PREDICTING CONSUMPTIVE USE OF WATER BY IRRIGATED CROPS IN MANITOBA

A Thesis
Presented to
The Faculty of Graduate Studies and Research
University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Agricultural Engineering

by
Banthoeng Sakdinan
July, 1970

ABSTRACT

Prediction equations were developed for daily latent evaporation (evaporation from the black Bellani plate atmometer) and evaporation from a U.S.W.B. Class A pan from meteorological data (observed at the experimental station) and astronomical data (Smithsonian Table, 1951). Multiple regression analysis showed the correlation coefficients for latent evaporation equations are considerably more reliable than those from the Class A pan. Prediction equations for daily latent evaporation were selected for this study. These equations were compared with those of Baier and Robertson (1965) and it was found that only one of their equations (Method VII) can be applied meaningfully to the Carberry area.

The ratios of consumptive use to evaporation for various crops grown at Vauxhall, Alberta and reported by Sonmor (1963) were investigated and it was found that they can be transferred to some areas in Manitoba. The seasonal consumptive use in inches for four major crops estimated using black Bellani plate ratios developed for Vauxhall was as follows: alfalfa, 20.6; sugar beets, 15.6; potatoes, 14.1; and wheat, 14.0. These figures are much lower than the values reported for Vauxhall by Sonmor (1963) and at Swift Current by Pohjakas (1966). This is probably due in part to the unusual 1969 summer weather which was slightly cooler than normal years.

ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Dr. G.E. Laliberte, Professor and Head, Department of Agricultural Engineering, for his continual guidance and the arrangement of financial assistance throughout the research program.

Special thanks are due to Dr. C.F. Shaykewich, Department of Soil Science, for his helpful suggestions. Dr. K.M. Adam of the Civil Engineering Department was always willing to help in every way and this is very much appreciated. Thanks are also due to Mr. M. Pawloski of the Plant Science Department for his assistance with the field data collection and to Mrs. I. Hamel for her neat typing job of this manuscript.

The author is also indebted to the members of staff of the Department of Agricultural Engineering for the cooperation and warm hospitality both he and his wife received while studying at the University of Manitoba.

TABLE OF CONTENTS

Chapter Page

ABSTRACT ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF TABLES ix

LIST OF FIGURES xi

LIST OF APPENDICES xii

LIST OF SYMBOLS xiii

I INTRODUCTION 1

II REVIEW OF PAST RESEARCH 3

2.1 The Concept of Evapotranspiration 3

2.1.1 Actual evapotranspiration (AE) 3

2.1.2 Potential evapotranspiration (PE) ... 3

2.2 Direct Measurement of Actual Evapotranspiration 5

2.3 Estimation of Actual and Potential Evapotranspiration from Evaporimeters and Empirical Formulae 6

2.3.1 Pan and atmometer evaporation 7

2.3.2 Evaporation formulae 9

2.3.3 Comparison of empirical relationships for estimating potential evapotranspiration 12

2.4 Relationships of Soil Moisture, Plants and Potential Evapotranspiration to Actual Evapotranspiration 14

III THEORIES REGARDING EVAPOTRANSPIRATION 19

3.1 Evaporation 19

3.2 Humidity Near the Earth's Surface 20

3.2.1 Water vapour 20

3.2.2 Saturation 21

3.2.3 Methods of expressing partial saturation........................... 21

3.3 Conversion Principles for Heat Energy and Water 23

IV EXPERIMENTAL EQUIPMENT 29

4.1 Temperature 29

4.2 Humidity 29

4.3 Wind 29

4.4 Solar Radiation 30

4.5 Evaporation 30

4.6 Precipitation 32

4.7 Installation of Instruments.............. 32

V PROCEDURES 35

5.1 Choice of Evaporation Estimation Technique 35

5.2 Extraction of Field Data 36

5.2.1 Daily maximum temperature 36

5.2.2 Daily temperature range 36

5.2.3 Daily vapour pressure deficit 36

5.2.4 Total daily wind run 37

5.2.5 Total solar radiation 37

5.2.6 Solar energy at the top of the atmosphere 37

5.2.7 Evaporation from duplicate black Bellani plate atmometers 38

5.2.8 Evaporation from U.S.W.B. Class A pan 38

5.2.9 Precipitation 38

5.3 Estimation of Missing Data 38

5.4 Investigation of Past Evaporation Records in Manitoba.............................. 39

5.5 Selection of Crops and Growing Periods for the Present Study 39

5.6 Derivation of an Evaporation Equation 40
    5.6.1 Model of equation 41
    5.6.2 Computation of equations 42
    5.6.3 Types of equations 42
5.7 Testing of Equations 42
    5.7.1 Testing the applicability of the Baier and Robertson (1965) equations 43
    5.7.2 Testing the difference between the derived equations of latent evaporation for Carberry and the equations of Baier and Robertson (1965) 43
    5.7.3 Test the significant difference among the regression coefficients of the three equations for alfalfa, potatoes and cereals................. 43
5.8 Estimation of Seasonal Consumptive Use..... 44
    5.8.1 Estimates from Vauxhall coefficients (Sonmor, 1963) 44

VI RESULTS AND DISCUSSION 45
6.1 Correlation Analysis 45
    6.1.1 Simple correlation between evaporimeters and meteorological variables . 45
    6.1.2 Simple correlation between individual meteorological variables 46
6.2 Latent Evaporation 47
    6.2.1 Equations of three meteorological variables 52
    6.2.2 Equations of four meteorological variables 52
    6.2.3 Equations of five meteorological variables 54
    6.2.4 Equations of six meteorological variables 55
    6.2.5 Summary 56
6.3 Evaporation from the U.S.W.B. Class A Pan . 57

6.3.1 Equations of three meteorological variables 57

6.3.2 Equations of four meteorological variables 62

6.3.3 Equations of five meteorological variables 62

6.3.4 Equations of six meteorological variables 63

6.3.5 Summary 64

6.4 Comparison Between Prediction Equations of Latent Evaporation and Class A Pan Evaporation 65

6.5 Testing of Equations 65

6.5.1 Testing the equations of Baier and Robertson (1965) for the meteorological data of the present study 65

6.5.2 Testing the difference between the regression coefficients of Baier and Robertson equations (1965) and those of each of the derived equations for latent evaporation at Carberry 69

6.5.3 Testing the significant difference among the regression coefficients of the three equations for alfalfa, potatoes and cereals 70

