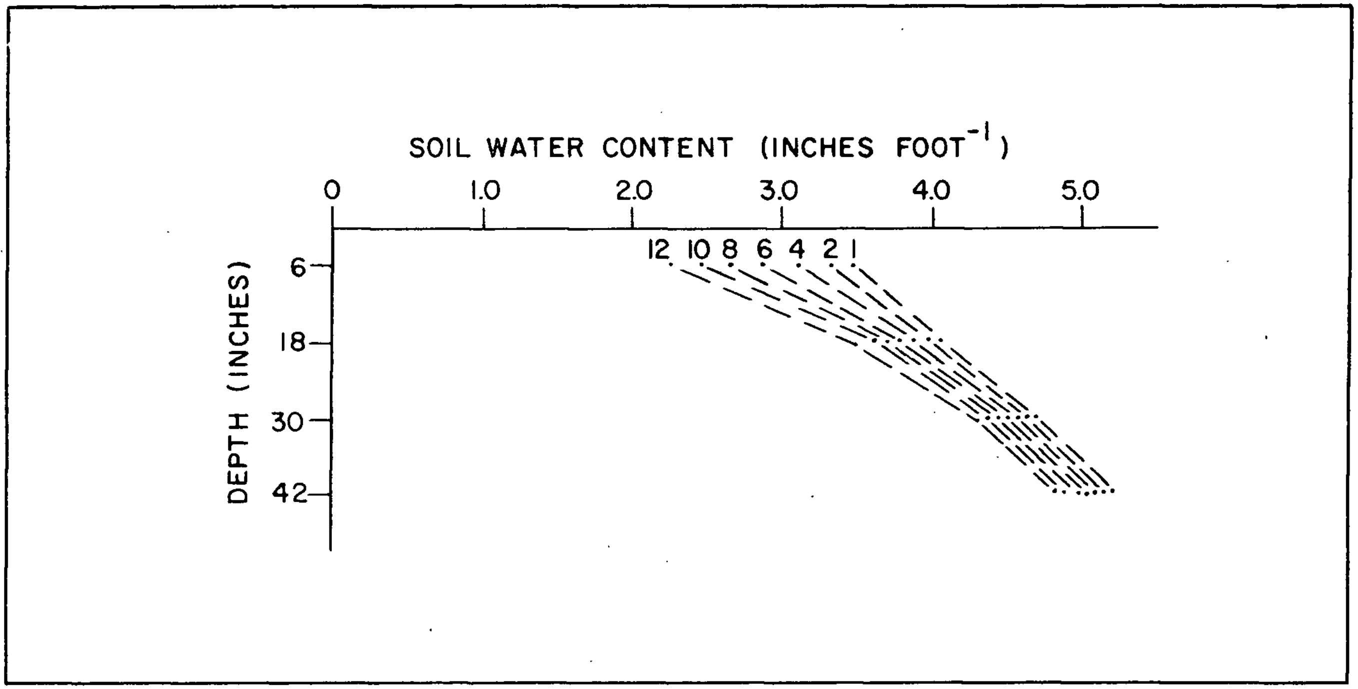

Figure 4.1 Soil Water Content in an Alfalfa Rooting Zone on Various Days following an Irrigation.

The irrigation manager is more specifically concerned with the effects of the non-uniform rooting distribution on the availability of water to irrigated crops. The accumulated loss from each foot depth is shown in figure 4.2, again indicating that the water loss from the top two feet decreases below its potential after approximately 15 days, while there is a relatively constant loss from the lower two feet throughout the drying cycle. This decrease in water loss from the upper root zones was not a result of cool weather reducing ET rates, as the prevailing weather was almost consistently hot throughout this period. The water balance model for this particular plot indicated that the alfalfa began to wilt 14 days after the irrigation was applied, or approximately at the same time the rate of water loss from the upper root zones decreased below the combined loss from the lower root zones. This result suggests that the available water supply in the lower root zones is not sufficiently large to maintain optimum growth rates during warm weather conditions in the South Okanagan after the upper root zones have dried out.

The fact is further verified in table 4.2, which shows the relative water-loss rate at the four foot depths for the three irrigation treatments used in the experiment (see Chapter 5). The alfalfa crop never wilted in treatment 1, and only wilted on the occasional day in treatment 2, but there was considerable wilting of alfalfa in treatment 3. Over 80 per cent of the water lost from the two non-wilting treatments was removed from the top two feet of the root zone. This figure dropped to 60 per cent for the third treatment, in which wilting occurred. Consequently, it would appear that optimum growth rates and, therefore, yields for alfalfa growing in the South Okanagan will only be obtained when the upper root zones are adequately supplied with water.

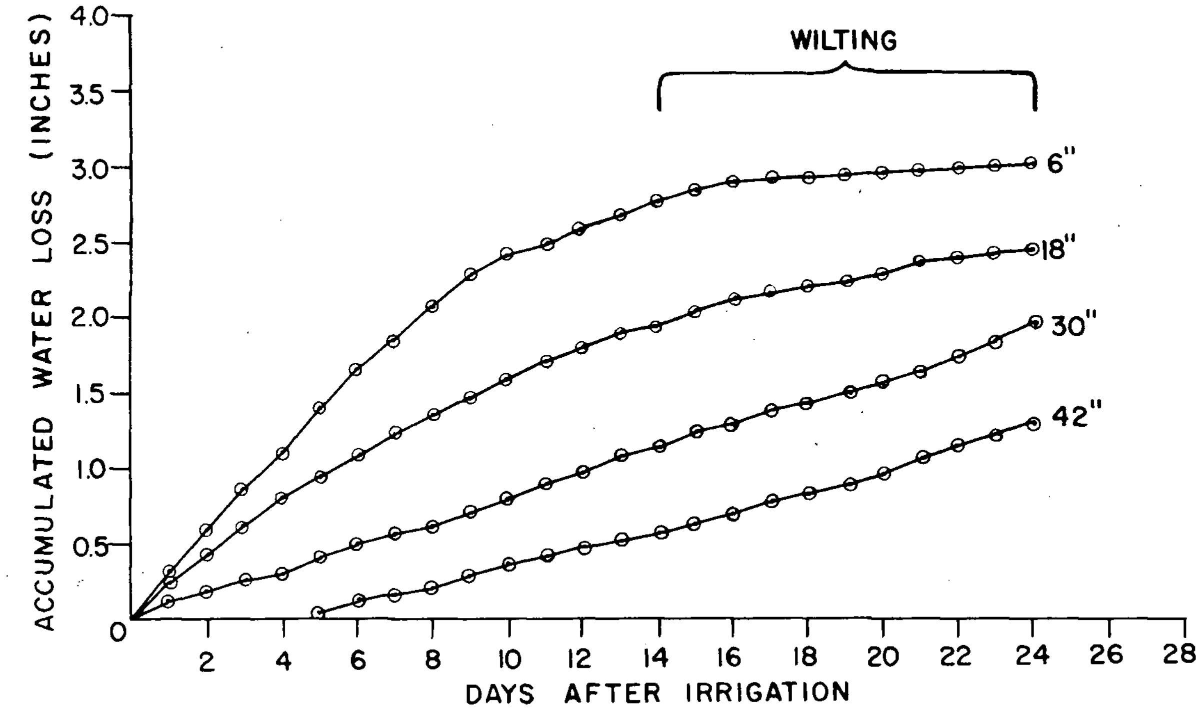

Figure 4.2 Accumulated Water Loss from Various Soil Depths following an Irrigation.

TABLE 4.2

AVERAGE RELATIVE RATES OF WATER LOSS
FROM FOUR DEPTHS IN THE ALFALFA ROOT ZONE
FOR THREE IRRIGATION TREATMENTS AT SUMMERLAND, B. C. 1967-68

Treatment	6 inches per cent	18 inches per cent	30 inches per cent	42 inches per cent
T1	52.4	29.3	12.2	6.2
T2	55.6	30.4	11.4	2.6
T3	31.0	29.3	28.3	11.4

The Soil Water Budget

The soil water budget is an essential component of any irrigation scheduling model (Thornthwaite and Mather, 1955), as it is the only technique which enables the irrigator to keep a continuous record of the amount of available water remaining within a root zone of a crop. Such a budget should be easy to use, yet realistic in its description of the natural processes which explain the removal of water from the soil root zone. The soil water budget used by Wilcox in the Okanagan is not realistic, because it fails to simulate the differential extraction rates of soil water from the various root zones. This omission is partly compensated by his reorder rule, which recommends application when 50 per cent of the total available water has been removed from the crop root zone (Wilcox, 1962b). It will be shown later (Chapter 6) that this reorder point approximately coincides with the start of the falling phase of water extraction rates from the upper root zone (see also figure 4.2), though this situation only occurs during highly advective weather periods. His existing model will tend to over-irrigate during cooler weather periods.

Recently, Baier and Robertson (1966) have produced a more realistic model, in which soil-water is extracted at varying rates according to the rooting characteristics of the crop. They determined a set of K-coefficients which express the amount of water in per cent of ET extracted by plant roots from different zones in the soil profile. Their model simulated the soil water budget under a non-wilting alfalfa crop reasonably well, but its recent modification (Baier, 1967a) to suit drought conditions was not as successful when tested against the soil water budget under a wilting alfalfa crop.

A Stochastic Model of Soil Water Loss

The models of soil water extraction from the root zone described thus far have emphasized the deterministic processes involved, i.e. that the rate of extraction from one part of the root zone is dependent upon the water content of the soil in other parts of the root zone. However, one of the objectives of this chapter is to show that soil water loss is, in fact, a stochastic process, dependent upon both the fluctuations in the atmospheric demand and the level of soil water in various parts of the root zone. Consequently, a series of multiple regression models were developed to determine all the significant climatic and soil variables that affect the rate of water loss from each root zone (table 4.3).

TABLE 4.3

CORRELATION AND REGRESSION STATISTICS OF RELATIONSHIPS BETWEEN WATER LOSS FROM FOUR SOIL DEPTHS AND VARIOUS CLIMATIC AND SOIL VARIABLES

Model	Dependent Variable	Regression Equation	R	R^2	SE	No. Observations
1	loss from 1 foot zone	$\Delta\Theta_1 = 0.58 - 0.013M + 0.0256\Theta, + 0.00015R_s + 0.000685t_m$	0.92	0.85**	0.067	52
2	loss from 2 foot zone	$\Delta\Theta_2 = -0.108 + 0.2199\Theta_1 + 0.00915\Theta_2 + 0.00015R_s$	0.92	0.84**	0.034	55
3	loss from 3 foot zone	$\Delta\Theta_3 = 0.073 - 0.0073\Theta_3 + 0.0203\Theta_2 - 0.0158\Theta_1$	0.58	0.33**	0.032	43
4	loss from 4 foot zone	Not significant				45

** significant at the 0.01 level.

where:

$\triangle\Theta_1$ = estimated water loss from zone i (inches day^{-1})

M = number of days following an irrigation

Θ_1 = water content of 1 foot zone (per cent available water)

Θ_2 = water content of 2 foot zone (per cent available water)

Θ_3 = water content of 3 foot zone (per cent available water)

R_s = solar radiation (langleys day^{-1})

t_m = mean daytime temperature (^oF)

Models 1 and 2 are both highly significant, approximately 85 per cent of the total variation in the daily water loss from the one and two foot zones being explained by the designated variables. They are both stochastic models, since a significant amount of the daily variation from the upper root zones is accounted for by the stochastic climatic variables - solar radiation (R_s) and mean day-time temperature (t_m). However, the water loss from the three foot zone is essentially a deterministic model, dependent only upon its own soil water content (Θ_3) and that of the two root zones above it. The lower level of statistical significance of model 3 is probably largely explained by the relative inaccuracy of the soil water recording techniques (see Appendix I). As there was little daily variation in the four-foot water loss rates (see figure 4.2), no regression model was found to be significant.

It has been shown that due to a non-uniform root distribution, the alfalfa crop will only grow at optimum rates when there is an adequate supply of soil water in its upper root zone. Furthermore, the rate of water loss from this upper zone is controlled to some extent by the stochastic fluctuations in the atmospheric energy demand. Accordingly, in the following section, in which soil water availability is considered to be a stochastic variable, the parameter describing soil water content will represent the integrated value of only the one foot and two foot zones.

The Water Stress Model

The second hypothesis stated that the loss of soil water due to transpiration is a joint function of the atmospheric energy demand which promotes ET from the soil and plant surfaces and the soil water available to supply this evaporative demand. To illustrate this joint function, the relative rate of transpiration, i.e. the ratio of the actual loss (AE), measured by means of the water balance model (see equation 4.6) to the estimated potential loss (LE), calculated by the energy balance equation (see equation 3.10) was plotted against the integrated soil water tension in the top two feet of the alfalfa root zone (figure 4.3). Points were plotted for each of the three natural weather periods analysed in Chapter 3, producing the three significantly different functions shown on the figure. On overcast, cool days (weather type 1), on which the ET rate varied between 0.05 and 0.15 inches day^{-1}, the alfalfa crop transpired water at potential rates until the average soil water tension in the top two feet of soil was approximately four atmospheres. Under partly cloudy conditions (weather type 2), when the daily ET rate varied between 0.16 and 0.23 inches, ET began to decrease below estimated LE at approximately 2.3 atmospheres of tension, while on hot, sunny days (weather type 3), with warm air advection being utilized by the crop, the relative rate of transpiration decreased below unity at approximately 1.6 atmospheres of tension.

Denmead and Shaw (1962) call the point at which the relative transpiration curve drops below unity the "turgor loss point" (Θ_K) i.e. when the plant cells lose turgor and their growth rate decreases below the maximum rate under the prevailing weather conditions. From the above results it would appear that the amount of available soil water held in the top two feet of the alfalfa root zone at this turgor loss point is a stochastic function of the prevailing atmospheric energy demand. In figure 4.3 for illustration purposes, this functional relationship has been drawn as a discrete function. It is, of course, a continuous function, which is illustrated in figure 4.4. This curve expresses the average soil water

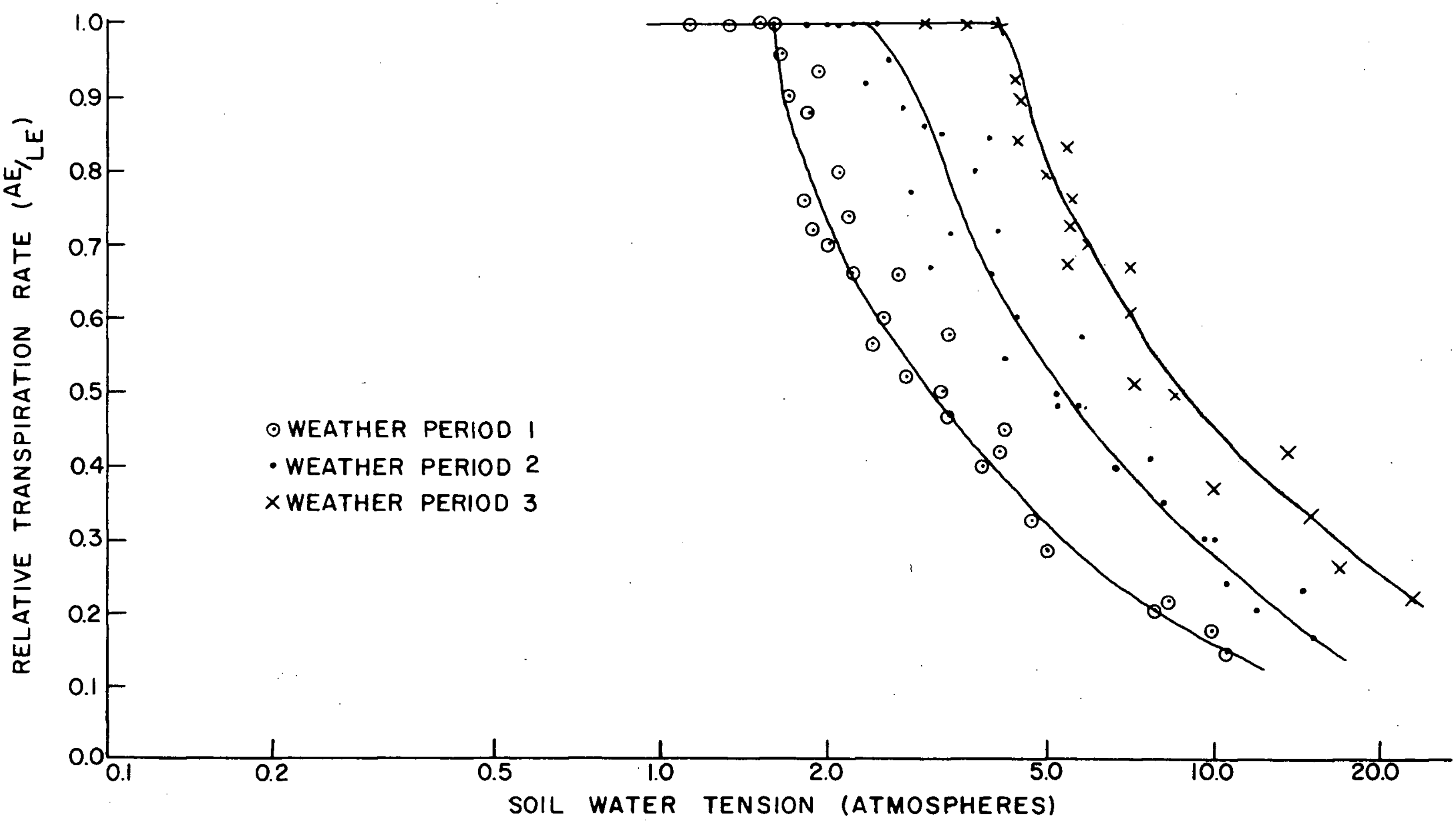

Figure 4.3 Actual Transpiration Rate from Irrigated Alfalfa as a Function of Soil Water Content during Three Natural Weather Periods, Summerland, B. C.

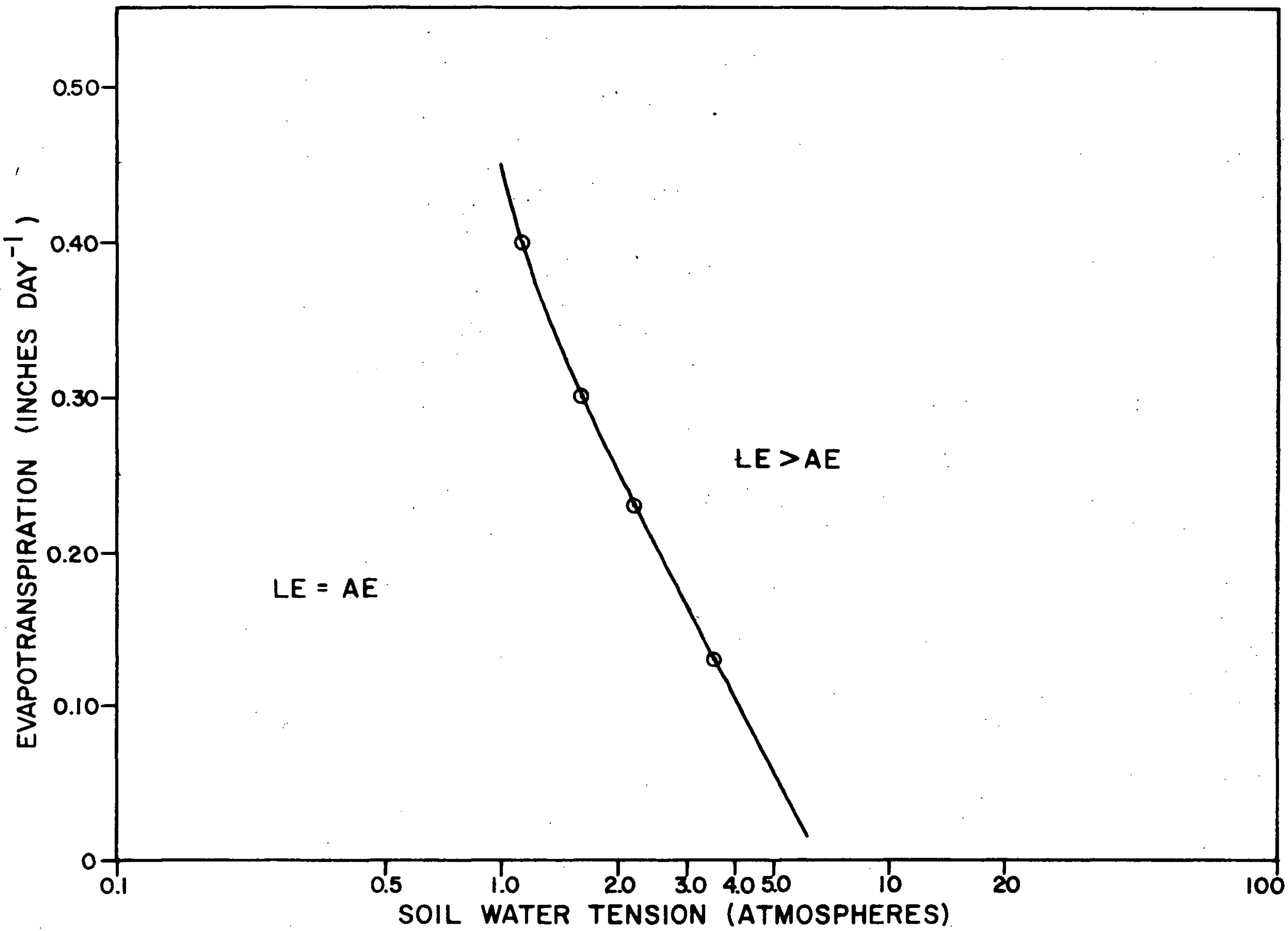

Figure 4.4 Soil Water Tension in Top Two Feet of Alfalfa Root Zone at Turgor Loss Point as a Function of Daily ET.

tension of the top two feet of the alfalfa root zone at turgor loss point as a function of ET.

Any day on which the combination of ET and the available soil water tension in the upper root zone is plotted to the left of the curve is designated a non-stress day (Dale and Shaw, 1965), i.e. the alfalfa is transpiring at optimum rates throughout the day. Any day on which the water tension - ET combination falls on or to the right of the curve is designated a water stress day and the alfalfa crop is assumed to be wilting during a major part of the day. Thus, to determine whether any day during the irrigation season is a stress day or a non-stress day, two parameter estimates are necessary:

(1) The average tension (or another related soil water parameter) of the soil water held in the top two feet of the alfalfa root zone, and

(2) The minimum soil water tension necessary to prevent alfalfa wilting, i.e. turgor loss point determined by estimation of the daily ET rate (see Chapter 3) and the functional relationship expressed in figure 4.4.

Summary

It was shown that the actual amount of soil water required to maintain optimum growth rates in irrigated alfalfa crops depended upon several factors that control the demand and supply of water. One of the most important variables influencing the supply of water to the crop was found to be its rooting distribution. Due to the high concentration of alfalfa roots in the upper root zones, optimum growth rates were only maintained when the upper two feet of the alfalfa root zone were adequately supplied with water. The smaller concentration of roots in the lower root zone could not extract sufficient water to maintain turgor.

The second part of the chapter related the supply of water in the upper root zone necessary to maintain optimal growth rates with the level of atmospheric energy demand. An important relationship between the integrated soil water tension in the upper root zone at turgor loss point and rates of ET was determined. This suggested that the wilting point or turgor loss point is not a deterministic parameter as conceived by many soil and plant scientists, but should also include a stochastic component dependent upon the energy stress acting upon the aerial part of the plant. Expressed symbolically:

$$\Theta_K = f(\Theta_U, ET) \qquad (4.7)$$

where

Θ_K is the turgor loss point,

Θ_U is the tension or amount of soil water in the upper root zone,

ET is the level of atmospheric energy demand.

The optimum decision rules concerning the time to irrigate can now be stated as follows:

1. Compare soil water tension[1] in upper root zone with relationship expressed in figure 4.4.
2. If, under the prevailing ET rates, the soil water tension is greater than the turgor loss point, do not irrigate.
3. If, under the prevailing ET rates, the soil water tension is equal to or less than the turgor loss point, irrigate.

---

1 The soil water tension in the upper root zone may be measured directly by means of electrical resistance blocks, or estimated by the soil water budget technique. Because it is based on many of the concepts relating to soil water availability discussed in this chapter, the writer advises the use of Baier and Robertson's "new versalite soil moisture budget" (Baier and Robertson, 1966).

CHAPTER 5

IRRIGATION WATER PRODUCTIVITY

The previous chapter presented the set of decision rules for determining the optimum time to irrigate. This chapter establishes the accompanying decision rules concerning the amount of water that should be applied at each irrigation. Again, these rules must conform to the efficiency objectives, i.e. to minimize the amount of water actually applied without reducing crop yields at minimum total cost. Irrigation water productivity is defined as the crop yield per unit of water applied. This definition is an improvement over the concept of transpiration ratio[1] because it relates crop yield not only to the water directly transpired and evaporated from the crop surface but also to the water lost as drainage below the root zone.

The objective of this chapter is to compare the productivity of water used in three experimental irrigation treatments, one of which employs the set of optimum decision rules controlling the time of irrigation and the amount of water to apply. The alfalfa crop yields will also be tested for any significant differences between irrigation treatments. Before this experimental design can be analysed, however, the necessary decision rules concerning the optimum amount of water that should be applied at each irrigation must be formulated. This procedure requires an examination of the drainage component of the crop water balance model.

Analysis of the Drainage Loss

Drainage of water below the crop root zone in excess of that required for soil leaching purposes is the major reason for the present

1 Transpiration Ratio is defined as the transpirational loss of water per unit of dry matter produced during the growing season (Daubenmire, 1947, p. 147). This ratio is also known as the transpiration efficiency.

inefficiency of irrigation water use in the Okanagan Valley. The proposed Shuswap Diversion Canal Report (B. C. Water Investigations Branch, 1966, Appendix 4) accepts the fact that, at present, approximately 52 per cent of the applied irrigation water percolates through the root zone into the ground water system and eventually re-enters the Lake. Only a small fraction of this return flow is available for reuse by the irrigators in the Okanagan Lake region[1], where little Lake water is directly applied by farmers, though a portion of it could be used in the Okanagan River region south of Penticton. Furthermore, it is possible that this drainage water contains a varying amount of pesticide, fertilizer and soil nutrient leachate, a source of contamination that the watershed can ill afford in the light of a growing concern over the rising levels of pollution from industrial and municipal wastes (Coulthard and Stein, 1968).

Drainage is a gravitational movement of water within the soil profile and follows Darcy's law (Gardner, 1960):

$$V = K_w \frac{d\phi}{dz} \qquad (5.1)$$

$$D = \int_o^t vdt \qquad (5.2)$$

where

V is the vertical flux of water at depth z (cm. sec.$^{-1}$)

K_w is the hydraulic conductivity of soil at depth z (cm. sec.$^{-1}$)

$\frac{d\phi}{dz}$ is the potential gradient of water in the soil at depth z (cm. sec.$^{-1}$)

D is the total drainage loss during unit time t (cms.)

The drainage component is difficult to measure quantitatively, not only because the estimation of the hydraulic conductivity (K_w) requires highly sensitive instrumentation (Rose and Krishnan, 1967), but because

1 Area lying north of Penticton, surrounding Okanagan Lake. It contains over 80 per cent of the present irrigated acreage (see table 2.1)

any analytical model would also have to account for hysteresis and pore size distribution (Biswas et al., 1966). Consequently, this important parameter has either been estimated indirectly (Rose et al., 1965; Rose and Stern, 1965) or derived empirically (Wilcox, 1960a; Richards et al., 1956; Ogata and Richards, 1957). In this irrigation experiment it was estimated as the residual in the water balance model (see equation 4.1).

$$D = \Delta\Theta - LE \qquad (5.3)$$

where

D = drainage loss per unit time (ins.)

$\Delta\Theta$ = measured volumetric change in soil water content (ins.)

LE = estimated ET using Bowen Ratio method (ins.)

An examination of equations 5.1 and 5.2 indicates that the drainage flux is proportional to the hydraulic conductivity of the soil (K_w) and to the potential gradient within the soil water system. Since both of these parameters are dependent upon soil water content, it follows that the drainage component should also be related to soil water content, i.e. the higher the soil water content, the greater the drainage flux (Biswas et al., 1966). It is also postulated that the amount of water applied (which controls the depth of saturation) should also affect the drainage flux. Therefore, it is hypothesized that the drainage loss following an irrigation D_I[1] will be a function of the depth of irrigation (I) and the amount of water remaining in the upper and lower root zones respectively at the time of irrigation (Θ_{UI}, Θ_{LI}). Expressed symbolically:

$$D_I = f(I, \Theta_{UI}, \Theta_{LI}) \qquad (5.4)$$

---

1 $D_I = \sum_{i=1}^{m} D_i$ where D_i is the daily drainage loss and m is the number of days with drainage following an irrigation.

Results

The accumulated drainage loss following a light and heavy irrigation on two alfalfa plots with similar initial soil water contents is shown in figure 5.1. This figure indicates that the 5-inch application lost almost twice as much drainage water as the 2-inch application. The heavier irrigation probably saturated the entire four-foot root zone of the alfalfa crop, allowing only a small potential gradient $-\frac{d\phi}{dz}$ to become established within the root zone and therefore a large drainage loss resulted.

The initial distribution of soil water within the root zone before the irrigation is also an important parameter controlling drainage. If the soil in the lower root zone is initially wet, drainage will occur immediately following an irrigation (figure 5.2a). If, however, the lower root zone is relatively dry, the irrigation water will wet this zone first before drainage below the entire root zone can take place (figure 5.2b). This process will not only delay the drainage loss but also reduce its total amount. For example, approximately 4.40 inches were applied to two different alfalfa plots with initial soil water contents of 15.8 per cent (1.1 atmospheres) and 8.6 per cent (4.5 atmospheres) respectively in their lower root zones. The "wet" plot lost a total of 1.35 inches of water due to drainage, while the "dry" plot lost only 0.87 inches.

A multiple regression model was constructed to analyse statistically the functional relationship expressed in equation 5.4, with the accumulated drainage loss (D_I) as the dependent variable, and the depthof irrigation (I), initial soil water content of lower root zone (Θ_{LI}) and initial soil water content of the upper root zone (Θ_{UI}) as the independent variables.

The results of the multiple regression analysis are shown in table 5.1. This regression model with a variance ratio of 108 and with 2 and 27 degrees of freedom is highly significant at the 0.01 level of significance. The coefficient of determination (R^2) indicates that approximately 90 per cent of the variation in total drainage following irrigations is explained by the variation in the amount of water applied and the initial soil water content of

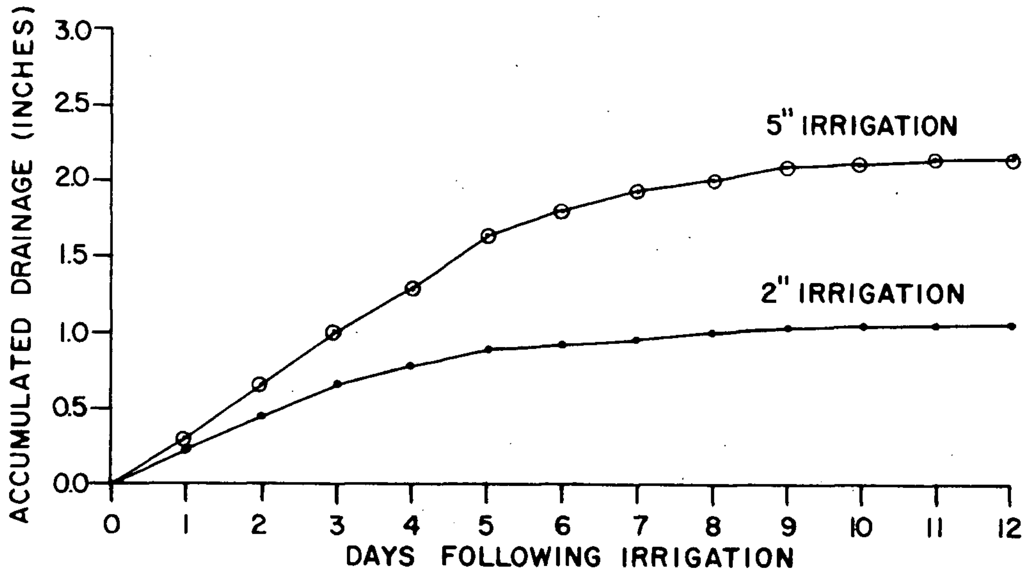

Figure 5.1 Accumulated Drainage Following Two Irrigations.

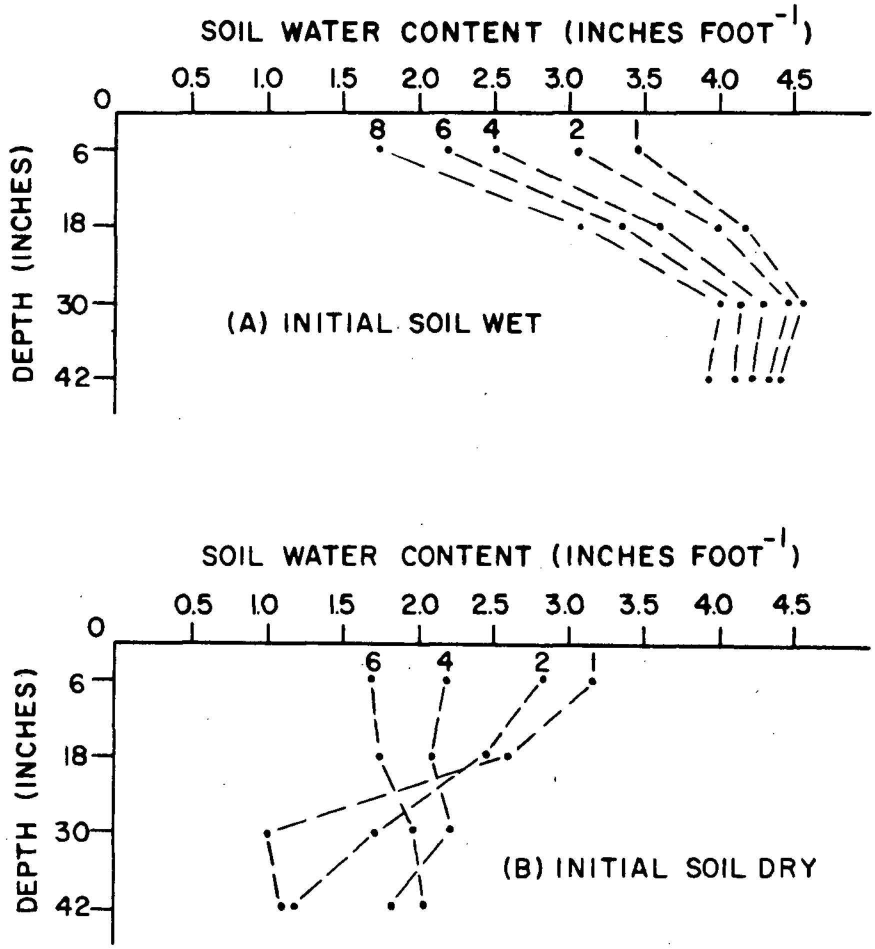

Figure 5.2 Redistribution of Irrigation Water within Soil Profile.

the lower root zone. The relative importance of the two significant independent variables is indicated by their standard regression coefficients. These show that the total drainage loss can be largely controlled by regulating the amount of irrigation water in accordance with the amount of water in the lower root zone.

TABLE 5.1

MULTIPLE REGRESSION AND CORRELATION COEFFICIENTS FOR THREE INDEPENDENT VARIABLES ON ACCUMULATED DRAINAGE LOSS FROM IRRIGATED ALFALFA PLOTS AT SUMMERLAND, B.C., 1967-68

Variable	Mean	Reg. Coeff.	Standard Reg. Coeff.	R	R^2	SE
I	4.10 inches	0.584 **	0.61	0.95	0.90	0.309 inches
Θ_{LI}	14.15 per cent	0.073 **	0.32			
Θ_{UI}	11.31 per cent	0.084 N.S.	0.07			

$$D_I = -2.05 + 0.384\ \Theta_{LI} + 0.073\ \Theta_{UI} \pm 0.309 \quad (5.5)$$

Decision Criteria Controlling Irrigation Application

The above results have shown that a large drainage loss and, consequently, low irrigation water productivity occurs when large amounts of water are applied to a soil where the lower root zone is relatively moist. Furthermore, it was shown in the previous chapter that the soil water extraction rate is a function of the crop root distribution and therefore soil water is lost more rapidly from the upper root zone than from the lower root zone. Therefore, instead of wetting the entire root zone to field capacity with every irrigation Wilcox (1965), irrigation water could be utilized more productively if the upper root zone was irrigated to field capacity with each application and the entire root zone only wetted when the soil water content in the lower root zone was initially less than a critical level - Θ_{LK}, at which the lower roots could no longer readily absorb water (approximately 5 atmospheres of tension in this experiment)[1]. Because the water loss rate from the lower root zone was approximately 50 per cent of that lost from the upper root zone, it was only necessary to wet the entire soil profile once in every two applications. The details of these decision criteria will vary with plant rooting distribution, soil type, prevailing atmospheric energy demand and the leaching requirements of the irrigated soils. In summary:

(1) Compare soil water content in lower root zone with Θ_{LK}.