6.6 Selection of Prediction Equations in Estimating Seasonal Consumptive Use 70

6.7 Estimation of Seasonal Consumptive Use ... 74

6.7.1 Transferability of Hobbs and Krogman's (1968) curves and Vauxhall coefficients to Manitoba 75

6.7.2 Estimates from Vauxhall coefficients

6.7.3 Estimates from curves of Hobbs and Krogman (1968) 76

6.7.4 Estimates of consumptive use at Brandon by the method of Coligado et al. (1968) 78

6.7.5 Comparison of estimated results 79

VII CONCLUSIONS 81

VIII RECOMMENDATIONS 83

REFERENCES 84

APPENDICES 89

LIST OF TABLES

Table		Page
I	ESTIMATING GROWING PERIODS OF CROPS	40
II	LIST OF DEPENDENT AND INDEPENDENT VARIABLES	41
III	LIST OF METEOROLOGICAL VARIABLES INVOLVED IN EACH METHOD	42
IV	CORRELATION COEFFICIENT MATRIX OF DEPENDENT AND INDEPENDENT VARIABLES	45
V	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF ALFALFA (153 DAYS)	48
VI	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF POTATOES (124 DAYS)	49
VII	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF CEREALS (110 DAYS)	50
VIII	SUMMARY OF THE SIGNIFICANT 't' VALUES FOR REGRESSION COEFFICIENTS FROM PREDICTION EQUATIONS FOR LATENT EVAPORATION	51
IX	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF ALFALFA (153 DAYS)	58
X	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF POTATOES (124 DAYS)	59
XI	MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF CEREALS (110 DAYS)	60
XII	SUMMARY OF ALL THE 't' VALUES FOR REGRESSION COEFFICIENTS FROM THE PREDICTION EQUATIONS FOR CLASS A PAN EVAPORATION	61
XIII	MULTIPLE CORRELATION AND REGRESSION COEFFICIENTS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION (AFTER BAIER AND ROBERTSON, 1965)	66

XIV STATISTICAL PAIRED 't' TEST FOR LATENT EVAPORATION COMPARING OBSERVED VALUES AT CARBERRY AND CALCULATED VALUES USING THE METHODS OF BAIER AND ROBERTSON (1965) 67

XV STATISTICAL 't' TESTS OF THE DIFFERENCE BETWEEN REGRESSION COEFFICIENTS FOR BAIER AND ROBERTSON'S EQUATIONS AND THOSE OF EACH OF THE DERIVED EQUATIONS FOR LATENT EVAPORATION AT CARBERRY 68

XVI THE 't' VALUES FROM TESTS OF SIGNIFICANCE OF THE DIFFERENCE AMONG THE REGRESSION COEFFICIENTS OF THE THREE EQUATIONS 71

XVII ESTIMATION OF SEASONAL LATENT EVAPORATION 72

XVIII SEASONAL EVAPORATION 74

XIX SEASONAL CONSUMPTIVE USE FROM THE VAUXHALL COEFFICIENTS 76

XX SEASONAL CONSUMPTIVE USE AT BRANDON BY THE METHOD OF COLIGADO ET AL. (1968) 79

XXI SEASONAL CONSUMPTIVE USE BY VARIOUS METHODS 79

LIST OF FIGURES

Figure Page

1 Some relationships between actual evapotranspiration rate and available soil moisture 17

2 The saturation vapour pressure of water shown as a function of temperature (after Penman, 1955) 22

3 Components of the day-time heat exchange at the earth's surface. (Adapted from Geiger, 1959 by Rose, 1966) 25

4 Pyrheliometer 31

5 Bellani plate atmometer 33

6 Weather station from the north west corner 34

LIST OF APPENDICES

Appendix Page

A TYPICAL HYGRO-THERMOGRAPH CHART 89

B TYPICAL PYRHELIOGRAPH CHART 90

C INSTRUMENT INSTALLATION PLAN OF CARBERRY WEATHER STATION 91

D SEASONAL EVAPORATION FROM U.S.W.B. CLASS A PAN AT BALDUR, MORDEN CDA, WINNIPEG INTERNATIONAL AIRPORT AND RIDING MOUNTAIN PARK (1963-1969) 92

E SUMMARY OF EVAPORATION AND METEOROLOGICAL DATA USED TO DERIVE EQUATIONS INCLUDING MEAN AND STANDARD DEVIATION OF EACH VARIABLE .. 93

F CONSUMPTIVE USE FOR VARIOUS CROPS AT TABER AND VAUXHALL, 1950-1961 (AFTER SONMOR, 1963) .. 99

G MEAN WEEKLY EVAPOTRANSPIRATION OF WHEAT AND BELLANI PLATE EVAPORATION AT BRANDON, 1955-1959 (AFTER FERGUSON, 1965) 100

H RATIO OF MEASURED EVAPOTRANSPIRATION TO CALCULATED EVAPOTRANSPIRATION IN SOUTHERN ALBERTA (AFTER HOBBS AND KROGMAN, 1968) 101

I ESTIMATION OF SEASONAL CONSUMPTIVE USE FROM FIELD DATA FOR POTATOES, ALFALFA, SUGAR BEETS AND CEREALS (WHEAT) 102

LIST OF SYMBOLS

AE	Actual evapotranspiration.
CU	Consumptive use of water.
E	Evaporation rate.
E_L	Latent evaporation.
E_{pan}	United States Weather Bureau Class A pan evaporation.
F	Statistical 'F' test.
F.C.	Field capacity.
G	Heat flux density into ground.
H	Sensible heat flux density into the atmosphere.
L	Latent heat of vaporization of water.
M_w	Molecular weight.
N	Daylength or duration of day light.
P	Precipitation.
PE	Potential evapotranspiration.
P.W.P.	Permanent wilting point.
Q_o	Solar energy at the top of the atmosphere.
Q_s	Total sky and solar energy on a horizontal surface.
R	Multiple correlation coefficient.
R^2	Coefficient of determination.
R_N	The total net radiation flux.
R_L	Net flux density of long-wave radiation.
R_S	Flux density of total short-wave radiation.
R_T	Total solar radiation.
R_u	Universal gas constant.
S_b	Standard error of estimate of regression coefficient.
S_{ee}	Standard error of estimate.
T	Absolute temperature of water vapour.
T_{dp}	Dew point temperature.
T_w	Wet bulb temperature.
U	Underground water storage.

U.S.W.B.	United States Weather Bureau.
V.P.D.	Vapour pressure deficit.
X	Independent variable.
Y	Dependent variable.
a	Constant in multiple regression equation.
b	Regression coefficient.
b_c	Regression coefficient of the Carberry equation.
b_B	Regression coefficient of the Baier and Robertson (1965) equation.
cal.	Calorie.
cc	Cubic centimeter.
e	Vapour pressure of water.
e_s	Saturation vapour pressure at the air temperature.
e_w	Saturation vapour pressure at dew point atmosphere.
gm.	Gram.
h_r	Relative humidity.
in.	Inch.
k	Number of independent variable.
n	Duration of bright sunshine.
r	Simple correlation coefficient.
sec.	Second.
t	Statistical 't' test.
ΔD	Increase in surface detention.
ΔM	Increase in soil water storage.
$\int Edt$	Total evaporation or evapotranspiration.
ρ	Albedo (or reflection coefficient).
ρ_v	The density of water vapour.
*	Significant at the five percent level.
**	Significant at the one percent level.

CHAPTER I

INTRODUCTION

Evapotranspiration or consumptive use of water is the basis for estimating project water demands. Planning for the optimum utilization of available water supplies involves consumptive use of water as its basic factor for the future development of any area, whether the requirement be for irrigation, power, municipal uses or for multi-purpose use. Estimation of evapotranspiration has been studied for more than half a century. The same type of estimates still apply today but greater accuracy is required. In some areas where water supplies are limited, increased competition for the water resource is resulting in a more urgent need for accurate estimates. Many drainage problems can be avoided or time of occurrence predicted in advance if accurate evapotranspiration estimates are available.