(2) If greater, irrigate the upper root zone to field capacity.

(3) If equal or less, irrigate the entire profile to field capacity.

Irrigation Treatment Experiment

The irrigation experiment conducted on the Summerland Experimental Farm consisted of three irrigation treatments, each with four replications. Treatment 1 attempted to simulate the practice observed by many irrigators in the region. The typical farmer irrigates continuously, or almost continuously, throughout the irrigation season, moving his equipment every 12 hours. He, therefore, will completely irrigate his acreage within a standard period of time, depending upon the capacity of his equipment, regardless of the prevailing weather conditions. In this experiment, water was applied to the entire root zone every 8 days.

Irrigation treatment 2, the "model treatment", was based upon the decision rules controlling the timing and the amount of water applied during each irrigation. In contrast to treatment 1, the length of the irrigation interval was a stochastic variable, dependent upon the prevailing atmospheric energy demand. The decision rules controlling the amount of water applied were only included in this treatment during the 1968 irrigation experimental period.

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1 Crops growing in soils where there is an accumulation of salts in the lower root zone may require deep irrigations more frequently for soil leaching purposes.

In irrigation treatment 3, the alfalfa crop was irrigated only after it had been harvested, or approximately every 30 days. The crop wilted severely towards the end of each growth cycle after the upper root zone had dried out and it was hoped that a yield loss function could be developed.

The definition of irrigation water productivity given in the introduction to this chapter suggested that the optimum irrigation scheduling model would be one that could maintain optimum crop yields with minimum drainage loss. More specifically, this optimum scheduling model should maintain the soil water content in the upper root zone at or slightly above the amount at turgor loss point. Accordingly, to indicate how closely each of the three irrigation treatments compared with this theoretical optimum scheduling model, the daily integrated soil water tension in the upper root zone of the plot in each treatment was plotted against the daily turgor loss point (figure 5.3).

The top curve shows the measured soil water regime for the "wet" treatment 1, during the 1968 experimental period. The regular irrigation schedule constantly maintained the soil water tension in the upper root zone well above the turgor loss point, indicating over-irrigation and a large drainage loss. The middle curve is that for the model treatment 2, and, as expected, the soil water tension follows the turgor loss tension more closely than treatment 1. Although there were only two irrigations compared with three for treatment 1, the alfalfa crop was never subject to significant water stress. The lower curve depicts the situation for the "dry" treatment 3, and indicates that water stress developed within the alfalfa from the beginning of July until harvest on July 12.

Water Loss[1] Results

Parameters indicating the relative efficiency[2] of irrigation water use in each of the three irrigation treatments are presented in table 5.2.

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1 Water loss includes both ET losses and drainage losses.

2 The efficiency of irrigation water use is defined here as the proportion of total application directly transpired by the crop.

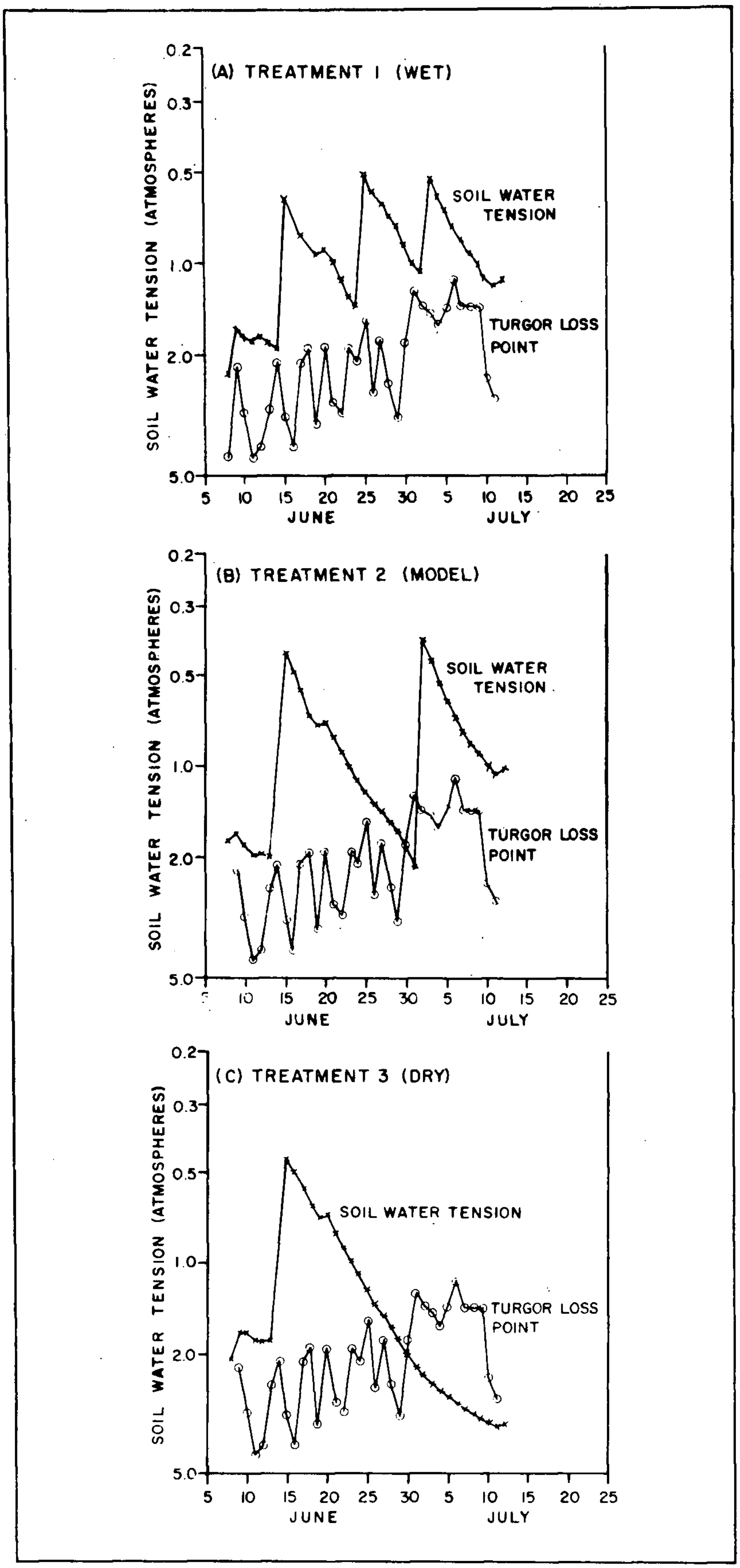


Figure 5.3 Daily Soil Water Tension in Upper Root Zone and Estimated Turgor Loss Point for Three Irrigation Treatments, 1968.

This table is an abstraction of the complete irrigation water loss data shown in Appendix IV. The inefficiency of irrigation water use as represented in treatment 1 is indicated by the large drainage loss (11.41 inches or 32 per cent of the total irrigation application), compared to drainage losses of only 4.54 inches (15 per cent) in model treatment 2 and 4.49 inches (22 per cent) in treatment 3. The same conclusion can be drawn from the relative use of water shown in row five, which indicates that treatment 1 lost 141 per cent of the water that the alfalfa crop actually required for ET compared to 115 per cent in model treatment 2 and 100 per cent in treatment 3. However, this statistic is only an average figure for the entire experimental period, for treatment 3 lost a considerable amount of water in drainage (due to large irrigation applications) and also suffered large water deficits (4.96 inches). Without doubt, the model treatment 2 was the most efficient user of irrigation water, since it minimized its drainage loss without encountering significant water stress.

This result is further emphasized in figures 5.4 and 5.5, which show the accumulated total water loss and drainage loss respectively for three plots in each of the irrigation treatments. The difference between the accumulated water loss curves for treatments 1 and 2 in figure 5.4 is mainly due to the large drainage loss from treatment 1, since the accumulated deficit in model treatment 2 is insignificant. However, the difference between the water lost in treatment 2 and 3 must be due to the water deficits accumulated in treatment 3, since the drainage loss from these two treatments is similar (see figure 5.5).

The average amount of irrigation water saved by irrigating according to the decision criteria followed in model treatment 2 instead of the traditional procedure represented by treatment 1 is approximately 20 per cent. This figure is probably an underestimation, since the major period of experimentation was undertaken during the exceptionally warm summer of 1967, when the differences between the two treatments would be at a minimum. The experiments in 1968 did not provide a good comparison between the productivity of water use for the two treatments because the

TABLE 5.2

WATER LOST FROM IRRIGATED ALFALFA PLOTS SUBJECTED TO THREE IRRIGATION TREATMENTS AT SUMMERLAND, B. C., 1967-68

	Treatments								
	1			2			3		
Irrigations	1967	1968	Total	1967	1968	Total	1967	1968	Total
No. of irrigations	6	3	9	4	2	6	2	1	3
Total water applied	26.88	8.35	35.23	23.27	5.72	28.99	17.59	2.30	19.89
Total water needed[a]	18.99	7.31	26.30	18.99	7.31	26.30	18.99	7.31	26.30
Total water lost[b]	27.79	9.76	37.30	22.25	8.07	30.32	20.32	6.64	26.84
Relative use of water[c]	146.3%	130.0%	141.3%	117.1%	110.3%	115.2%	106.4%	91.5%	100.1%
Total drainage	8.80	2.83	11.41	3.72	0.82	4.54	3.90	0.59	4.49
Total deficit	0.00	0.00	0.00	0.37	0.04	0.41	3.69	1.27	4.96

a Estimated by summing the daily LE calculations obtained by the Bowen Ratio method.

b The total amount of water lost to ET and to drainage.

c Ratio of water lost (row 4) to water required (row 3).

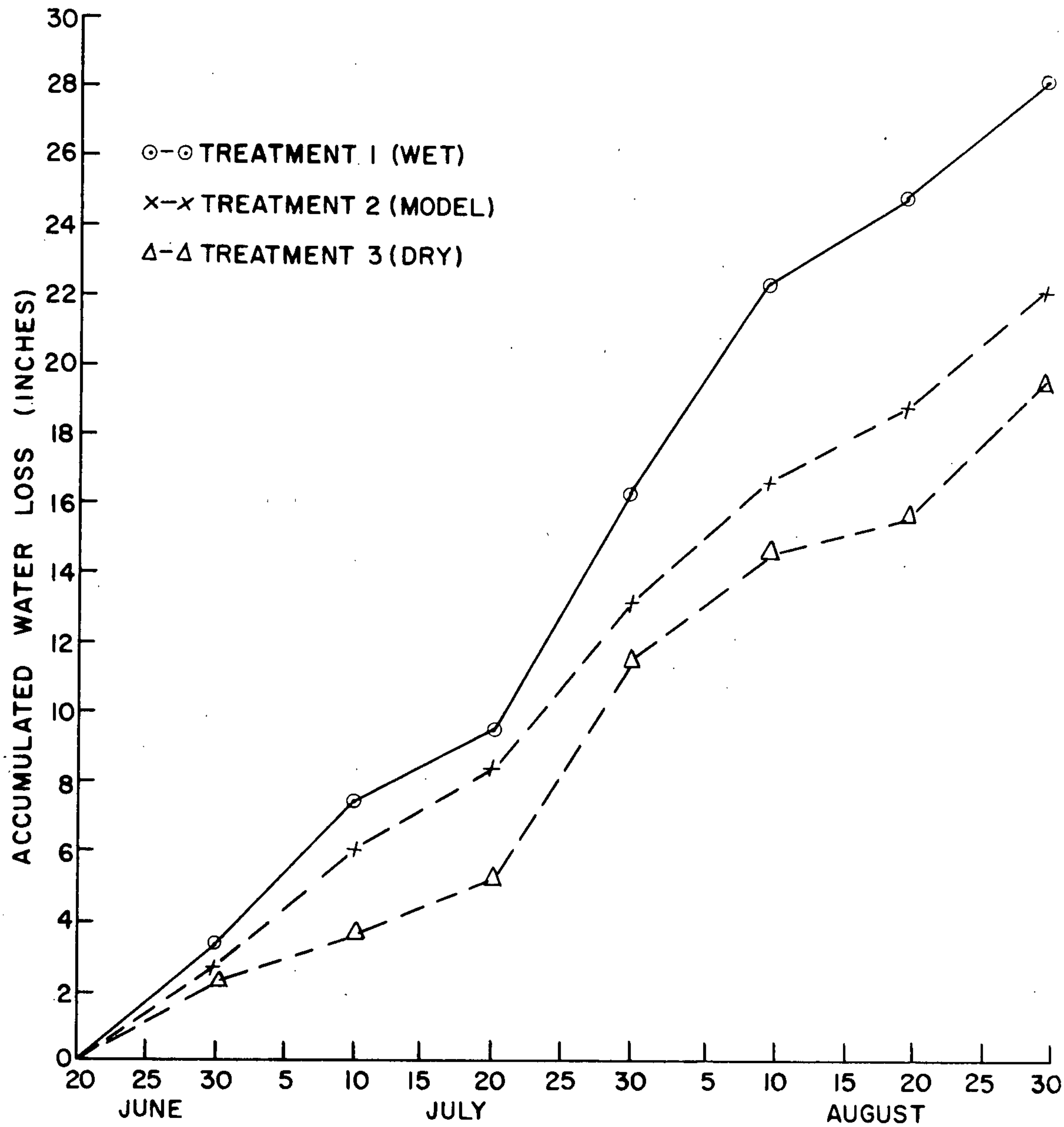


Figure 5.4 Accumulated Water Loss from Three Plots Subjected to Three Different Irrigation Treatments, 1967.

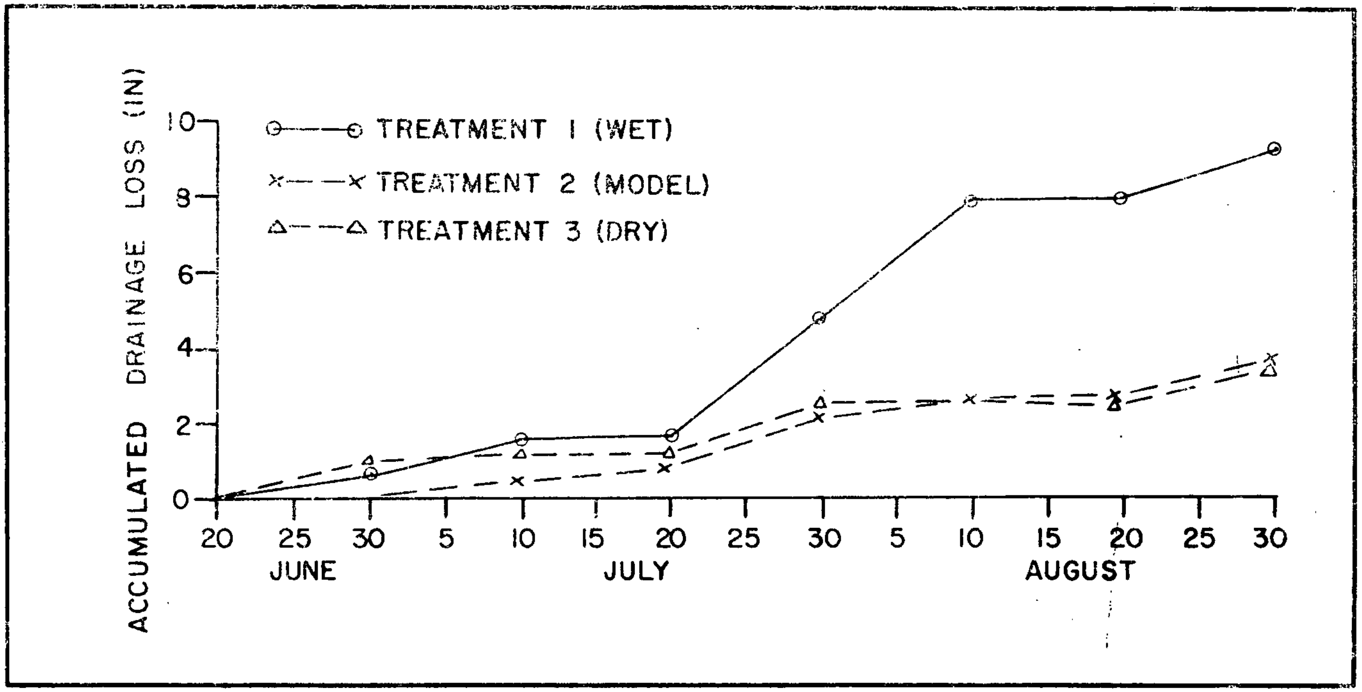


Figure 5.5 Accumulated Drainage Loss from Three Plots Subjected to Three Different Irrigation Treatments, 1967.

amount of water applied per irrigation on treatment 1 followed the same decision criteria as in model treatment 2 due to technical reasons (see Appendix II).

The definition of irrigation water productivity related the amount of water lost from the alfalfa plots to crop yield. It has already been shown that model treatment 2 can save a significant amount of irrigation water compared to traditional irrigational practices in the Valley. Is this saving achieved at the expense of a drop in optimum crop yield?

Crop Yield Results

The variation in average alfalfa crop yield for the three irrigation treatments is shown in table 5.3. There is apparently little difference between treatment 1 and model treatment 2, despite the reduction in water used by the second treatment. There is, however, a drop in yield for treatment 3 and the following section will test whether these variations in crop yield are statistically significant.

It is important to notice that the productivity of irrigation water is maximized in model treatment 2 (row 4). This parameter represents the total amount of water lost from the soil root zone due to both ET and drainage per unit of alfalfa crop yield. Thus, model treatment 2 lost a total of 2.78 inches of water for each pound of dry mater produced, compared to 3.40 inches lost from treatment 1 and 3.00 inches lost from treatment 3. The optimization of irrigation water productivity is an important criterion in irrigation scheduling, because it indicates that the amount of water not directly used for crop growth is at a minimum.

TABLE 5.3

AVERAGE YIELD OF ALFALFA FOR THREE IRRIGATION TREATMENTS AT SUMMERLAND, B. C., 1967-68

	Treatment		
Yields	1	2	3
Lbs. per plot	10.96	10.90	8.95
Est. tons per acre	2.71	2.70	2.23
Relative Yield[a]	100.00	99.5	81.1
Inches of water lost per lb.	3.40	2.78	3.00

a Per cent of crop yield in Treatment 1

Crop Yield Analysis of Variance

The irrigation experiment was originally established as a randomised complete block experimental design with three irrigation treatments and four replications (see Appendix II). However, since plot 1 was unfortunately disturbed by the movement of farm machinery, the first replication was removed for crop yield analysis of variance.

TABLE 5.4

RANDOMIZED COMPLETE BLOCK ANALYSIS OF VARIANCE OF ALFALFA CROP YIELDS FOR THREE IRRIGATION TREATMENTS AT SUMMERLAND, B. C., 1967-68

Cut	Source of Variation	Variance Ratio	Degrees of Freedom	Error Mean Square
1. July, 1967	Treatments	6.76 *	2 and 4	1.52
	Replications	1.54	2 and 4	
2. August, 1967	Treatments	7.82 *	2 and 4	0.59
	Replications	0.01	2 and 4	
3. July, 1968	Treatments	18.43 **	2 and 4	0.10
	Replications	1.52	2 and 4	

Table 5.4 shows the results of the analysis of variance of alfalfa crop yields for the three irrigation treatments during the experimental period. In each of the three alfalfa cuts there are significant differences in yield between treatments at the 0.05 level of significance. The table also indicates that there was no significant variation between the replications in any of the experiments and, therefore, to increase the power of the test, the experiments were re-analysed as completely randomized experimental designs (table 5.5). A significant difference between treatment yields remained for the second and third cuts, but disappeared for the first cut, which was not surprising since the irrigation equipment was not operational until the end of June 1967, by which time all the treatments had suffered some degree of water stress.

TABLE 5.5

COMPLETELY RANDOMIZED BLOCK ANALYSIS OF VARIANCE OF ALFALFA CROP YIELDS FOR THREE IRRIGATION TREATMENTS AT SUMMERLAND, B. C., 1967-68

Cut	Source of Variation	Variance Ratio	Degrees of Freedom	Error Mean Square
1. July, 1967	Treatments	4.90	2 and 6	1.79
2. August, 1967	Treatments	10.00 *	2 and 6	0.39
3. July, 1968	Treatments	15.67 **	2 and 6	0.12

The New Duncan's Multiple Range Test was performed on the means of each irrigation treatment yield to test for differences between individual means (table 5.6).

TABLE 5.6

TESTS FOR DIFFERENCES BETWEEN IRRIGATION TREATMENT MEANS

Cut	Treatment Means (lbs. per plot)		
	1	2	3
1	13.94	14.95	11.62
2	8.18	7.18	6.29
3	10.61	10.13	9.06

Any two treatment means not underscored by the same line are significantly different at the 0.05 level of significance. Thus, there was no significant difference between the average crop yields for treatments 1 and 2 in the second and third experiments, when the irrigation equipment was fully operational. There was, however, a significant difference between the yields of these two treatments and the yield from the third treatment. This result confirms the hypothesis that model treatment 2 can save as much as 20 per cent of water used in present irrigation practice (treatment 1) without any significant loss in crop yield.

Treatments 1 and 2 experienced few, if any, water stress days, while the third treatment was under considerable water stress towards the end of each alfalfa growth cycle (see figure 5.3). This relationship forms the basis of a yield loss function presented in the following section.

A Yield Loss Function

Because cell turgidity is essential for optimum growth, it is postulated that crop growth will be reduced on a water stress day and that alfalfa yields should be directly proportional to the number of stress days during each growth cycle. A regression model testing this relationship is presented in table 5.7. Both the linear and quadratic components of variance were included in the model, since it was thought that crop yield reduction would increase exponentially as the number of stress days increased.

TABLE 5.7

REGRESSION ANALYSIS OF VARIANCE OF YIELD LOSS[1] AND ACCUMULATED STRESS DAYS FOR ALFALFA AT SUMMERLAND, B.C., 1967-68

Source of Variation	Degrees of Freedom		Sums of Squares		Mean Square	F	R
Regression	2		11.01		5.56	7.22**	0.690**
Linear		1		3.99	3.99		
Quadratic		1		7.02	7.02		
Error	16		12.37		0.77		
Total	18		23.38				

Regression Model: $Y = 0.041 + 0.0618S + 0.0105S^2 \pm 0.43$ (5.6)

where

Y is loss in yield (lbs. per plot).

S is number of stress days during alfalfa growth cycle.

The results of the regression analysis indicate that both the linear and quadratic components of variance are significant and are therefore included in the regression model. The curvilinear model, significant at the 0.01 level of significance, explains approximately 47 per cent of the total variation in alfalfa crop yield reduction. This relatively low percentage is partly due to the various inaccuracies encountered in the harvesting

1 The average yield in treatment 1 was assumed to be the optimum yield under the prevailing climatic conditions.

techniques (see Appendix II) and partly because it was unlikely that the average yield in treatment 1 was, in fact, the optimum yield.

The model suggests that the occasional day of water stress will not significantly reduce the alfalfa crop yield (as shown by model treatment 2), but that the crop yields will be considerably reduced if this water stress is maintained over a period of several days (as shown by treatment 3). Therefore, the emphasis that Wilcox (1967c) places on the need to maintain a soil water supply in the crop root zone at or above the peak demand rates would appear to be unwarranted on both theoretical and practical grounds. A considerable saving of irrigation water and operational costs could be achieved without a significant reduction in crop yield if the scheduling model followed a policy in which the occasional stress day was expected[1].

Summary

Two sets of decision rules controlling the timing and the amount of water to apply during each irrigation have been theoretically determined from an examination of the S. P. A. S. Both of these control actions were incorporated into a model irrigation treatment, designed to increase the efficiency of water use in irrigated agriculture. Various water efficiency and productivity parameters were calculated for this model treatment from experiments with irrigated alfalfa and these were compared with the same parameters calculated from two other irrigation treatments, one simulating the present irrigation practice in the Valley and the other designed to allow a significant amount of crop wilting. In all aspects, the model treatment was the most efficient user of irrigation water. The experimental results showed that at least 20 per cent of the present irrigation application could be

1 This is frequently a desirable policy when making decisions under uncertainty (McMillan and Gonzales, 1965).

saved without reducing crop yields significantly. Finally, an exponential yield loss function was developed relating the loss of yield in treatment 3 with the total number of stress days experienced during the alfalfa growth cycle. This analysis indicated the feasibility of constructing an irrigation scheduling model in which the occasional stress day was expected.

CHAPTER 6

AN IRRIGATION CONTROL MODEL

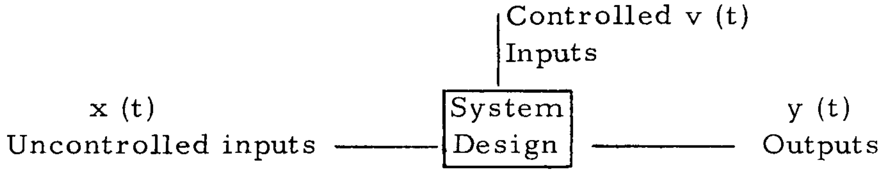
In chapters 4 and 5, two irrigation control actions were formulated from physical theory and tested against the objective function, viz. to minimize irrigation water without reducing crop yields. These "optimum" control actions are now inserted into an irrigation control model, which will enable the water resource manager to obtain maximum efficiency of use from his irrigation water supplies. The purpose of this chapter is to construct this model and to test its performance on irrigated alfalfa plots at Summerland.

Elements of the Model

It is necessary to understand the various elements of the irrigation water resource system before describing the actual design of the control model. A system is defined as "a set of objects together with relationships between the objects and between their attributes" (McMillan and Gonzales, 1965, p. 1). There are four major objects in the irrigation water resource system - water, climate, soil and plants. Attributes are the properties of these objects that affect the operation of the system. For example, the object, plant, has attributes such as height, root distribution, leaf area, albedo, all of which affect its ability to transpire water.

At any point in time these attributes may be measured and their value is known as a variable because attributes either vary in time or space, or both. There are three classes of variables acting within the system - exogenous (input), status and endogenous (output) variables (figure 6. 1).

Figure 6. 1 A Control System



Exogenous variables are independent of the system being modelled - "they act upon the system but are not acted upon by the system". (Maylor et al., 1966). They may be controlled or uncontrolled. The set of control inputs is denoted by an m-vector v(t), whose components v(t), . . . , v_m (t) are functions of time and represent such control actions as the number of irrigations, amount of irrigation water applied, cost of irrigation equipment, etc. The uncontrolled input x(t) is represented by the atmospheric energy demand variable (ET).

Status variables describe the state of the system at any point in time. An important status variable in the system described here is the integrated soil water stress in the upper root zone of an alfalfa crop for it is a major variable for determining the optimum time to irrigate (see chapter 4).

Endogenous variables are generated from the interaction of the system's exogenous and status variables according to the functional relationships operating within the system. In this case, the model output is an n-vector y (t), where y (t) . . . , y_n (t) denote such parameters as total irrigation water transpired, total drainage loss, total crop yield, etc.

The functional relationships that exist between the objects and their attributes tie the system together. They are either time or space dependent and transform status variables from one state to another. The important functional relationships have already been developed in the earlier chapters of this thesis, e.g. a demand function, a rooting function, a water availability function, a drainage function.

The major objects, their attributes and functional relationships of the irrigation water resource system are described in the table 6.1. Most of the functional relationships have already been modelled and tested and their text reference is provided in the table.

The analytical solution of the model is to devise v (t) so that the system output y (t) meets the efficiency in water use objective function noted above. Generally speaking, the desired system performance will not be attainable, due to the stochastic disturbance function x (t) - atmospheric energy demand. The water resource manager will therefore attempt to

TABLE 6.1

IMPORTANT ELEMENTS OF AN IRRIGATION WATER RESOURCES SYSTEM

Elements	Attributes	Functional Relationships
Climate	Net radiation, wind, temperature, vapour pressure deficit, LE/R_n ratio, weather period type, time of year, Bellani plate evaporation, precipitation	Multiple regression equation (3.6). Natural weather period covariance analysis. Bellani plate correction factors.
Crop	Leaf area, height (roughness factor), albedo maturity index (consumptive use factor), root distribution, crop type, crop acreage, yield.	LE/R_n ratio for alfalfa (figure 3.3), albedo (Appendix III), rooting regression equations (4.3), consumptive use factor function. Yield loss function (eq. 5.6)
Soil	Water holding capacity (storage), crop water availability, crop water level in upper and lower root zones, turgor loss point in upper zone, drainage criterion in lower root zone.	Desorption curves, calibration curves of volumetric soil water content (see Appendix I), soil water stress model (figure 4.4), drainage function (equation 5.1). Soil water loss functions (table 4.3).
Irrigation	Amount of water supplied, timing of application, number of days following an irrigation, number of irrigations, drainage loss, transpirational loss, total water loss.	Drainage criteria (equation 5.1), water stress model (figure 4.4), rooting effects in soil water loss (figure 4.2), expected atmospheric demand (see Chapter 6), drainage loss function (equation 5.1), soil water loss functions (table 4.3).

minimize the difference between the systems actual response and desired response by selecting an optimal set of control actions from all those permissible under prevailing technical and economic restraints (Sworder, 1966).

If a control input V_1 and a model output Y_1 are given for a unit of time (for example irrigation season), the criterion of performance h(l) is given as

$$h(V_1 Y_1) = \min (V_1 - Y_1)^2 \qquad (6.1)$$

where V_1 represents the total amount of water applied by the irrigator and Y_1 the minimum amount of irrigation water lost[1] from a soil-plant system during an irrigation season without reducing crop yields. Because there are no existing data to specify Y_1 for the region, the model cannot be solved analytically at present. Therefore, the dissertation approaches the problem from a different angle by determining an efficient irrigation application schedule (V_1) through experimentally formulating a set of decision rules concerning the timing and quantity of irrigation applications, and thereby ensuring that the performance criterior $h(V_1 Y_1)$ approaches a minimum. The model can then be solved by using either experimental data or simulated data.

Design of the Model

The primary objective of the irrigation control model is to find the minimum amount of water to be applied to irrigated land in a region without reducing crop yields and at a minimum total annual irrigation cost.

The model is envisaged as a type of inventory control problem (Buchan and Koenisberg, 1963; Pritchard and Eagle, 1965; Naddor, 1966), designed to analyze the management of a firm's stock. An inventory is

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1 Includes ET and drainage.

taken on the level of soil water in both the upper and lower root zones. In inventory control terminology, the time of irrigation becomes the reorder point and the amount applied becomes the reorder quantity. Crop wilting (i.e. stress days) becomes analogous to a stockout, which is represented by the yield loss function (equation 5.6).

More specifically, the irrigation control model is equated with the optional replenishment model of inventory control systems (McMillan and Gonzales, 1965). This model makes periodic reviews (in an irrigation control model, they could be daily or weekly reviews) of the level of inventory, replenishing the stock level only if the inventory (Θ_U) has fallen to or below a pre-determined critical level (Θ_K). The decision rules, therefore, are:

(a) Review the inventory status variables at intervals of duration R.

(b) If inventory $\Theta_U \leq \Theta_K$, order I units.

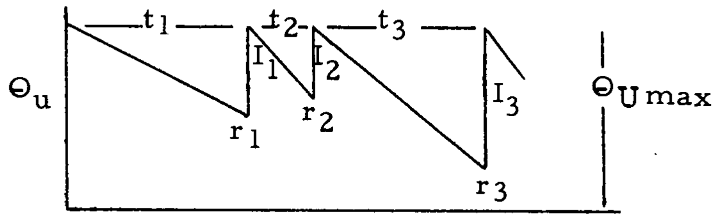
(c) If inventory $\Theta_U > \Theta_K$, do not order.

Reverting to irrigation control terminology, Θ_U is the level of soil water in the upper root zone; Θ_K is the turgor loss point determined by the joint function relating ET and soil water stress (see figure 4.4) and I is the amount of water applied and will depend upon the amount of water in the lower root zone (see Chapter 5).

The fact that the reorder point (r_i) is a stochastic variable determined by the prevailing atmospheric demand increases the complexity of the model. Thus, both the irrigation interval (t), and the irrigation quantities (I) are also stochastic variables as shown in figure 6.2. The model is deterministic in form because there is, at present, no simple solution to its stochastic counterpart (Gates and Anvari, 1968). However, this limitation is partly offset by using simulation techniques (see later section).

The model has a number of important advantages. Firstly, it subjects the soil water balance in both root zones to systematic analysis. Secondly, the optional replenishment model is flexible. As long as the reviewing period is short (a day is recommended), it can restock during advection weather in the middle and late summer without allowing significant crop water stress, or it can delay the reorder time during prolonged periods of cool, wet weather. Thirdly, the model is conceptually simple and can be easily adapted from existing mathematical analyses (Naddor, 1966).

Figure 6.2 Optional Inventory Control Model



where:

t_i is irrigation interval,

I_i is amount of irrigation water applied,

r_i is the reorder point,

Θ_{Umax} is total storage capacity of upper root zone.

The design of the model is shown as a flow diagram in figure 6.3. The programme must initially state all the important status variables associated with soil and crop conditions at the beginning of the irrigation season (April 15). If the model is designed for simulation, it should also read in the relevant climatic parameters required for estimating ET. The programme starts at day 1, which represents the beginning of the irrigation season. The soil water levels in the upper (Θ_U) and lower (Θ_L) root zones respectively for each day during the irrigation season are estimated according to the following procedures.

1. Calculate (or simulate) daily latent evaporation from Bellani plate atmometers (E).
2. Transform E into daily ET from a crop by using one of the set of semi-empirical coefficients appropriate to the prevailing natural weather type.
3. For annual crops, such as alfalfa, employ a consumptive use factor

(C. U.). This factor is defined as the ratio of consumptive use of water by a crop to ET (Coligado et al., 1968). It will be less than 1.00 for immature crops that do not cover the ground (see figure 3.6).

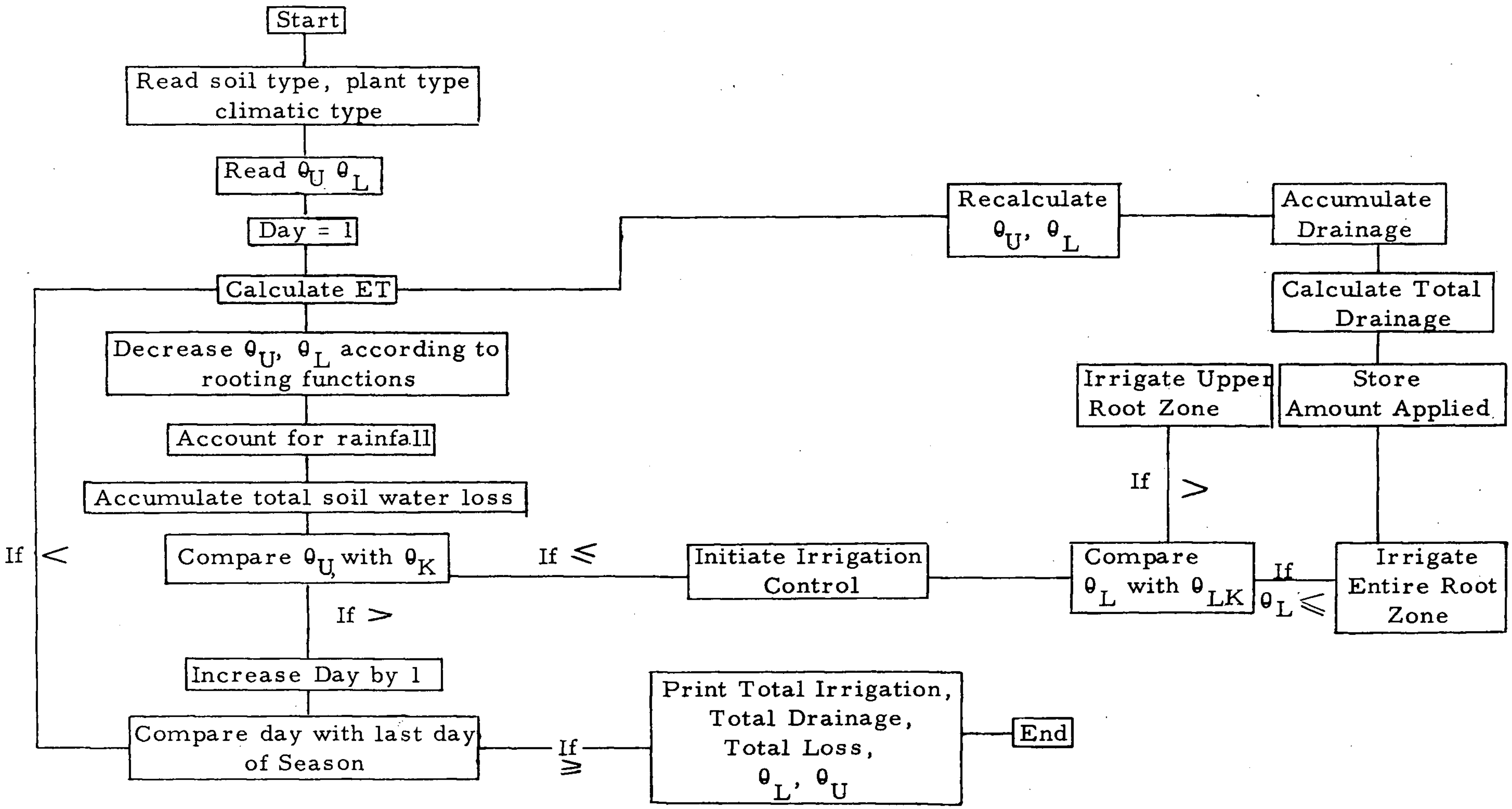
4. ET loss is prorated to 12-inch layers of the total crop root zone according to experimentally derived weighting factors determined by the distribution of effective rooting length and soil water amount in each crop root zone (see equation 4.5).
5. When rainfall exceeds the daily ET, the daily balance decreases by the amount of the difference. Experimental evidence has shown that this excess will increase Θ_U to its field capacity before wetting the lower root zone.