The operational wastes of some irrigation projects can be reduced by predicting water deliveries several days in advance. Accurate information on evapotranspiration by crops has become more important especially in the semi-arid regions of the Canadian Prairies where sprinkler irrigation is widely applied. Where the source of irrigation water in this region is groundwater, sprinkler irrigation design requires accurate, short period estimates for one day to seven days to assure adequate but economic capacity to meet peak demands.

When an irrigation project is being planned, engineers must be able to predict the evapotranspiration rate for an area before crops are grown so that they can estimate the acreage of land which will be served by a given supply of water, or how much water is required for a given demand.

Generally, these estimates are dependent on available climatological and meteorological data. In some cases, engineers do not have enough time or funds to make measurements in the area for which estimates are needed. Several estimation techniques of evapotranspiration have been proposed and the choices depend on available materials and local conditions and, of course, the more practical and accurate estimates are preferred.

The purpose of the present study was to:

1. Develop evaporation formulas from the meteorological observations of this study.

2. Test the applicability of the Baier and Robertson (1965) techniques for some areas in Manitoba.

3. Determine the transferability to Manitoba of Vauxhall ratios of consumptive use to evaporation developed by Sonmor (1963).

The results above will be used in predicting consumptive use of four crops: alfalfa, potatoes, sugar beets and cereals (wheat) and also to study the performance of the black Bellani plate atmometer and the U.S.W.B. Class A pan in the area of this study.

CHAPTER II

REVIEW OF PAST RESEARCH

2.1 The Concept of Evapotranspiration

2.1.1 Actual evapotranspiration (AE)

Actual evapotranspiration or consumptive use of water is defined as the sum of the depths of water transpired by the plants and evaporated from the soil surface and from intercepted precipitation, Coligado (1968). Generally consumptive use of water will be expressed in acre-inches per acre (depth in inches) for annual, seasonal, weekly or daily periods. Consider a dry land area where water is deficient; the vegetation is less crowded than that in the land where water is more available. A distinction is usually made between the amount of water that actually transpires and evaporates such as in dry land, and that which would transpire and evaporate if water were more available. In arid regions evapotranspiration rate depends only on the climate and will reach a maximum when the water supply is not limited. The evapotranspiration under these circumstances may be called "potential evapotranspiration" as distinguished from actual evapotranspiration.

2.1.2 Potential evapotranspiration (PE)

Potential evapotranspiration is defined as the maximum quantity of water capable of being lost as water vapour, in a given climate, by a continuous stretch of vegetation covering the whole ground and well supplied with water (World Meteorological Organization, 1966). According to the definition, the potential evapotranspiration depends only on the climatic conditions and it is not controlled by type of soil or crop. The rate of evapotranspiration from soil and plant surfaces is strongly influenced by the energy available to vaporize water and the rate at which the soil or the plant can move water to the evaporating surface. This depends on the available soil moisture and the conditions of plant and soil surfaces. Baier (1967) concluded that "because these factors change continually with time, evapotranspiration is a function of meteorological, physical and biological processes".

Penman (1956) defined PE as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water". Penman also stated three general concepts about PE (following Baier, 1967):

1. The PE rate is the same, without regard to plant or soil type, provided that the soil cover of different plant communities is complete and has the same reflection coefficient.

2. The rate of PE is determined by prevailing weather; and

3. the rate of PE cannot exceed the rate of evaporation from an open water surface exposed to the same environmental conditions.

The concept of potential evapotranspiration has been studied by many researchers. In 1948 it was developed by two separate groups and almost the same results were reported. Thornthwaite (1948) attempted the estimation of PE over large areas in the United States and he assumed that PE varies with temperature and daylength. The equation was developed for estimating PE on a monthly basis from mean monthly air temperature and daylength. Multiplication by local coefficients enabled the estimation of the consumptive use of various crops.

Penman (1948) conducted his research in England. He applied the energy balance equation to calculate the evaporation from a free water surface. The evaporation equation was developed from the meteorological data such as mean air temperature, duration of bright sunshine, mean vapour pressure and mean wind speed. A crop factor was then applied to convert evaporation to potential evapotranspiration.

Most of the recent research on evapotranspiration has been conducted based on the PE concept developed by the above two researchers. Several modifications in methods of calculating the rate of PE have been applied. More meteorological variables were involved in the estimation equations to give more accurate results within the required periods.

Blaney and Criddle (1950) developed a simple method for determining evapotranspiration from climatological and irrigation data. In their procedure, the evapotranspiration data from the field for different crops were correlated with the monthly temperature, percentage of daytime hours in the period of observation and length of growing season. The coefficients relating these variables were then applied to determine the evapotranspiration for other areas where only climatic data are available.

2.2 Direct Measurement of Actual Evapotranspiration

The actual evapotranspiration is usually determined from potential evapotranspiration rate by applying the consumptive use factor (ratio of AE to PE) which depends on type of crops and their stage of maturity.

The direct measurement of evapotranspiration is possible by means of lysimeters which can be classified into two types, non-weighing and weighing lysimeters. The first are suitable for long term measurements such as seasonal and annual evapotranspiration; the latter are widely used for shorter periods, such as weeks or days. Weighing lysimeters were developed using a mechanical scale as described by Harrold and Dreibelbis (1958). In recent years, Pruitt (1960), Pelton (1961), and Bloemen (1964) developed hydraulic weighing systems which give data with high accuracy and sensitivity. It is most important in using lysimeters to ensure that the lysimeter surface represents a fair sample of the surrounding crop. The reliability of data from lysimeters also depends on correct design, installation and maintenance. Measurement of actual evapotranspiration by lysimeters is laborious, time consuming and expensive. The more convenient method is to use a soil moisture budget as described by Robertson and Holmes (1959). The consumptive use of water is calculated by combining the measured rainfall and irrigation received, and subtracting or adding, as necessary, the change in soil moisture content between the beginning and end of the period of interest.

2.3 Estimation of Actual and Potential Evapotranspiration from Evaporimeters and Empirical Formulae

Estimation of PE is very important in agricultural research, especially in irrigation work. Direct measurements and methods previously described are often impractical in the field. Several instruments and techniques have been developed to estimate PE from open-water-surface evaporation and then to relate these estimates to actual evapotranspiration. These instruments and techniques have been widely used and the results are quite accurate in irrigation work.

2.3.1 Pan and atmometer evaporation The direct measurement of evaporation from evaporimeters such as pans and atmometers is widely used and results are quite reliable in estimating the evapotranspiration. In Canada, considerable irrigation research on estimating consumptive use of water by irrigated crops has been conducted based on pans and atmometers. Black Bellani plate atmometers as described by Robertson (1954), Mukammal and Bruce (1960) and Carder (1960) seem to be more widely used among the various types of atmometers. Holmes and Robertson (1958), Robertson and Holmes (1959), and Wilcox (1963) considered the black Bellani plate atmometer as a superior instrument for the measurement of evaporation, particularly for obtaining an estimate of water lost from crop plants. Wilcox (1963) also recommended the black Bellani plate atmometer for use as a standard evaporimeter. Mukammal and Bruce (1960) correlated evaporation with radiation and concluded that the Bellani plate atmometer is not as reliable as the evaporation pan. Pelton (1964) recommended the United States Weather Bureau Class A pan as described by Rohwer (1934), because it is as reliable as any of the other commonly used evaporimeters and because of its widespread use in meteorological networks throughout the world. Pelton and Korven (1969^2) also recommended the Class A pan for general use in semiarid regions.