   If the total root zone water balance is at field capacity, the excess is assumed to be lost as run-off or deep percolation.

At the end of each day, the soil water level in the upper root zone (Θ_U) is compared with the turgor loss point (Θ_K) for the prevailing atmospheric energy demand conditions. If Θ_U is greater than Θ_K, the above procedure is repeated for the following day and continues until Θ_U is equal to or less than Θ_K. Then the irrigation control routine is activated. The amount of water applied depends upon Θ_U (see figure 5.2) and Θ_L (see irrigation decision rules on page 82). In either case, the amount irrigated is stored and accumulated throughout the irrigation season.

After each irrigation, the total drainage quantity (D_I) is calculated according to equation 5.4. It is accumulated throughout the irrigation season as return flow, which may or may not be a useful output depending upon the physiography of the irrigation watershed. This drainage total is not subtracted from the amount of water applied to the crop when recalculating Θ_U and Θ_L at the beginning of the next irrigation cycle, since drainage is part of the total loss functions used to reduce Θ_U and Θ_L each day. The seasonal transpiration requirement (consumptive use) for the crop may be obtained by subtracting accumulated drainage loss from the accumulated total soil water loss.

Figure 6.3 Flow Diagram of an Irrigation Control Model



The programme continues until the end of the irrigation season (September 30), when it prints the required outputs:

(a) total amount of irrigation water applied to the crop,

(b) total estimated return flow,

(c) total estimated soil water loss.

(d) soil water amounts in upper and lower root zones. These may act as a guide to calculating θ_U and θ_L at the start of the following year's irrigation season.

Analysis of Results

The seasonal march of soil water in the upper root zone is shown in figure 6.4 for two of the nine years for which sufficient data were available to test the model.[1] The upper root zone held approximately 5.0 inches immediately following an irrigation. The upper curve describes the soil water budget during the 1964 irrigation season, which was unusually cool and moist. Only five irrigations were necessary during the irrigation season, totalling 15.64 inches. The lower curve is that for the 1967 season, one of the driest summers this decade, in which nine irrigations were necessary, totalling 25.75 inches. It was assumed that crop yields were optimum as neither season experienced any water stress days.

The drainage loss, or return flow, was estimated at 2.63 inches in 1964 and 4.98 inches in 1967, or 14.3 and 16.3 per cent respectively, of the total amount of irrigation water applied. These figures compare very favourably with the present estimated 52 per cent return flow of applied irrigation water and a 32 per cent drainage loss from treatment 1, which simulated present irrigation practice in the Valley. Similar results for all eight irrigation seasons for which data were available at Summerland are shown in table 6.2.

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1 In both cases, the soil water balance was assumed to be at storage capacity at the start of the irrigation season.

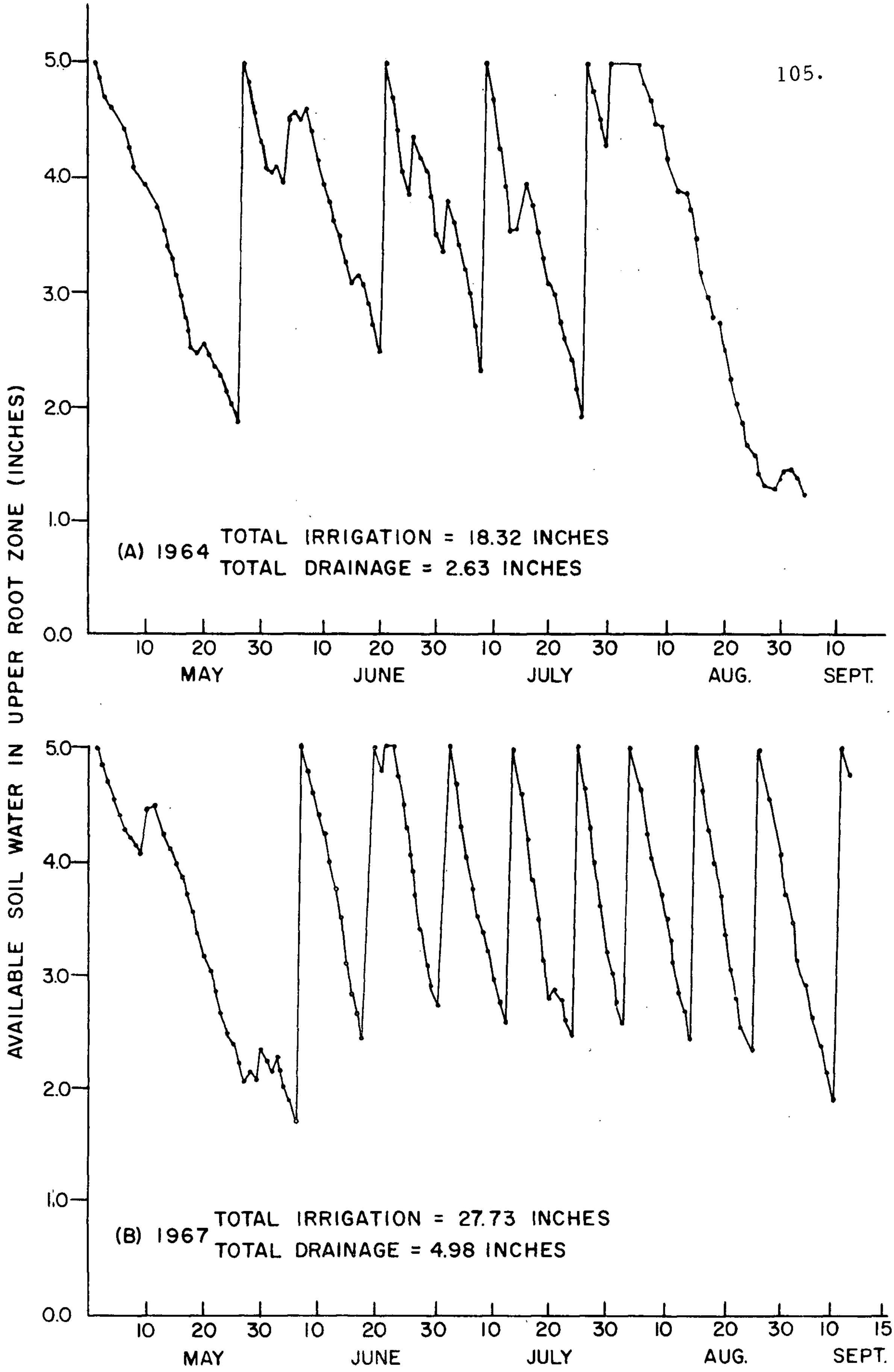


Figure 6.4 Estimates of Soil Water Held in Upper Root Zone of Irrigated Alfalfa for the Irrigation Seasons of 1964 and 1967 at Summerland, B. C.

TABLE 6.2

ESTIMATED IRRIGATION APPLICATION AND DRAINAGE LOSS FROM A SILT-LOAM UNDER ALFALFA WITH A 12-INCH STORAGE CAPACITY AT SUMMERLAND, B. C.

Year	Irrigation Water Applied	Total Drainage	Total ET	Rainfall
	inches	inches	inches	inches
1959	24.62	4.02	23.86	3.26
1960	26.13	4.26	23.77	2.90
1962	20.23	3.09	21.17	4.03
1963	22.42	3.50	23.18	4.26
1964	18.32	2.63	20.64	5.81
1965	19.72	2.87	21.53	4.68
1966	19.54	3.05	21.05	4.46
1967	27.73	4.98	25.70	1.95

Figure 6.4 also indicates that neither the irrigation interval (t_i) nor the amount of irrigation water applied (I) are time invariant, but vary according to the prevailing weather conditions, although during the 1967 season almost constant advection conditions from the middle of June until the end of August reduced their variation. Generally speaking, the greater the number of irrigations per season, the greater the total absolute drainage loss. Thus, in table 6.2, the total irrigation application shows greater seasonal variation than the estimated total ET.

Table 6.2 demonstrates the importance of the atmospheric energy demand variable in the input vector x(t). It directly influences the model outputs of total irrigation water application and drainage loss. To provide some indication of its variability during the irrigation season at Summerland, the expected value[1], 20 per cent[2] and 80 per cent probabilities of daily ET

1 Expected value $E = \sum_{i=1}^{n} Pi \;\; ET$

2 Probability (p_i) is expressed as an accumulated percentage and indicates the number of years out of 100 when the values cited are equalled or exceeded.

are shown on figure 6.5. The expected values of ET range from 0.12 inches day^{-1} during advection weather of July, decreasing to 0.11 inches day^{-1} in early September. In two years out of ten, however, ET from a mature alfalfa crop would be at least 0.30 inches day^{-1} by early June, increasing to a maximum of at least 0.35 inches in the middle of July.

Specific ET values, with their associated probabilities, can be used in conjunction with the joint relationship $\theta_K = f(ET)$ developed in figure 4.4 to estimate the amount of soil water required in the upper root zone to prevent soil water stress in the crop. These derived probabilities are shown in figure 6.6 for the silt loam used in the irrigation plot experiments. For example, to ensure that alfalfa will not be wilting on a day in early May, eight years in ten, only 35 per cent of the available soil water is needed in the upper root zone, but more than 60 per cent available soil water is necessary throughout July, with a peak requirement of 65 per cent during the second week of July.

Figure 6.6 demonstrates the need of a flexible reorder point rule in irrigation scheduling. The Wilcox model, which suggests irrigating when 50 per cent of the available soil water remains in the root zone, will tend to over-irrigate during the early and late weeks of the irrigation season when the ET is low and may allow some crop wilting during advective conditions. However, the expected value curve does indicate that his reorder rule is generally applicable from the end of June until the middle of August. This criticism should be qualified, since Wilcox developed his model to suit a wide range of soil and crop types for a field irrigation system. Nevertheless, there is no doubt that a constant reorder point strategy will not allow the optimum productivity of irrigation water resources in a region with significant climatic variability during its irrigation season.

Simulation

The second objective of the irrigation model is to test the sensitivity of its components by determining the relative importance of the various

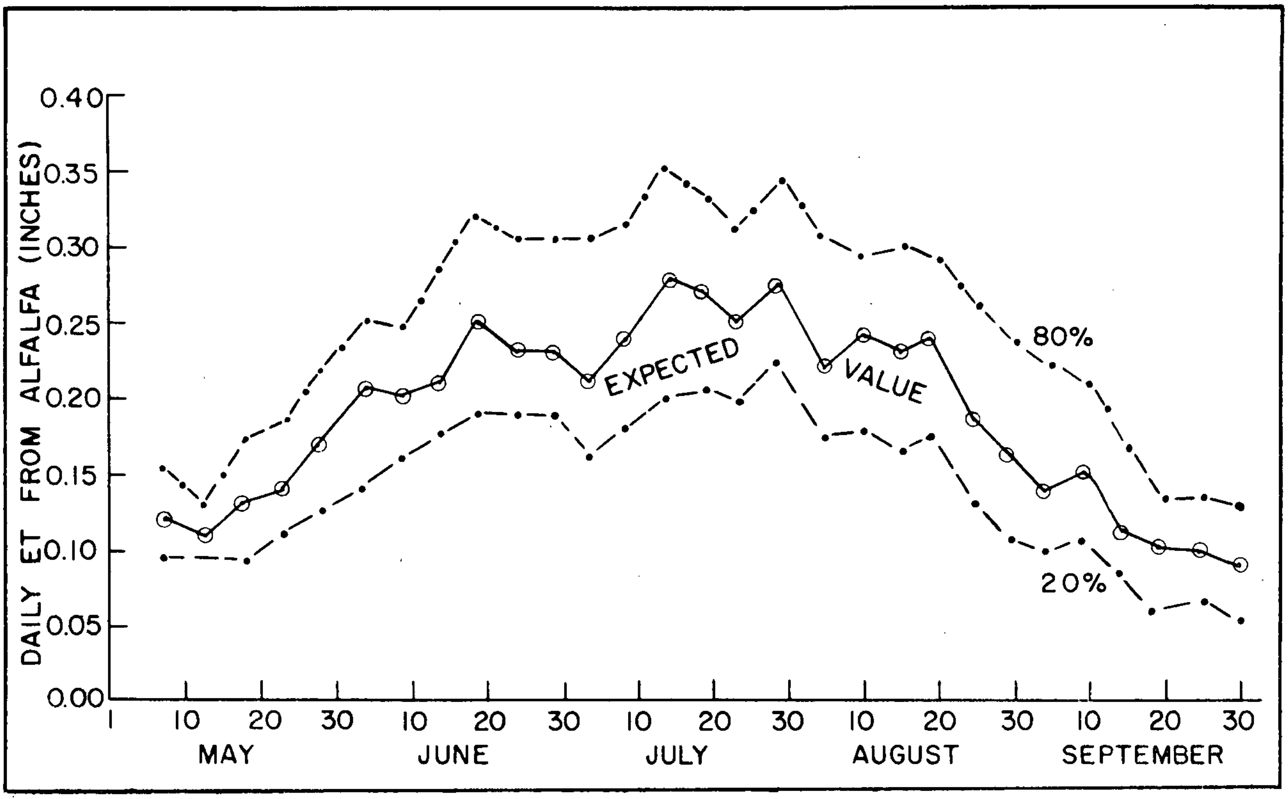


Figure 6.5 Seasonal Pattern of Estimated ET from Irrigated Alfalfa and Per Cent Chance of Exceeding Indicated Values at Summerland, B. C., 1959-1967.

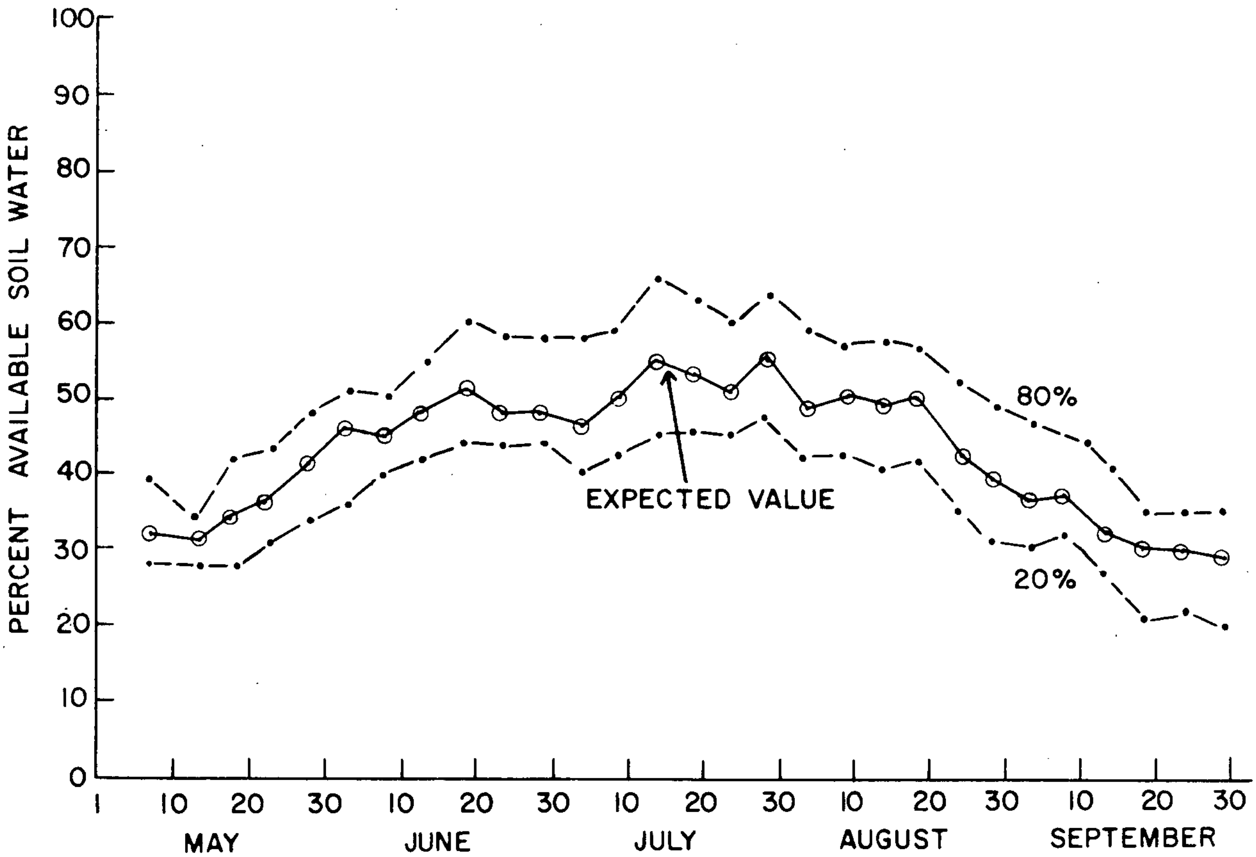


Figure 6.6 Soil Water Needed in Alfalfa Upper Root zone to Prevent Water Stress with Indicated Probability at Summerland, B. C., 1959-1967.

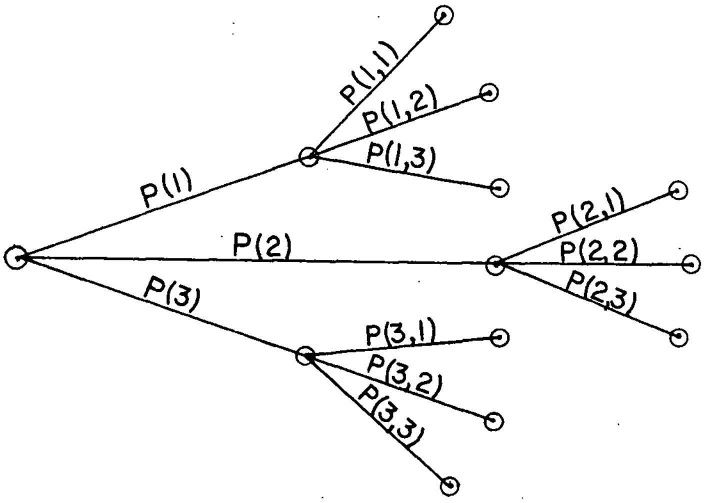
exogenous variables upon all the generated endogenous variables. This process requires solutions to the model. Since although there is no simple analytical solution to this complex stochastic problem, the resource manager can resort to simulation techniques.

Simulation has been defined as "dynamic representation achieved by building a model and moving it through time" (McMillan and Gonzales, 1965, p. 13). The model has already been built, its dynamic realization consists in using a digital computer to generate time paths of the exogenous variables and then programme these through the model. As indicated in the previous section, the level of atmospheric energy demand is the major exogenous variable determining irrigation requirements in the Valley.

Simulation of this stochastic process is based upon the probability parameters of its original distribution. Recently, a stochastic first-order Markov chain model has been used successfully to describe certain persistent patterns in climatological phenomena (Gabriel and Neumann, 1962; Hopkins and Robillard, 1964; Caskey, 1963). Evidence of the accuracy of this model for describing wet and dry spells in the south-central Interior of British Columbia has been presented by O'Riordan (1966). It is postulated that three natural weather periods described in Chapter 3 follow a Markov chain model. It should be remembered that these weather periods determine the semi-empirical coefficients used to convert Bellani plate evaporation into atmospheric energy demand.

The Markov chain model describes a system that shows a sequence of distinguishable states over discrete time intervals, each state being dependent upon a previous state. If the system is in state "i" at the beginning of one period, the probability that it will be in state "j" at the beginning of the next period is defined at $P(i,j)$. This statistic $P(i,j)$ is known as a transitional probability, since it indicates the probability of moving from one state (weather type) to another state or remaining in the same state as time passes. For each time interval $P(i,j) = 1$. These initial and transitional probabilities are illustrated in figure 6.7 by means of a probability "tree".

Figure 6.7 Tree Diagram of Markov Process through Two Trials



where

P(1) = probability of an initial day being a type (1) day (cool, cloudy).

P(2) = probability of an initial day being a type (2) day (partly cloudy).

P(3) = probability of an initial day being a type (3) day (hot, sunny).

P(1, 1) = probability of a type (1) day, the previous day being type (1),

and

P(1, 2) = probability of a type (2) day, the previous day being type (1).

The first step in the simulation process is to estimate the transitional probability matrix P(i, j) of the three weather period types affecting evaporation rates in the South Okanagan. This matrix, for a first order Markov chain, is presented in table 6.3. Statistical procedures (Feyerhern and Bark, 1965) based on the chi-square test indicated that the matrix did follow a first-order Markov chain model.

An analysis of table 6.3 underlines a number of points made in earlier chapters. Firstly, the probability of cool, wet days (type 1) is greatest in May and June but decreases rapidly in July and August, when the warmer, drier weather becomes more persistent.

TABLE 6.3

INITIAL AND TRANSITIONAL PROBABILITIES FOR A FIRST ORDER MARKOV PROCESS ON NATURAL WEATHER PERIODS IN THE SOUTH OKANAGAN

Probability	May	June	July	August	September
P (1)	0.30	0.23	0.13	0.17	0.30
P (2)	0.64	0.52	0.38	0.43	0.51
P (3)	0.06	0.24	0.50	0.40	0.19
P (1,1)	0.50	0.23	0.46	0.44	0.51
P (1,2)	0.50	0.74	0.49	0.56	0.49
P (1,3)	0.00	0.03	0.05	0.00	0.00
P (2,1)	0.20	0.25	0.13	0.16	0.27
P (2,2)	0.75	0.66	0.61	0.61	0.65
P (2,3)	0.05	0.09	0.26	0.23	0.08
P (3,1)	0.14	0.16	0.04	0.07	0.05
P (3,2)	0.57	0.35	0.14	0.21	0.27
P (3,3)	0.29	0.49	0.82	0.72	0.69

Secondly, the chance of advection weather (type 3) increases in July and August, when, as noted in Chapter 2, the soil-plant systems surrounding the irrigated areas have dried out. Thirdly, a comparison of the initial probability P(i), and the transitional probability P(i,i) for any month indicates the importance of the persistence effects of all three weather types. This result suggests that the weather type on any one day depends at least upon the weather type occurring on the preceding day. It is quite possible that for some weather types for some months this approximation might be improved by a second-order Markov chain, i.e. a day's weather depends on events occuring two days previously, though it is doubtful whether this improvement would be worth the additional computational effort.

Monte Carlo Simulation

The second stage in the simulation process is to generate these Markovian probability parameters on a computer. This process can be achieved by the Monte Carlo technique (McMillan and Gonzales, 1965). The ingredients of this method are a random variable (atmospheric energy demand), its probability distribution function and a sequence of random numbers. Each number in a list of two-digit random numbers is assumed to occur as frequently as any other two-digit number.

For example, the transition matrix of weather period types in May was calculated (see table 6.3):

		(1)	(2)	(3)
	(1)	0.50	0.50	0.00
P =	(2)	0.20	0.75	0.05
	(3)	0.14	0.57	0.29

To generate a sequence of process states, random numbers are assigned to the outcomes according to the probabilities in the matrix rows:

	(1)	(2)	(3)
(1)	0-49	50-99	-
(2)	0-19	20-94	95-99
(3)	0-13	14-70	71-99

The procedure is to specify the initial state, P(i), (which could also be generated by the Monte Carlo method using a cumulative distribution), obtain a random number from a random number generator, evaluate it and repeat the operation. For example, suppose the initial state is determined as type 1 and the following four two-digit random numbers are selected, 25, 84, 71 and 10. These four weather types would then be type 1, type 2, type 2, type 1.

Discussion

The results of processing the inventory control model of the irrigation water system (see table 6.2) indicate that it provides a reasonably accurate representation of the dynamic characteristics of water transfer through the S.P.A.S. in response to changes in environmental conditions (Woo et al., 1966). Unfortunately, no complete data from other field experimentation are available to compare the simulated results with those of actual experimentation. The dynamic model, developed in the present study, however, provides an integrated approach for a physical-statistical study of the complete irrigation water system.

The simulation of the atmospheric energy demand component of the exogenous vector, x (t), will allow the irrigation resource manager to generate several "irrigation seasons" on a computer and compare the results of the endogenous variables with the performance criterion. This process would permit a continuous reassessment of the model as feedback is incorporated in the system design. The decision maker can employ the yield loss function in conjunction with the Monte Carlo method to design a strategy-consequence matrix (Thall, 1954), by varying the allocation of irrigation water supplies to areas within the region. Not only will the irrigator gain from this improved allocation process, but all other water resource users in the Valley should also benefit in both physical and economic terms from a reduction in the irrigation "wastage". In addition to this potential serving, the water resource manager will have the satisfaction of knowing that his water resources are being utilized more productively.

By varying certain exogenous status variables, the decision maker will be able to programme several strategy-mixes into the model and observe their effect on output. For example, he can increase the acreage under irrigation by steps according to economic predictions of the demand for irrigated land (Ruttan, 1965). He will, therefore know in advance how much irrigation water he will require to meet these prospective demands and thus programme his supply function more efficiently. Similarly, he can estimate how a redistribution of crop acreage, for example, an increase in alfalfa at the expense of tree fruits, would affect the total seasonal irrigation water requirements.

The model can also be used on a sub-regional scale. The expected frequencies of seasonal irrigation water requirements for any irrigation district or farm unit could be obtained once the various exogenous variables were known and quantified. The decision maker could programme the total potential irrigated acreage of each district into the model and discover the possibility of transferring irrigation water from irrigation districts with potential surpluses to districts with potential deficits. This could be achieved with the aid of dynamic programming (Nemhauser, 1965).

The control model contains manifold economic implications for the irrigator. Since it is an efficiency model, it will enable him to minimize his capital costs and labour requirements (Wilcox, 1967b; Gray et al., 1966). It is assumed that the irrigation control model not only minimizes the amount of water applied by the irrigator, but also minimizes his frequency of irrigations. He could stimulate several "irrigation seasons" using various levels of capital equipment outlay to discover his optimum strategy regarding his irrigation system design and operational costs. Using the yield loss function, an irrigator could justify on economic grounds a risk of a water deficiency and accept some measure of under design. The level of this risk factor would be determined by the economic value of the crop and the physical characteristics of the S.P.A.S. Although there is not sufficient information available at the present time to assess such cost savings, it is evident from the exponential nature of the yield loss function that significant reductions in capital cost could be achieved by the use of evaporation frequency data.

Summary

An irrigation control model, based on the theory of inventory control was found to be a useful tool for managing irrigation water supplies. The use of a flexible reorder point strategy, which allowed irrigation applications to be in phase with varying levels of atmospheric energy demand, improved the control model's performance compared with a constant reorder point system design.

The frequency distribution of weather period types, which influence the level of atmospheric energy demand, were shown to follow a first order Markov chain model. Given the transition matrix for any month during the irrigation season, and a table of random numbers, a sequence of process states can be generated on a computer with the Monte Carlo method. Several managerial and economic implications resulting from the use of simulation were presented. It was suggested that a more rational approach to irrigation equipment design may be accomplished by using probability theory when estimating peak rates of ET.

CHAPTER 7

IRRIGATION POLICY IMPLICATIONS

Before discussing the irrigation policy implications of this study, the model is evaluated in terms of its operational characteristics. The accuracy of the model's output will depend upon two factors: (1) the accuracy with which the input variables are estimated or projected, that is, atmospheric energy demand, initial status variables for soil water levels in both root zones, amount of irrigated land, etc., and (2) the adequacy with which the functional relationships that are built into the control model describe the actual behaviour of the S.P.A.S. If model construction and parameter estimation are satisfactory, model outputs will have a greater influence on policy analysis.

Evaluation of the Model

Statistically estimated coefficients of the various functional relationships in the model appear to meet the tests of significance sufficiently well to permit control model simulation in environments similar to the one described in this thesis. Unfortunately, there is a complete lack of comparative data for different soil and crop types in other parts of the region to test the model. The building of such a data bank is a long-term project beyond the scope of this thesis, which was restricted to constructing a framework for an irrigation control model and testing the model under one set of environmental conditions.

Before the model is implemented throughout the region similar experiments should be carried out on a wide range of soil and crop types in order that the appropriate statistical parameters may be determined. Substantial modifications to the irrigation control actions could occur on sandy soils, where the total amount of available water is a small fraction of the water-holding capacity of the soil and where drainage rates are more rapid than in a silt loam (Wilcox, 1959). Because of the greater drainage loss from these soils, the model could save substantially more irrigation water than was estimated for a silt loam (Wilcox, 1962a).

The empirical estimation of net radiation is perhaps the most serious source of experimental bias. According to some investigators (Tanner and Pelton, 1960; Fitzpatrick and Stern, 1966), the techniques used in this dissertation (see Appendix III) can lead to a 10 to 15 per cent error. Since net radiation was the most important parameter used in the estimation of ET, the equations using the energy balance and water balance identities probably do not have a high order of accuracy. This source of error does not apply to the statistical analysis of natural weather periods (distinguished by their LE/R_n ratios), as the error would cancel itself. Despite this bias, the Bowen Ratio method probably produced more accurate measurements of ET than the other empirical methods used in the Valley (Baier, 1967b).

Failure to distinguish between the drainage loss and ET loss from each root zone in the soil profile is an important shortcoming in the water balance model. In the future, realistic water balance models must attempt to schedule the gains and losses of soil water in each significant root zone if an accurate assessment of the water budget is to be achieved (Baier and Robertson, 1966). Basic research in soil physics is required to solve this problem and to act as a check to the recent proliferation of empirical water balance models, some of which omit the drainage loss entirely. Recently, Wilcox (1968) has noticed that the ratio ET/E[1] when measured in the field immediately following an irrigation is significantly higher than experimentally determined values using a lysimeter. The most likely source of error is his failure to take full account of the drainage loss component. The more elaborate model produced by Baier and Robertson (1966) also amalgamates the drainage and ET losses from each layer of the root zone.

There are several reasons why the drainage component of the

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1 ET/E is the ratio between consumptive use (ET) and latent evaporation from Bellani plate atmometers (E).

water balance model should be more accurately estimated. Firstly, it is the major source of "wastage" of irrigation water and therefore should be controlled. Secondly, in some regions, irrigation water drainage, or return flow, is an important input into the water supply system for use by other water resource consumers downstream (Hartman and Seastone, 1965). Thirdly, in several semi-arid regions, including the Okanagan, a certain amount of drainage is necessary to prevent the accumulation of salts in the crop root zone.

Certain modifications to the yield loss function might result if a different yield criterion was employed. In this study, the dry weight of alfalfa was considered to be the commercially important yield criterion, but in the case of the tree fruits the yield of fruit is obviously more important. Several investigators (Richards and Wadleigh, 1963) have shown that orchards can experience a large number of stress days without suffering a significant reduction in fruit yield. The inclusion of this factor in the model could reduce tree fruit irrigation needs and lower present levels of capital investment in orchard irrigation equipment.

Institutional Constraints

Despite the limitations of the model and the qualifications of some of the empirical results discussed above, the irrigation control model does advance the analysis of the regional demand for irrigation water a step beyond that achieved by Wilcox and his associates. It simulates the dynamic characteristics of water transfer through the S. P. A. S. in response to changes in environmental conditions. By specifying soil, plant and climatic parameters for different parts of the region, the model's dynamic equations can estimate areal irrigation crop water requirements. It is anticipated that these results will be significantly smaller than those produced in the B. C. Department of Agriculture Reclamation Committee Reports. The failure to fully consider this non-structural alternative for solving water supply problems in the Okanagan is partly due to the information gap already described and partly due to the fact that efficiency in use measures fall outside the present policy framework of the Provincial water resources service. What,then are the implications of this study for the present institutional arrangements in water resources policy and law with reference to efficiency in irrigation water use?

Implications for Water Policy

Traditionally, most of British Columbia's water supply problems have been solved by engineering agencies responsible for construction. Because most engineers are unaccustomed to considering all possible alternative policy decisions in water management, there has been little attempt or incentive on the part of the decision maker to broaden his terms of reference and include non-structural measures. Furthermore, as the structural approach often earns federal financial support, it is often preferred by local governments, even when it is less efficient. So long as the tools for hydrologic analysis and dam construction are more advanced than those of conservation techniques, the engineering alternative may, in fact, be easier to implement. Thus, by default, decisions regarding solutions to the Province's water supply problems may be taken in ignorance or neglect of alternative solutions which may possibly yield better and more lasting social benefits.

The key issue in the study of water resource decision making is the adequacy and reliability of the information - technical, economic and social, that is available to the decision maker (Marshall, 1965). It seems to the writer that the Provincial government could become better informed on water resource issues if it wished, but a variety of circumstances, mainly due to institutional arrangements and professional bias, conspire to aid those in favour of construction projects and hinder their opponents from exposing possible alternatives. Injection of professional talent from the managerial sciences into the water resource administration would not only increase the body of knowledge available to the decision maker, which is essential for rational choice, but also, in the long-term produce more flexible policies to suit the demands of a dynamic society. Furthermore, social scientists could make the decision-making process more responsive to advances in science and technology that increase the efficiency of water use (National Academy of Sciences, 1966, 1968).

More research is necessary to discover better ways of co-ordinating both theory and practice in irrigation water management to meet the broad objective of efficiency in use. White (1961) has repeatedly pointed out that a large and widening gap exists between the scientific knowledge of efficient methods in resource management and its practical application by resource users, and that this gap is a major reason for the present inefficient use of resources. The irrigator must be made aware of all the alternatives that promote efficient water use through more effective means of the various communication media. To co-ordinate and organize this public education programme, irrigation resource managers, trained in efficient irrigation management techniques should be permanently employed at selected locations within the region.

Public hearings for all proposed policy measures would also help in solving this problem. At present the public is neither aware of the range of choice available to them, nor the associated costs, effects and consequences of implemented strategies (White, 1966). Public participation in the decision-making process would not only inform the decision maker of public preferences, but would help the individual resource user to identify himself with the problems and encourage him to increase his water use efficiency. Since public money is being invested, the public has a right to participate in the decision-making process.

Assuming that a resource manager makes a decision to increase the efficiency of water use, how can this strategy be implemented by the resource user? It is well known that the social resistance to change is great, especially in agricultural regions (White, 1962). Although the scheduling model devised by Wilcox has been in practical operation for four years, only a very small proportion of the Valley's farmers at present use it. One of the more productive avenues of research lies in identifying and evaluating the factors that promote this inertia. The resistance to change should be examined in the context of the age of the farmer, the way he perceives the water resource, the cost/price relations in which he acts and how he views his future gains and losses. More research is also needed to understand the processes by which social change can be achieved in water resource management. For example, there has been little investigation into the results of technical assistance efforts and the factors that account for their successes and failures (Fox, 1966a).

Federal and Provincial policy has long made water available for irrigation at less than cost and certainly less than the value in some other uses (Wollman, 1962), consequently the manner in which water is used is not determined by the cost of supplying the water, or by its value in other uses. Since 1918 the Provincial government has assisted the development of irrigation in the Okanagan by generously subsidizing irrigation development through the provision of interest-free capital and more recently under the A.R.D.A. cost-sharing programme for irrigation district rehabilitation. This policy has been justified on social and political grounds - that public investment in irrigation, even if not profitable according to market economy criteria, can contribute to the growth and stability of the region (Haveman, 1965). Departure from optimum water resource productivity might be justified if rapid expansion of the present irrigated acreage in the Valley was necessary to meet food requirements or if water allocated to irrigation had few alternative uses. The fact is, however, that there is no urgent need to expand irrigated acreage; there is plenty of water already stored in the tributary watersheds to meet current demand <u>if it is used efficiently</u>, and important alternative uses for water are rapidly emerging.