For more convenience in converting evaporation data from pans and atmometers directly to PE and AE, ratios of consumptive use of water to evaporation from various evaporimeters have been established. Holmes and Robertson (1958) correlated evaporation from open pans and latent evaporation (evaporation from Bellani plate atmometer) with potential evapotranspiration from an evapotranspirometer, with highly significant correlation. The ratio of 0.0032 inches of open-pan evaporation and 0.0034 inches of potential evapotranspiration from irrigated fields for each cubic centimeter of latent evaporation has been tentatively established. The evapotranspiration-evaporation ratio of 0.0034 was also confirmed by Krogman and Hobbs (1965) in their study of evapotranspiration by alfalfa in a condition of complete ground cover. They also recommended the ratio of 0.0030 for irrigation scheduling in the spring before complete ground cover was established.

Sonmor (1963) studied evapotranspiration in southern Alberta for 13 irrigated crops based on 102 crop-years of data. Ratios between consumptive use and evaporation were determined for these crops to permit estimation of evapotranspiration from evaporation as measured by a black Bellani atmometer, a buried 4-foot pan of a type described by Carder (1961), and a Class A pan. Sonmor recommended these estimations as a practical means of computing the total water requirements for crops to be grown in a given irrigated area or in estimating the acreage that could be served by a given supply of water. The consumptive use evaporation conversion technique has been used sucessfully in irrigation scheduling in southern Alberta for many years.

In southwestern Saskatchewan, Pohjakas et al. (1967) studied the consumptive use of water by crops at Swift Current; the paper also presented the consumptive use: evaporation ratio for 16 crops based on a 5-year study. The consumptive use values were somewhat higher than those reported by Sonmor (1953). This difference is probably due to the higher average wind speeds and to soil texture, but the ratios are not much different.

2.3.2 Evaporation formulae Actually, evaporation from evaporimeters is a measure of the drying ability of the air, and not of potential evapotranspiration. Evaporation data from pans and atmometers appear to integrate the influence of the four meteorological factors: sunshine, wind, temperature and water vapour pressure. Because such evaporation records are not always available over periods long enough for a frequency analysis as described for irrigation requirements by Baier and Robertson (1967), climatic data available for many stations in agricultural areas over long periods are often used. It is interesting to consider the possibility of using the standard climatic data such as temperature, humidity, wind, etc. in estimating PE, and to find out which climatic elements should be used in an appropriate expression for estimating PE. Many evaporation equations have been developed and used for various purposes. Basic empirical methods developed by Thornthwaite, Penman and Blaney and Criddle as previously described, have been widely and successfully used.

Studies of evaporation equations relating one or more of the meteorological variables to potential evapotranspiration have been extensively developed. Harrold (1955) studied evaporation rates for various crops. He found a close relationship between temperature and evapotranspiration on a monthly basis, but not on a daily basis.

Jensen and Haise (1963) reported their studies in estimating evapotranspiration from solar radiation. They applied the energy balance concept which hypothesizes that heat energy is the main factor of the evaporating process. In their methods, solar radiation is considered to be the main parameter which can be directly measured or estimated from the empirical formulas. An equation relating evapotranspiration to solar radiation was derived from the energy balance equation and the ratio between actual evapotranspiration and solar radiation was calculated. Existing evapotranspiration data of the past 35 years in Western United States were tested on this relationship. Results indicated that evapotranspiration estimated from solar radiation is reasonably reliable. The report also provides an empirical relationship for estimating potential evapotranspiration from mean air temperature and solar radiation.

Skidmore et al. (1968) studied the contribution of wind to calculated evapotranspiration under the climatic conditions of the Great Plains. They found calculated potential evapotranspiration was much higher than actual evapotranspiration especially on windy days.

Eagleman (1967) developed an equation for determining evapotranspiration rates based on the temperature and relative humidity. Comparing his equation with that of the five previously developed equations based on the same number of variables, he found his equation more accurate but not quite as accurate as those based on more meteorological variables.

In Canada, Wilcox (1963) studied the relationships in southern British Columbia between each of four weather elements and evaporation (from Bellani plates) and evapotranspiration respectively. He found that evaporation from Bellani plates gave higher direct correlations with evapotranspiration than did any of the routine weather-station records obtained on temperature, radiation, wind or humidity. On a daily or weekly basis, temperature gave the highest correlations with evapotranspiration, but on a two-hour basis, radiation gave the highest correlations. He concluded that if weather records are used to estimate evapotranspiration, all four of them should be used.

In southwestern Saskatchewan, Pelton (1964) studied the performance of three different evaporimeters (Bellani plate atmometer, the Class A pan and the Experimental Farms buried tank) in terms of their response to solar radiation, temperature, vapour pressure deficit and wind. Each of these evaporimeters responded well to each of the meteorological variables except wind, as indicated by simple correlation coefficients. His findings also agree in several instances with the conclusions of Wilcox (1963) and demonstrated that these four meteorological variables collectively made about the same contribution to evaporation for Western Canada in both cases.

In southern Alberta, Hobbs and Krogman (1966), using alfalfa as the indicator crop, found that the highest correlation coefficients between evapotranspiration from alfalfa and the four meteorological variables occurred when the crop was at the growing stage of full ground cover (or at the potential condition). They concluded that only simple correlations between variables by themselves do not adequately explain the relationships. For example wind is not correlated with evaporation or evapotranspiration but a significant contribution was found when combined with other meteorological variables in predicting evaporation.

Baier and Robertson (1965) used multiple correlation analysis on meteorological and astronomical data to develop prediction equations for latent evaporation. The independent variables involved in their methods were daily observations of maximum temperature, temperature range (maximum minus minimum), wind, vapour pressure deficit, solar energy at the top of the atmosphere, and total sky and solar energy on a horizontal surface (both obtained from Smithsonian Tables, 1951). They presented eight estimating equations relating latent evaporation to three variables (maximum temperature, temperature range and solar energy at the top of the atmosphere) and up to a maximum of six variables. By their methods, the daily data recorded at six stations across Canada over several years were collected and involved in the regression. For this reason, they suggested that all the developed equations should be applicable to most parts of Canada.

2.3.3 Comparison of empirical relationships for estimating potential evapotranspiration Empirical techniques for estimating PE from climatic data and evaporimeters have been widely used. The applicability of these techniques has been studied.

In studies conducted by Halkias (1963) in California, water use by crops was determined from climatic data based on the Blaney-Criddle (1950), Thornthwaite (1948), and Penman (1952) procedures. He concluded that:

1. The Blaney-Criddle method had been developed primarily to estimate seasonal water use by crops. Application of this method, in determining the monthly water use, with a constant coefficient gives a considerable deviation from measured consumptive use.

2. Estimates based on Thornthwaite's method may be quite variable depending on the type of climate.

3. Penman's method should be used for crops which are fully shading the ground. The variable coefficients which have been suggested for determining the monthly water needs during the summer season diminish the possibility for wide use of this method.

In western Canada, Hobbs and Krogman (1966), in studies at Vauxhall, Alberta, estimated evapotranspiration for alfalfa from meteorological data by using the methods of

Blaney and Criddle (1962), Thornthwaite (1948) and Penman (1948) with some modifications applied for relevance to the local area. They found that correlation coefficients between calculated and measured evapotranspiration were highly significant. These findings support the use of meteorological data in predicting evapotranspiration. These researchers also concluded that these three methods were of equal reliability in estimating evapotranspiration and the application of each method depends on the available data of that specific area. In irrigation scheduling for short periods they also concluded that the estimates from evaporation conversion techniques are preferable.

At Swift Current, Saskatchewan, Pelton and Korven (1969[1]) studied the usefulness of the three well known equations described above. Evapotranspiration from alfalfa was measured by a lysimeter which was used as the standard of comparison over 53 days. They concluded that the Thornthwaite and the Blaney-Criddle methods underestimated actual evapotranspiration by about 40 percent and 31 percent respectively. These two methods were not recommended for estimating daily values but were considered more accurate on a weekly basis. These investigators found that about 65 percent of the variation of measured values of daily evapotranspiration were accountable by relation to the independent variables as estimated by Penman's method. This method also requires extensive modification before application to this semiarid climatic region.

Pruitt (1960) studied various evaporimeters and compared measured values of evaporation consumptive use of water by ladino clover. He reported that the coefficient relating evaporation from pans to consumptive use depends upon the type, size and environment of the pans; the pans in non-cropped environment are more exposed and also are affected considerably by advection. Thus a much lower coefficient is required for these pans in estimating consumptive use of water. His findings that the relationship between actual consumptive use of water and estimated use remained quite constant throughout the season for all the pans, the atmometers and the Penman procedure, show that estimates based on these methods should be quite reliable for predicting consumptive use for crops which have an ample moisture supply and which are fully shading the ground.

In southern Alberta, Hobbs and Krogman (1968) studied the observed and estimated evapotranspiration of sugar beets, potatoes, alfalfa and wheat. They estimated potential evapotranspiration (PE) from the method of Jensen and Haise (1963) which utilizes solar radiation and temperature. Actual evapotranspiration (AE) was measured by soil moisture depletion techniques. Ratios of AE/PE were determined, curves of daily AE as a function of stage of growth and the relationship between measured AE and calculated PE (ratio AE/PE) throughout the growing season were presented based on those four crops. They found the AE/PE ratio curves were similar to those of Jensen and Haise (1963). The general curve shapes for forages, cereals and row crops are similar and the AE/PE ratios are approximately the same at equivalent stages of crop development. From these results the authors recommended that the presented curves should be applicable to other areas.

2.4 Relationships of Soil Moisture, Plants and Potential Evapotranspiration to Actual Evapotranspiration

Available soil water, with reference to the availability of soil water for plant growth, is taken as the amount of water retained in a soil between field capacity and the permanent wilting point. This range has considerable practical significance in assessments of the agricultural value of soils. Numerous experiments with various plants and soils under natural and controlled conditions have been carried out in order to determine the relationship between soil moisture and transpiration.

Veihmeyer and Hendrickson (1955) reported results obtained mostly from the experiments in containers which demonstrated that soil moisture is equally available to plants for transpiration over the entire range of moisture contents between field capacity and permanent wilting point.

Denmead and Shaw (1962) studied the availability of soil water to plants as affected by soil moisture content and meteorological conditions; they found that the availability of soil moisture to plants within the field capacity-wilting point range decreases linearly with decreasing soil moisture. One of their conclusions was: "It is pointed out that as the soil dries, the actual transpiration rate should fall below the potential rate and that this decline in relative transpiration should occur at higher and higher soil moisture contents as the potential transpiration rate increases. Since the decline in relative transpiration rate (actual/potential) results from a loss of turgor in the plant, the soil moisture content at which plants wilt should also increase as the potential transpiration rate increases." The report also noted a highly significant relationship between daily transpiration rate at field capacity and the estimated evaporation of an open-water surface computed from observations of net radiation, temperature, humidity and wind velocity by Penman's method (1956).

Several methods have been proposed for relating available soil water to the ratio of AE/PE so that AE can be estimated from empirical estimates of PE. Thornthwaite and Mather (1955) found that the ratio AE/PE decreases approximately linearly from field capacity to the permanent wilting point represented by type curve C in Figure 1.

Veihmeyer and Hendrickson (1955) found that AE/PE is approximately unity until the permanent wilting point is reached; the remaining water is unavailable represented by type curve A.

Type curve B assumes no substantial reduction in transpiration rate except in very dry soil, as studied by Holmes (1961).

Holmes and Robertson (1963) obtained a curve of type D in their studies on the relationship between AE and PE explored in a growth chamber experiment and they recommended that this type of curve should be applied to a problem in arid zone agriculture.

In studies of the relationships between soil moisture and plant production, Holmes and Robertson (1963) found that wheat yields at Lethbridge were not significantly correlated with PE; the depletion of soil moisture was more significantly related to yields than was AE.

Jensen et al. (1961) studied available water for crops grown in the Columbia basin and found that soil moisture levels above 35 percent of the available water were still sufficient for plant growth. Some researchers found that even though this soil moisture was decreased to 30 percent of the available moisture it still was adequate for plants, Taylor and Slatyer (1955). Hammon and Code (1954) studying soils with root zones of six to twelve inches of available moisture for row crops, found that the

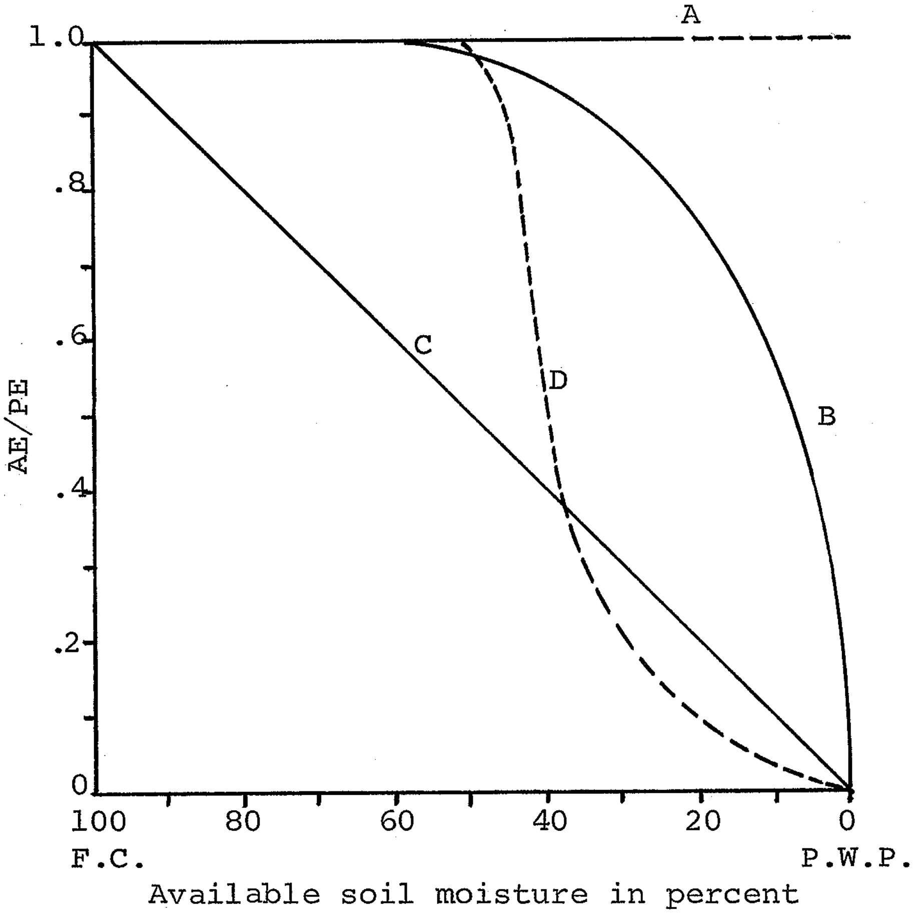


Figure 1. Some relationships between evapotranspiration and available soil moisture.