By consistently expanding water supplies whenever they are demanded by an extension of the presently irrigated system, the Provincial government has indirectly encouraged the inefficient use of water (Krutilla, 1966). At present, gross annual irrigation water requirements for irrigation purposes in the Okanagan watershed are estimated at approximately 190,000 acre feet (see table 2. 1). It was estimated that by employing the irrigation control model, savings of at least 20 per cent of this total application could be achieved. Thus, approximately 38,000 acre feet of water could be released from its present use and reallocated either onto an extension of the irrigated acreage or for alternative uses in industry and municipalities.

This result suggests the desirability for re-examining Provincial policy with reference to the proposed Shuswap Diversion Scheme (B. C. Water Resources Investigation Branch, 1966). Because most of the land not presently irrigated is marginal in terms of soil productivity or inaccessibility of cheap water supplies, it is doubtful whether the economic returns from irrigating this acreage will be as high as the present low productivity returns. This is especially true in areas where water will have to be pumped onto the bench-land from Okanagan Lake[1].

At a time when the nation is concerned about its rate of economic growth and when the Federal government is cutting down its public expenditures, it is questionable, to say the least, to invest heavily in a project where costs exceed prospective returns. This is not to argue that planning to meet future demands is not desirable. There would seem to be a strong case, however, for pursuing the efficiency of use alternative now that construction costs are large, and delaying implementation of future engineering projects until market forces support the implications of projected costs and returns (Hirschleifer et al., 1960).

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1 Kaleden I. D. obtains its irrigation water supplies by pumping water from Skaha Lake. The irrigation tax is $48 per acre compared with an average $21 in other districts.

Implications for Water Law

Provincial water law, like Provincial water policy has also tended to inhibit the efficient use of water resources. At present, all consumptive uses of water are licenced and priority is assigned to seniority in licence tenure (DeBeck, 1967). Irrigation districts hold property and water rights as trustees for the irrigators within their jurisdiction, and are entitled under the law to a specific quantity of water, which as was pointed out in Chapter 2 is considerably more than is actually required for crop irrigation. Yet, there is no incentive to irrigators to conserve water, for neither the irrigation districts nor the irrigators themselves receive any benefit or credit for using less than their full legal entitlement. They are, in fact, encouraged to use their full water right every year and thereby waste part of their water in wet years because of a beneficial use obligation, which could deprive them of their water right for failure to use all their licenced supply on their lands. As new means for achieving efficiency are discovered, less water will be required and thus the irrigation licence should either be reduced or part of it transferred to irrigate more land or put to some other water use[1].

It is this large scale, low productivity use of irrigation water that is forcing the Province to invest heavily in the development of future water supplies for the Okanagan Valley. An increase in irrigation efficiency would not only release large amounts of water for more productive uses, but would also make irrigation water use productivity more competitive (Clark, 1967). Thus, implementation of the conservation strategy would benefit, directly or indirectly, every water user in the Valley.

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1 The present Provincial water law contains a provision for the transfer of a water licence from one landowner to another and from one use to another subject to the discretion of the Comptroller of Water Rights (DeBeck, 1967, p. 52).

Modernizing the Institutional Process

How can the present Provincial water legislation and policies be improved to encourage more efficient irrigation water use in the Okanagan? Firstly, there should be a change in the present pricing policy. As mentioned earlier, prices now charged to irrigators are considerably less than the real cost of supplying that water. In all irrigation districts, with the exception of Vernon, an irrigator pays a fixed irrigation tax to cover the annual operating costs of the district. As this is assessed on an acreage basis only, he can use all the water available to him at no extra cost. When marginal costs are zero, the resource is generally considered worthless and there is a tendency to waste it (Howe and Linaweaver, 1967).

Studies (Moore, 1962) have indicated that irrigation water is price elastic, that is, an increase in price will lower the quantity used. Thus, a more rational pricing policy would include a toll on the amount of water applied by the irrigator, in addition to the acreage tax. An irrigation metering network would have to be established to monitor the amount of water used by each irrigator. This metering network could be integrated with a system of gauges on reservoir outlets and stream diversion points to provide a complete picture of irrigation water supply and demand patterns throughout the Valley.

Secondly, implementation of the efficiency alternative would require a major reorganization of the existing farm units. At present, many irrigators operate marginal farm units, covering between five and ten acres, often on a part-time basis. The irrigation control model described in this thesis would obviously be more operational on large, efficient farm units, operated by full-time farmers. Amalgamation of the smaller farm units into larger profitable enterprises would, no doubt, increase the agricultural returns in the Valley, though these increased economic returns would have to justify the social costs of dislocation. Moreover, the consolidation of farm units would simplify the installation of an irrigation metering network.

In addition to farm unit reorganization, some of the smaller irrigation districts would need to amalgamate into more comprehensive administrative units. They could then pool their resources and establish a more efficient, technical organization better suited to analysing the model and implementing the appropriate irrigation controls within the region. Under such an efficient irrigation control system, the water resource manager would know how much water was being used in each irrigation district and, therefore, could constantly reassess the spatial variation of irrigation water supply and demand.

Implications for Future Research

There are two main avenues for future research in addition to the testing of the model's functional relationships for various plant, soil and climatic conditions mentioned earlier. These include (a) the evaluation of marginal value productivity in irrigation water resources and (b) modifications to the model to incorporate inter-regional as well as intra-regional optimizing criteria.

Marginal Productivity

It was pointed out earlier that a more rational policy for allocating water supplies should be based upon the simulation of market criteria, where the cost of water for irrigation will depend not only on the water supply functions but also on the value of water in alternative uses (Steiner, 1965). Such an analysis requires the evaluation of the marginal productivities of water in each of the various uses, and will likely become more important as competition among water users increases within most water resource areas.

The marginal value product is the value of the additional output resulting from the increase of one unit of input. The model could simulate "irrigation seasons" in which the number of irrigation applications was deliberately reduced below the optimum to decrease yields. The programme could then be re-run with step-wise increases in the number of irrigation applications and the resulting yield increases could be converted into marginal productivity units. The results of this research could be incorporated into the input matrix of the farm productivity analysis already established by the B. C. Department of Agriculture (Pankratz and Chan, 1966). The improved productivity analysis of irrigation farms in the region would be an invaluable tool in the possible consolidation of existing marginal farm units as well as providing the water resource manager with information concerning both the spatial and temporal variations in irrigation water productivity.

Inter-regional Aspects

From either the Provincial or the federal perspective, optimization of water resource use among regions as well as within regions is a desirable objective (Margolis, 1959). Inter-regional transfers of water are already a reality in some areas (Quinn, 1968) and may be expected to occur in the southern Interior of British Columbia in the near future. Since transfers of water are public investment decisions, the irrigation control model should be broadened to analyse and permit transfers of irrigation water from one region to another where the difference in marginal value product is sufficient to cover capital and transportation costs.

Conclusions

The variety of measures for improving irrigation water use efficiency discussed in this dissertation could be incorporated into plans for improving the water utilization system in the Okanagan Valley. Planning, however, is only the first step in the management problem. The system must be implemented and this chapter has shown that there are presently a number of restrictions in both the planning and policy phases of water resource management in British Columbia that prevent such comprehensive development of the Okanagan Valley's water supplies.

Identifying alternatives for a water resource management system and devising plans that combine them optimally is a demanding task.

Moreover, planning and implementation are complicated by the diverse decision-making responsibilities for the various components of such a system. Despite these problems, there are indications that comprehensive river basin planning, which incorporates the efficiency in water use alternative will earn more respect in future policy and planning of British Columbia's water supplies. Recently, the federal Government announced plans to co-operate with the Provincial Government in a pilot study of water quality and quantity control in the Okanagan Valley. It is hoped that the results of this dissertation will have some influence on the proposed study, for in the development of water use efficiency models lie the major hopes for improving rational water resource management.

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APPENDIX I

DESCRIPTION OF INSTRUMENTATION

The level of accuracy of the experimental data should be in accord with the stated objectives of the research project. The principal objective of this research programme was to construct a regional irrigation control model, based upon a physical understanding of the soil-plant-atmosphere system. Detailed examination of the dynamic characteristics of water transfer through the S.P.A.S. would require expensive and sophisticated instrumentation, little of which was available to the researcher. It was believed, however, that the above objective could be achieved with a general understanding of the system characteristics and inter-relationships, making highly accurate experimentation unnecessary.

For convenience, the details of instrumentation and calibration have been divided into two parts, viz. the atmospheric environment and the soil environment. No direct instrumental recordings were made on the alfalfa crop. The period of experimentation extended from June 20 to August 30, 1967, and from June 7 to July 31, 1968.

The Atmospheric Environment

The climatic variables affecting the S.P.A.S. were recorded at the Experimental Farm weather station, situated approximately 500 yards north of the experimental plots, as well as at the plots themselves. All integrated daily records were observed at 07:30 hours, L.A.T.[1]

Solar Radiation

Daily totals of short-wave solar radiation (R_s) received by a horizontal surface near the ground were recorded on an Epply Pyrheliometer at the weather station. The instrument was operated and calibrated by officials employed by the Department of Transport. The hourly values

1 Local Apparent Time.

printed out by an integrator attached to the instrument were corrected for night-time instrumental recording errors and air temperature variations.

Sunshine

Total hours of bright sunshine were recorded daily on a Campbell-Stokes sunshine recorder situated on the weather station.

Wind

Total daily wind run (expressed in miles day^{-1}) was recorded on both the 2-foot and 4-foot recording cup anemometers. Since these instruments were relatively sensitive to local variations in wind speed, they did not provide very accurate records of the total daily wind run over the experimental plots.

Rainfall

Daily rainfall amounts were recorded in both a manual rain gauge and a recording tipping-bucket rain gauge situated on the weather station.

Evaporation

a) Class 'A' Pan. The 4-foot Class 'A' evaporation pan recorded daily rates of evaporation at the weather station. These recordings were probably somewhat greater than actual rates of pan water loss since the sides of the pan absorbed a significant amount of solar radiation (Mukammel and Bruce, 1960), which provided an additional supply of energy for evaporation.

b) Bellani Plate Atmometers. Daily rates of latent evaporation were recorded by two Bellani plate atmometers, situated at the perimeter of the experimental plots approximately 4 feet above the ground. A description of this apparatus can be obtained elsewhere (Livingston, 1935). The plates were cleaned regularly and were calibrated against Bellani plates situated on the weather station at the beginning and end of the experimental period each year. The daily data were standardized by means of a plate factor supplied for each plate by the manufacturing company.

Temperature and Humidity

a) Hydro-Thermograph. A hydro-thermograph provided a continuous trace of both air temperature and relative humidity in a standard Stevenson Screen located close to the experimental plots. The instrument was calibrated each week against an aspirated psychrometer. Daily maximum, minimum and mean air temperature during daylight hours were obtained from the temperature graph.

b) Aspirated Psychrometer. The vertical air temperature and vapour pressure gradients over the irrigated alfalfa crop were recorded with an aspirated psychrometer. To reduce the radiation errors to a minimum, both the wet and dry bulbs of the instrument were shielded (Pasquill, 1949).

There is considerable discussion concerning the appropriate heights at which the temperature and vapour pressure should be measured. Fritschen (1965) suggested that for small fields the gradients should be measured close to the ground, and used heights of 5 cms. and 40 cms. However, Munn (1966) noted that the Bowen Ratio is most accurate in environments where the radiative flux divergence is negligible. Since the radiative flux divergence is likely to be greatest near the ground, he suggested that the instrumentation should remain at least a meter above the ground. Suomi (1957) working in conjunction with the Great Plains Turbulence Programme, recorded the vertical gradients of temperature and vapour pressure between 0.4 and 0.8 meters. In consideration of these views, and because of the large roughness factor over an alfalfa field, the heights chosen for this experiment were 0.4 and 1.6 meters.

Since the component fluxes of the energy balance vary greatly throughout the day, recordings of the temperature and vapour pressure gradients should be taken approximately every half-hour (Suomi, 1957). Commitments to other aspects of the research programme only allowed recordings to be taken three times a day, at 07:30 hours, 11:30 hours and 15:30 hours, L.A.T. On three separate days in 1968, readings were taken hourly. It was found that the daily energy balance estimates, based on an average of the three daily recordings, did not differer significantly from the same estimates derived from the integrated hourly data. This fact has been observed by other investigators (Tanner and Pelton, 1960; Bavel, 1966).

The Soil Environment

The soil type in the experimental plot area was a Penticton silt loam (Kelley and Spilsbury, 1949). Its profile, extending to 4 feet in depth, was developed over a parent material composed of deep beds of stratified silt, clay and fine sands. The profile description is as follows:

Horizon	Depth	Description
A_1	0 - 10 inches	Brown to pale brown, silt loam; soft and friable, with fine granular structure. pH 7.6.
B_1	10 - 20 inches	Pale brown silt loam; massive and compact. pH 8.0.
B_2	20 - 42 inches	Greyish-brown silt loam; compact with specks of lime. pH. 8.6.

Three soil parameters were measured during the course of the experiment; (a) soil water content, (b) soil temperature and (c) soil density.

Soil Water

Three techniques were used to measure the soil water content.

(1) Electrical Resistance Blocks. The daily change in soil water content was measured by means of electrical resistance blocks. They are inexpensive, easy to use and provide a reasonably accurate measure of soil water content, particularly at soil water tensions greater than one atmosphere. The gypsum block has already been successfully used for irrigation scheduling at the Summerland

Experimental Farm (Wilcox and Stevenson, 1958).

In each of the 12 experimental plots, four holes were augured to a depth of four feet (figure A.1). At each of these four locations, electrical resistance blocks were placed at depths of 6 inches, 18 inches, 30 inches and 42 inches. The leading cords from blocks at each depth were identified by a different coloured tape and the electrical resistance was easily read by means of a transistorized conductivity bridge.

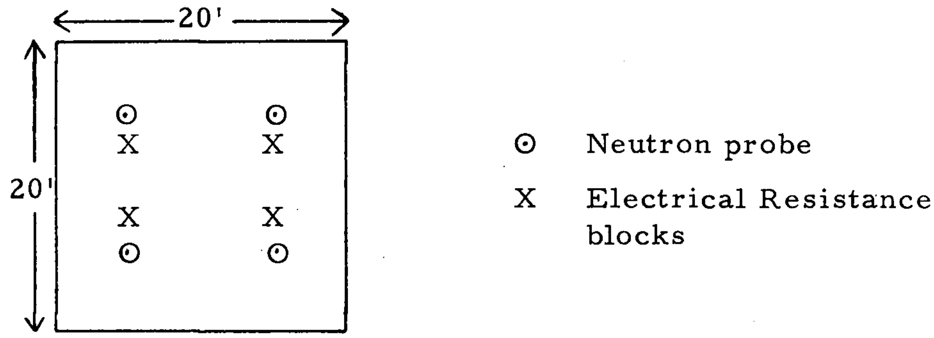


Figure A. 1 Location of Soil Water Measuring Equipment in an Experimental Plot

It was necessary to calibrate the readings obtained by the conductivity bridge against gravimetric and volumetric soil water content.

(2) Gravimetric Measurement. The gravimetric calibration consisted of plotting the block readings against the percentage of soil water obtained by gravimetric sampling techniques. Several times during the experimental period, samples were extracted from each of the four-foot depths close to a set of resistance blocks. Each sample was labelled and immediately weighed on an electrical balance. They were then oven-dried at 105°C until they reached a constant weight (approximately three days). They were then reweighed, the loss of weight representing the total water content of the original sample. This fraction was expressed as a percentage of the "dry" sample weight. Different calibration curves were drawn for each foot depth,

but as there was no significant variation in soil type between plots, the same set of curves was used for all plots.

(3) Volumetric Measurement. The block readings were also calibrated in volumetric units (expressed as inches of water per foot depth) obtained from neutron scattering techniques (Bowman and King, 1965). Each plot contained four neutron probe tubes, located mid-way between the centre of a plot and each corner (figure A. 1). Curves expressing neutron probe readings in volumetric units had already been drawn by Wilcox and these were easily translated into calibration curves expressing resistance block readings in volumetric units. Four curves were drawn for each foot depth. The blocks were recalibrated in June, 1968, resulting in minor modifications to each of the four curves.

Soil Water Tension

Soil water tension and its equivalent soil water percentage was measured directly by the pressure plate apparatus devised by Richards and Fireman (1943). Soil samples at each foot depth for each plot were air dried and screened through a 2 m.m. sieve. They were then placed on a membrane plate, saturated with water and subjected to pressure of 0.1, 0.5, 1.0, 5.0 and 15 atmospheres respectively. A pressure cooker apparatus was used to determine soil water percentages at 0.5 and 0.1 atmospheres. When the soil water content of a sample remained constant at one of the specified atmospheric pressures, it was weighed, oven dried and reweighed to obtain the water percentage.

The scatter of points between plots relating soil water tension with percentage of water for each foot depth was found to be greater than could be expected by chance on the basis of the χ^2 test. Separate desorption curves were therefore drawn for each plot for each foot depth to four feet.

Soil Temperature

Soil temperatures were recorded by electrical thermistors placed at 5, 10, 20 and 50 centimetres at one central location in the experimental area. The thermistors were read by an electrical conductivity bridge three times daily, at 07:30, 11:30, and 15:30 hours, L. A. T. The soil thermistors were calibrated in a temperature bath in a chemistry laboratory at the University of British Columbia.

Soil Density

A cylindrical core of known volume was forced into the soil at depths of 6 inches and 12 inches respectively, close to the soil thermistor site. The dry soil weight was determined after oven-drying the sample and its density was expressed in grams $c.c.^{-1}$.

APPENDIX II

EXPERIMENTAL PLOT PROCEDURES

Experimental Plot Design

The experimental area measured 140 feet by 100 feet and was situated within a large alfalfa field. It was subdivided into 35 plots, each 20 feet square, as shown in figure A.2. Twelve of these plots were selected as experimental plots. Each experimental plot was surrounded by a set of buffer plots, which were not used for experimental purposes.