level of available moisture should be maintained above 25 percent for crops to grow without injury.

Hobbs and Krogman (1963) studied the minimum allowable moisture levels for maximum yields from eight crops in the irrigated areas of southern Alberta. They found that potatoes clearly responded to the maintenance of available soil moisture at or above the 75 percent level. For soft wheat, peas, sweet corn and alfalfa maximum yields resulted when the minimum allowable soil moisture was about 50 percent of the available moisture. Sugar beets, barley and established stands of sweet clover produced maximum yields even when the moisture content was allowed to decrease to 25 percent of the available water. They recommended that irrigation should be applied after soil moisture has been depleted to the 50 percent level. This level is widely used by other researchers, Pohjakas et al. (1967) and Pelton and Korven (1969[1]).

CHAPTER III

THEORIES REGARDING EVAPOTRANSPIRATION

3.1 Evaporation

At any surface of water in contact with the atmosphere, for example, at the water surface of a lake or a very small water droplet on a wet leaf, there is an exchange of water molecules back and forth between the water and the atmosphere. If there is a net movement of molecules from the water surface to increase water vapour in the atmosphere evaporation is taking place. Evaporation of water to the atmosphere can occur directly from open water surfaces, bare soil and wet leaves. Most plants take up water at their roots and carry the water to the leaves. If the pores of the leaves, called stomata, are opened then the water vapour will be transmitted to the exterior of the leaf in a form of evaporation which is referred to as transpiration. Evaporation is an energy-requiring process and in order to maintain evaporation from a surface, the following physical conditions must be satisfied, Rose (1966):

1. There must be a supply of heat to provide the quite large latent heat of vaporization (590 calories $-gm^{-1}$).

2. The vapour pressure in the overlying air must be maintained at less than the vapour pressure at the evaporating surface, since evaporation (a net transfer of water vapour) is zero if there is no gradient in vapour pressure.

3. Water must continue to be available for evaporation, this being a limiting factor under dry conditions.

From the above requirements, it is obvious that the rate of evaporation is dependent on the temperature of the evaporating surface and the atmospheric pressure.

These two dominant factors are controlled directly by the energy balance at the earth's surface. Energy from the sun is the major factor controlling the temperature; an increase in temperature increases the vapour pressure of water. Under conditions of high temperature and low humidity, evaporation will increase. Low incoming solar radiation and low wind speed tend to reduce evaporation rate. The following explanation is relevant to the theories of evaporation of water from the earth's surface and the water in the atmosphere.

3.2 Humidity Near the Earth's Surface

3.2.1 Water vapour

Water vapour is always present in the atmosphere and adds a considerable pressure called the water vapour pressure to the air pressure. As stated by Dalton's law of partial pressures, "the pressure exerted by water vapour is independent of the pressure exerted by other atmospheric gases provided that there is no condensation or evaporation taking place in the volume under consideration". The behaviour of water vapour can be explained by the equation of state of an ideal gas which is represented by the equation below, Rose (1966):

$$e = \frac{\rho_v}{M_w} R_u \, T \qquad (3.1)$$

where:

e = vapour pressure of water (dyne-cm^{-2})

ρ_v = the density of water vapour (gm-cm^{-3}), referred to as the "absolute humidity" of the atmosphere.

M_w = molecular weight of water (18 gm-mole^{-1})

R_u = universal gas constant (8.31×10^7 erg-mole^{-1} - deg^{-1} K)

T = absolute temperature of the water vapour, usually taken as the temperature of the air of which the vapour is one component.

3.2.2 Saturation If a pan of water is placed in a closed container, under conditions of constant temperature, evaporation will occur and continue until it reaches equilibrium. This state of equilibrium, according to Dalton's law, is the same regardless of the presence of any other gas in the space inside the container. The air at this state of equilibrium is considered to be saturated. The vapour pressure under these conditions is known as the saturation vapour pressure which depends on the temperature. For convenience, Penman (1955) prepared a curve relating temperature and saturation vapour pressure; a typical curve is shown in Figure 2. Tabulated values of this relationship are also given in the Smithsonian Institute Tables (1951).

3.2.3 Methods of expressing partial saturation There are two ways of quantifying atmospheric humidity, by expressing it as vapour pressure e or vapour density ρ_v ; the latter is usually referred to as absolute humidity. Generally, in measuring the water vapour in the atmosphere, the term relative humidity (h_r) is widely used.

$$h_r = \frac{e}{e_s} \quad \text{(dimensionless, } \leq 1) \qquad (3.2)$$

where:

e = the actual vapour pressure of the air in inches of mercury or in millibars.

e_s = the saturated vapour pressure at the air temperature in inches of mercury or in millibars.

In estimating the evaporation rate of water from climate, the more useful value is the difference between e and e_s, $(e - e_s)$, which is defined as the saturation