Figure A. 2 Experimental Plot Design

Replications

3		2		1
6		5		4
9		8		7
12		11		10

Treatments

Plot Irrigation

Four sprinkler risers connected by rubber hoses were placed at the four corners of an experimental plot (figure A.3). The water pressure was adjusted so that each sprinkler irrigated a circle with a radius of approximately 19 feet. As figure A.3 indicates, only the experimental plot and buffer area surrounding it were irrigated at one setting. There were two complete sprinkler sets connected to the same main irrigation line and, consequently, when two plots receiving treatment 1 and 2 respectively were irrigated simultaneously, the same amount of water was applied to each. This amount was measured by a water meter fixed to the main irrigation line.

Details of the irrigation system are presented below:

Nozzle size = 5/16 inch.

Water pressure = 35 lbs. in.$^{-2}$.

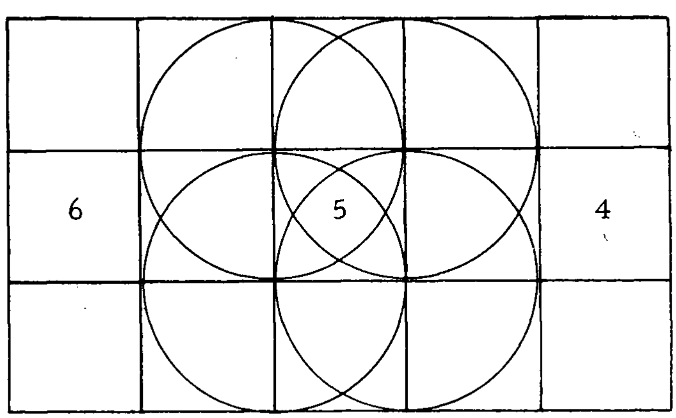
Rate of application = 1 U.S. g.p.m. or 0.24 in. hr.$^{-1}$.

Amount of water applied each hour $= \frac{4 \times 60}{7.48}$ c. ft.

$= 32.09$ c. ft.

Therefore 1 inch applied to a plot $= \frac{400 \times 4}{12} = 133.3$ c. ft.

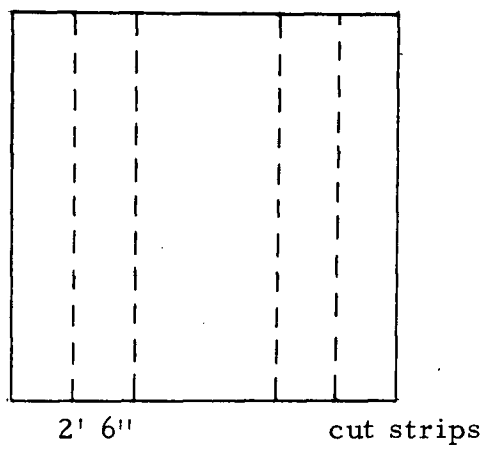
Figure A.3 Plot Irrigation Technique.



Harvesting Alfalfa

The alfalfa crop in each of the 12 experimental plots was cut by a field harvester, with a cutting blade 2 feet 6 inches wide. The alfalfa bordering the upper and lower perimeters of each replication was cut and removed, then two strips were cut within the plot (figure A. 4). The cut alfalfa was gathered into a tarpauling and weighed immediately on a field balance. The weight of the tarpaulin was subtracted to obtain the green weight of the sample. A small sample from this cut was extracted, weighed and then oven-dried at 70°C until completely dry and reweighed. The difference in weight represented the amount of water content contained in the green sample. The percentage of dry matter was calculated for each small sample and the green weight of each plot sample reduced to its dry matter yield.

Figure A. 4 Harvesting Alfalfa from an Experimental Plot



APPENDIX III

MEASUREMENT OF ENERGY BALANCE COMPONENTS

Estimation of Net Radiation (R_n)

Net radiation was estimated from the radiation balance model

$$R_n = (1 - a)\, R_s - R_b \quad (1)$$

where

R_n = net radiation (cal. cm^{-2} day^{-1})

R_s = solar short wave radiation (cal. cm^{-2} day^{-1})

R_b = terrestial long-wave radiation (cal. cm^{-2} day^{-1})

a = surface albedo of alfalfa crop

Terrestial radiation was estimated from Penman's model (Penman, 1948) based on relationships proposed by Brunt (1932) and Angstrom (1916).

$$R_b = \sigma T^4 (a + b \sqrt{e_s}) \quad (c + d\ {}^n/N) \quad (2)$$

where

σ = Stephan Boltzman constant = 1.17 ly. day^{-1}

T = surface temperature (^oK)

e_s = saturation vapour pressure (mb)

${}^n/N$ = percentage of total hours of bright sunshine

a, b, c, d, = constants (see below).

The original constants used by Penman for a humid climate were not thought to be appropriate to this semi-arid climate, in which a large percentage of the days are clear. Consequently, constants calculated by Fitzpatrick and Stern (1966) for a similar semi-arid climate in South Australia were used. These were

$$a = 0.352; \; b = -0.049; \; c = 0.3 \text{ and } d = 0.7$$

Albedo (a)

A simple light meter aimed at the sky was used to measure the direct incidence of solar radiation on the crop surface. It was then inverted over the crop to estimate the amount of reflected solar radiation. The ratio between reflected and incident solar radiation represents the albedo. The albedo varied between 0.30 immediately following an alfalfa cutting to 0.24 when the crop was fully mature. These results are in accord with results published by Tanner (1960) over an alfalfa crop.

Measurement of Soil Heat Flux (G)

The soil heat flux was determined by the integral method (Suomi, 1957)

$$G = \int_{o}^{x} (C_v \, \Delta T_s / \Delta t) \; d_z \qquad (3)$$

where

G = soil heat flux (cal. cm^{-2} day^{-1})

C_v = heat capacity of soil per unit volume (cal. $^oC^{-1}$ gm^{-1})

ΔT_s = change in soil temperature between two depths (^oC)

Δt = time interval between observations.

x = depth at which soil becomes isothermal (est. 50 cms.)

Since heat capacity (C_v) varies according to the water content of the soil, the following empirical relationship was used (Shaw, 1963).

$$C_v = B \, (C + \frac{P_w}{100}) \qquad (4)$$

where

B = bulk density (gm. $cc.^{-1}$)

C = specific heat capacity of dry soil, estimated at 0.23 cal. $gm.^{-1}$ ^oC.

P_w = percentage soil water content.

APPENDIX IV

IRRIGATION TREATMENT EXPERIMENT RESULTS

Treatment 1 (Wet) 1967

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply
Plot 1	June 21-30	2.86	3.21	0.35	0.37	3.86	4.23
	July 1-10	2.88	4.12	1.24	0.10	4.63	4.73
	July 11-20	2.08	2.11	0.03	0.02	5.03	5.05
	July 21-31	3.48	6.69	3.21	0.19	4.47	4.66
	Aug. 1-10	3.13	6.22	3.09	0.01	4.64	4.66
	Aug. 11-20	2.50	2.54	0.04	0.00	0.00	0.00
	Aug. 21-30	2.06	2.18	1.12	0.00	4.70	4.70
		18.99	28.07	9.09	0.69	26.73	27.42
Plot 6	June 21-30	2.86	3.98	1.12	0.37	3.86	4.23
	July 1-10	2.88	3.53	0.65	0.10	4.92	5.02
	July 11-20	2.08	3.54	1.46	0.02	5.01	5.03
	July 21-30	3.48	4.33	0.85	0.19	3.70	3.89
	Aug. 1-10	3.13	4.93	1.83	0.01	3.40	3.41
	Aug. 11-20	2.50	3.67	1.17	0.00	0.00	0.00
	Aug. 21-30	2.06	2.79	0.73	0.00	5.23	5.23
		18.99	26.77	7.81	0.69	26.12	26.81

Treatment 1 (Wet) 1967

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply
Plot 8	June 21-30	2.86	3.22	0.36	0.37	3.19	3.56
	July 1-10	2.88	3.42	0.54	0.10	5.05	5.15
	July 11-20	2.08	2.79	0.71	0.02	4.48	4.50
	July 21-31	3.48	5.22	1.74	0.19	3.89	4.08
	Aug. 1-10	3.13	5.66	2.53	0.01	3.90	3.91
	Aug. 11-20	2.50	3.21	0.71	0.00	0.00	0.00
	Aug. 21-31	2.06	3.28	1.22	0.00	5.46	5.46
		18.99	26.80	7.81	0.69	25.97	26.66
Plot 10	June 21-30	2.86	2.92	0.06	0.37	3.20	3.57
	July 1-10	2.88	3.73	0.85	0.10	4.96	5.06
	July 11-20	2.08	2.57	0.49	0.02	5.32	5.34
	July 21-31	3.48	5.47	1.99	0.19	4.91	5.10
	Aug. 1-10	3.13	7.05	3.92	0.01	5.06	5.07
	Aug. 11-20	2.50	3.46	0.96	0.00	0.00	0.00
	Aug. 21-31	2.06	4.31	2.25	0.00	5.23	5.23
		18.99	29.51	10.50	0.69	28.68	29.37

Treatment 1 (Wet) 1968

	Date	LE ins.	Loss ins.	Drain ins.	Rain ins.	Irrig. ins.	Total Supply ins.
Plot 6	June 9-18	1.69	2.59	0.90	1.14	2.20	3.34
	June 19-28	2.22	3.40	1.18	0.65	2.63	3.28
	June 29-8	2.90	3.25	0.35	0.00	3.40	3.40
	July 9-11	0.50	0.90	0.00	0.00	0.00	0.00
		7.31	10.14	2.43	1.79	8.23	10.02
Plot 7	June 9-18	1.69	1.67	0.00	1.14	2.94	4.08
	June 19-28	2.22	3.65	1.43	0.65	4.63	5.28
	June 29-8	2.90	3.37	0.47	0.00	2.50	2.50
	July 9-11	0.50	0.66	0.16	0.00	0.00	0.00
		7.31	9.35	2.06	1.79	10.07	11.86
Plot 11	June 9-18	1.69	2.86	1.37	1.14	2.50	3.14
	June 19-28	2.22	2.54	0.32	0.65	2.60	3.25
	June 29-8	2.90	4.02	1.12	0.00	2.14	2.14
	July 9-11	0.50	0.61	0.11	0.00	0.00	0.00
		7.31	10.03	2.72	1.79	6.74	8.53

Treatment 2 (Model) 1967

	Date	LE	Loss	Drain	Deficit	Rain	Irrig.	Total Supply
Plot 7	June 21-30	2.86	2.76	0.00	0.10	0.37	2.20	2.57
	July 1-10	2.88	2.96	0.08	0.00	0.10	5.58	5.68
	July 11-20	2.08	2.38	0.30	0.00	0.02	5.02	5.04
	July 21-31	3.48	4.46	0.98	0.00	0.19	0.00	0.19
	Aug. 1-10	3.13	4.08	0.95	0.00	0.01	4.85	4.86
	Aug. 11-20	2.50	2.60	0.10	0.00	0.00	5.96	5.96
	Aug. 21-31	2.06	3.58	1.52	0.00	0.00	0.00	0.00
		18.99	22.82	3.93	0.10	0.69	23.64	24.33
Plot 11	June 21-30	2.86	2.46	0.00	0.40	0.37	2.20	2.57
	July 1-10	2.88	2.92	0.04	0.00	0.10	5.39	5.49
	July 11-20	2.08	2.46	0.38	0.00	0.02	5.32	5.34
	July 21-31	3.48	5.03	1.55	0.00	0.19	0.00	0.19
	Aug. 1-10	3.13	4.00	0.87	0.00	0.01	4.84	4.85
	Aug. 11-20	2.50	2.47	0.00	0.03	0.00	0.00	0.00
	Aug. 21-31	2.06	3.75	1.69	0.00	0.00	5.50	5.50
		18.99	23.09	4.53	0.43	0.69	23.25	23.94

Treatment 2 (Model) 1967

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply	Deficit
Plot 3	June 21-30	2.86	2.45	0.00	0.37	2.20	2.57	0.41
	July 1-10	2.88	2.69	0.00	0.10	5.43	5.53	0.19
	July 11-20	2.08	2.02	0.00	0.02	0.00	0.02	0.06
	July 21-31	3.48	4.43	1.05	0.19	5.11	5.30	0.00
	Aug. 1-10	3.13	3.32	0.19	0.01	4.53	4.54	0.00
	Aug. 11-20	2.50	2.49	0.00	0.00	0.00	0.00	0.01
	Aug. 21-30	2.06	3.48	1.42	0.00	5.23	5.23	0.00
		18.99	20.88	2.66	0.69	22.50	23.19	0.67
Plot 5	June 21-30	2.86	2.61	0.00	0.37	2.20	2.57	0.00
	July 1-10	2.88	3.37	0.49	0.10	5.25	5.35	0.00
	July 11-20	2.08	2.48	0.40	0.02	0.00	0.02	0.00
	July 21-31	3.48	4.76	1.28	0.19	4.59	4.78	0.00
	Aug. 1-10	3.13	3.49	0.31	0.01	4.55	4.56	0.00
	Aug. 11-20	2.50	2.22	0.00	0.00	0.00	0.00	0.28
	Aug. 21-30	2.06	3.34	1.28	0.00	5.00	5.00	0.00
		18.99	22.22	3.76	0.69	21.59	22.28	0.28

Treatment 2 (Model) 1968

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply
Plot 5	June 9-18	1.69	2.22	0.53	1.14	2.20	3.34
	June 19-28	2.22	2.47	0.25	0.65	0.00	0.65
	June 29-8	2.90	2.59	0.00	0.00	2.21	2.21
	July 9-11	0.50	0.56	0.06	0.00	0.00	0.00
		7.31	8.14	0.84	1.79	4.41	6.20
Plot 9	June 9-18	1.69	2.23	0.54	1.14	2.50	3.64
	June 19-28	2.22	2.20	0.00	0.65	0.00	0.65
	June 29-8	2.90	2.80	0.00	0.00	2.46	2.46
	July 9-11	0.50	0.53	0.03	0.00	0.00	0.00
		7.31	7.76	0.57	1.79	4.96	6.75
Plot 10	June 9-18	1.69	2.21	0.52	1.14	2.50	3.64
	June 19-28	2.22	2.30	0.08	0.65	0.00	0.65
	June 29-8	2.90	3.33	0.43	0.00	5.30	5.30
	July 9-11	0.50	0.53	0.03	0.00	0.00	0.00
		7.31	8.37	1.06	1.79	7.80	9.59

Treatment 3 (Dry) 1967

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply	Deficit
Plot 2	June 21-30	2.86	3.83	0.97	0.37	2.20	2.57	0.00
	July 1-10	2.88	3.01	0.13	0.10	0.00	0.10	0.00
	July 11-20	2.08	1.25	0.00	0.02	9.76	9.78	0.83
	July 21-31	3.48	4.91	1.43	0.19	0.00	0.19	0.00
	Aug. 1-10	3.13	2.93	0.00	0.01	0.00	0.01	0.20
	Aug. 11-20	2.50	1.04	0.00	0.00	5.31	5.31	1.46
	Aug. 21-30	2.06	3.01	0.96	0.00	0.00	0.00	0.00
		18.99	19.98	3.49	0.69	17.17	17.86	2.49
Plot 4	June 21-30	2.86	3.05	0.19	0.37	2.20	2.57	0.00
	July 1-10	2.88	1.71	0.00	0.10	0.00	0.10	1.17
	July 11-20	2.08	1.72	0.00	0.02	9.44	9.46	0.36
	July 21-31	3.48	4.95	1.47	0.19	0.00	0.19	0.00
	Aug. 1-10	3.13	2.58	0.00	0.01	0.00	0.01	0.55
	Aug. 11-20	2.50	1.15	0.00	0.00	5.23	5.23	1.35
	Aug. 21-30	2.06	3.54	1.48	0.00	0.00	0.00	0.00
		18.99	18.70	3.14	0.69	16.87	17.56	3.43

Treatment 3 (Dry) 1967

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply	Deficit
Plot 9	June 21-30	2.86	3.48	0.62	0.37	2.20	2.57	0.00
	July 1-10	2.88	2.42	0.00	0.10	0.00	0.10	0.46
	July 11-20	2.08	1.85	0.00	0.02	0.00	0.02	0.23
	July 21-31	3.48	4.77	1.29	0.19	11.23	11.42	0.00
	Aug. 1-10	3.13	3.49	0.36	0.01	0.00	0.01	0.00
	Aug. 11-20	2.50	1.46	0.00	0.00	0.00	0.00	1.04
	Aug. 21-30	2.06	4.04	1.98	0.00	4.44	4.44	0.00
		18.99	22.74	4.25	0.69	17.87	18.56	1.73
Plot 12	June 21-30	2.86	2.37	0.00	0.37	2.20	2.57	0.49
	July 1-10	2.88	1.28	0.00	0.10	0.00	0.10	1.60
	July 11-20	2.08	1.51	0.00	0.02	0.00	0.02	0.57
	July 21-31	3.48	6.37	2.89	0.19	11.64	11.83	0.00
	Aug. 1-10	3.13	3.16	0.03	0.01	0.00	0.01	0.00
	Aug. 11-20	2.50	1.04	0.00	0.00	0.00	0.00	1.46
	Aug. 21-30	2.06	3.86	1.80	0.00	4.60	4.60	0.00
		18.99	19.59	4.72	0.69	18.44	19.13	4.12

Treatment 3 (Dry) 1968

	Date	LE	Loss	Drain	Rain	Irrig.	Total Supply	Deficit
Plot 4	June 9-18	1.69	2.08	0.39	1.14	2.20	3.34	0.00
	June 19-28	2.22	2.49	0.27	0.65	0.00	0.65	0.00
	June 29-8	2.90	2.06	0.00	0.00	0.00	0.00	0.84
	July 9-11	0.50	0.24	0.00	0.00	0.00	0.00	0.26
		7.31	6.87	0.66	0.79	2.20	3.99	1.10
Plot 8	June 9-18	1.69	1.79	0.10	1.14	2.50	3.64	0.00
	June 19-28	2.22	2.51	0.29	0.65	0.00	0.65	0.00
	June 29-8	2.90	1.92	0.00	0.00	0.00	0.00	0.98
	July 9-11	0.50	0.21	0.00	0.00	0.00	0.00	0.29
		7.31	6.43	0.39	1.79	2.50	4.29	1.27
Plot 12	June 9-18	1.69	1.97	0.28	1.14	2.50	3.64	0.00
	June 19-28	2.22	2.76	0.54	0.65	0.00	0.65	0.00
	June 29-8	2.90	1.67	0.00	0.00	0.00	0.00	1.23
	July 9-11	0.50	0.22	0.00	0.00	0.00	0.00	0.28
		7.31	6.62	0.72	1.79	2.50	4.29	1.45