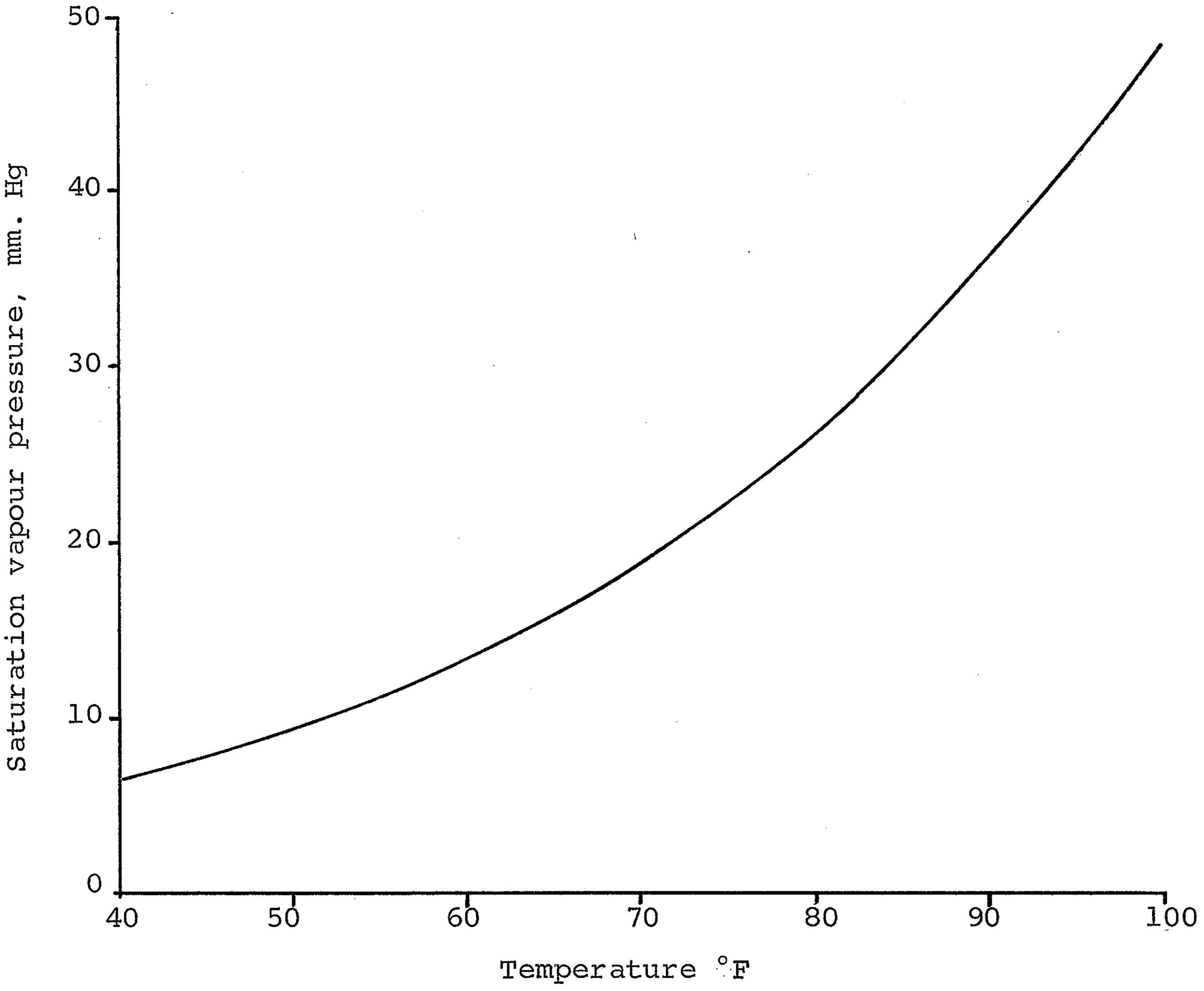


Figure 2. The saturation vapour pressure of water shown as a function of temperature (after Penman, 1955).

deficit. Relative humidity and saturation deficit are both dependent on the air temperature; for expressing the humidity condition the air temperature must be given.

Dew-point temperature (T_{dp}) Consider a volume of air under a particular temperature and humidity condition. If the air is cooled at constant pressure until the vapour is condensed as a liquid (or dew is formed), the temperature which corresponds to this degree of saturation is called the dew point.

Wet-bulb temperature (T_W) If water evaporates at a wet surface not only does an increase in the vapour pressure of the air above the surface result but also a decrease in the temperature of this air flow occurs because the energy required to evaporate the water is taken from the surrounding atmosphere. The process will follow the curve in Figure 2, in which the depression in the temperature will depend on the rate of the air flow. This relation will reach a certain state such that the temperature of the wet surface stabilizes at a value somewhat lower than before even if the air flow were increased. This is valid provided that the wet surface is thermally isolated from its surroundings. This steady temperature is called the wet-bulb temperature.

3.3 Conservation Principles for Heat Energy and Water

The heat energy from the sun on the earth's surface and the existence of water in the atmosphere (as vapour), or on the ground surface, are both main factors controlling the day-time microclimate. To explain the relevance of these two main factors to the climate on the earth's surface, two conservation principles have been introduced. The principle of energy conservation refers to heat energy and forms the basis of the energy-balance equation. The other is the principle of mass conservation of water which produces the water-balance equation.

Figure 3 illustrates the various components of the incoming radiation streams to the earth's surface. The widths of the arrows are taken to be proportional to the magnitudes of the energy fluxes. Some of the solar energy flows into the soil by thermal conduction, thus raising the soil temperature; some is re-radiated with the longer wavelength; some will be used for the evaporation process in which the energy is returned to the atmosphere with the evaporated water. The energy balance equation at the earth's surface can be developed by equating the net rate of incoming energy per unit area equals to the net rate of outgoing energy per unit area, therefore following Rose (1966):

$$R_S(1 - \rho) = R_L + G + H + LE \ (\text{cal-cm}^{-2}\text{-sec}^{-1}) \qquad (3.3)$$

where:

R_S = flux density of total short-wave radiation received by the ground surface from the sun and the sky.

ρ = albedo (or reflection coefficient) of the ground surface.

R_L = net flux density of long-wave radiation emitted by the surface, the difference between that emitted and absorbed.

G = heat flux density into the ground.

H = sensible (or non-latent) heat flux density into the atmosphere.

L = latent heat of vaporization of water (cal-gm^{-1}), and,

E = evaporation rate, negative for condensation ($\text{gm-cm}^{-2}\text{-sec}^{-1}$). Evaporation from plants is

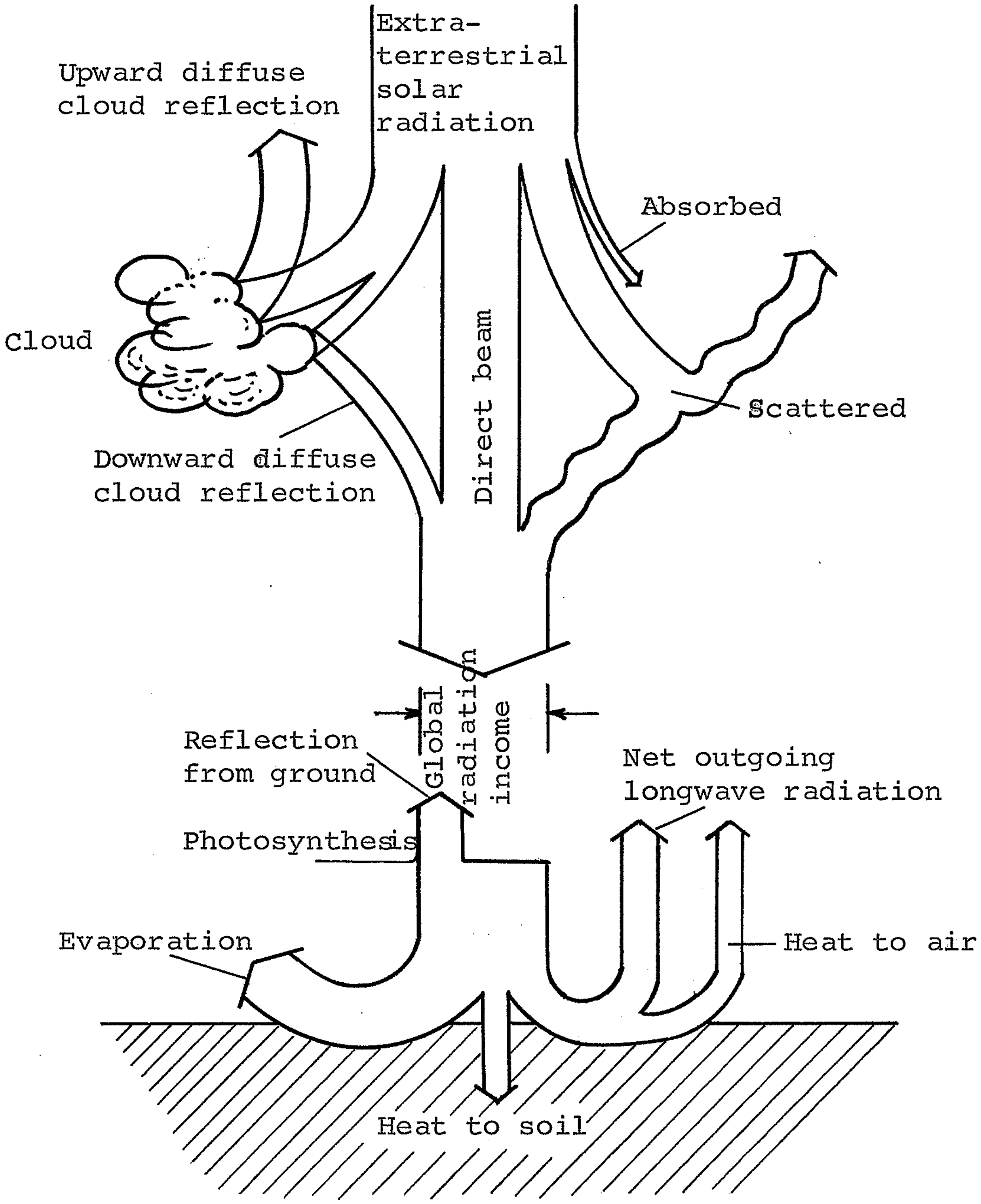


Figure 3. Components of the day-time heat exchange at the earth's surface. (Adapted from Geiger, 1959 as reported by Rose, 1966.)

included; this is often referred to as transpiration.

All terms in equation (3.3) have the dimensions of energy flux density with the units of cal-cm^{-2}-sec^{-1}, and the magnitude of each term can vary widely. For example, when the crops are experiencing active growth, and the soil surface is moist, solar energy will be utilized at the greatest rate in the evaporation of water. When the soil dries out, the solar energy required for the evaporating process will be less and this will result in a greater loss of sensible heat to the atmosphere. Rose (1966) concluded that "because it is based on the fundamental principle of energy conservation, this equation must always be satisfied, a change in any one term requiring a readjustment of another term or terms".

Equation (3.3) can be rearranged as follows:

$$R_S(1 - \rho) - R_L = G + H + LE \qquad (3.4)$$

The left hand terms include both short and long wave lengths which are referred to as the total net radiation flux and can be measured directly from the net radiometer. So equation (3.4) can be written:

$$R_N = G + H + LE \qquad (3.5)$$

where R_N is the total net radiation flux.

In this equation, the net solar energy is controlled by the amount of moisture in the soil. Conversely, the solar energy is the main factor affecting the presence of moisture in the soil. This indicates that there is a very close relation between the energy balance at the ground surface and the water-balance, which will further be discussed.

Consider a certain area. Water received on the area (by rain or irrigation water) may remain on the surface, infiltrate into the soil or become surface run off. Some of the received water will be evaporated back to the atmosphere. All these data can be determined to produce a water-balance equation by equating the inflow to the outflow of a particular area during a certain period of time. The following conservation balance equation must be satisfied for any given period and volume of soil, following Rose (1966).

$$P = S + \Delta D + \Delta M + U + \int E dt \qquad (3.6)$$

where:

P = precipitation received (including irrigation water applied) in the area for which the balance is considered.

S = net surface run off (represents all the sources of surface water supplies).

ΔD = increase in surface detention.

ΔM = increase in soil water storage due to water flux in any direction across the boundaries soil volume considered.

U = increase in underground and subsurface storage in layers below that for which ΔM was calculated, and

$\int E dt$ = total evaporation during the time t under consideration.

All the components of the above equation may be converted to equivalent depths of water in inches or centimeters. The evaporation rate E is expressed in centimeter per second. The term ΔD may be negligible. All the components may be measured except $\int E dt$ which is equal to evapotranspiration.

Equations of the same type as equation (3.6) are often applied to develop a soil moisture budget. Robertson and Holmes (1959) used such an equation in determining evapotranspiration for irrigated crops.

CHAPTER IV

EXPERIMENTAL EQUIPMENT

A weather station was set up at the Tony Adriaanson farm, located about ten miles north of Carberry. The location and topography of the project is similar to those agricultural farms typical of the Canadian Prairie region. The weather station was located about ¼ mile from the plots. Meteorological records were obtained on a daily basis during the period May 1 to September 30, 1969 (153 days). Daily records were collected in the following manner:

4.1 Temperature

Maximum and minimum air temperatures in degrees Fahrenheit were measured daily by maximum and minimum temperature recording thermometers in a standard Stevenson screen.

4.2 Humidity

Wet bulb and dry bulb temperature in degrees Fahrenheit were recorded daily at 8:00 am. Dew-point temperatures were also determined once a day at 8:00 am using a sling psychrometer.

Continuous temperature and relative humidity were also recorded on the hygro-thermograph charts during the whole period of 153 days. A typical curve is shown in Appendix A.

4.3 Wind

Daily wind travel in miles was recorded by two cumulative three-cup anemometers. One was placed at 2.0 meters and the other at 18 inches above the ground.

4.4 Solar Radiation

Total solar radiation in gram-calories per square centimeter per day was measured by a pyrheliometer placed six feet above the ground. An example of a pyrheliometer chart is shown in Appendix B. See Figure 4.

4.5 Evaporation

This was recorded daily from two sources.

1. A United States Weather Bureau (U.S.W.B.) Class A pan (Rohwer 1934) which is four feet in diameter, ten inches deep with the bottom supported six inches above the ground on a wooden frame. The water level is maintained at two inches below the rim of the pan by adding (or removing) water daily with a graduated cylinder. A point gauge within a stilling well indicates the proper water level. Daily maximum and minimum temperature of water in degrees Fahrenheit were also measured by submerged thermometers. Evaporation in inches was recorded daily at 8:00 am. See Figure 6.

2. A black Bellani plate atmometer. The instrument (Robertson and Holmes, 1957) consisted of a thin porous black ceramic disk, three inches in diameter and 1/8 inch thick, fused to the top of a glazed ceramic cup and supported horizontally at a height of 4.00 feet above the ground level. Water was conducted to the cup through a mercury valve from a 250 cubic centimeter burette which served as a reservoir and measuring device. The maximum daily water loss in cubic centimeters from duplicate installations was measured. When the difference in daily evaporation between the two instruments

Figure 4. Pyrheliometer.

exceeded five percent, the atmometer which produced the low reading was replaced. See Figure 5 for a view of the black Bellani plate atmometer installation.

4.6 Precipitation

Daily precipitation in inches was recorded by an automatic recording rain gauge. A standard ten-inch rain gauge was also installed for daily readings.

4.7 Installation of Instruments

See Appendix C for instrument installation plan and Figure 6.

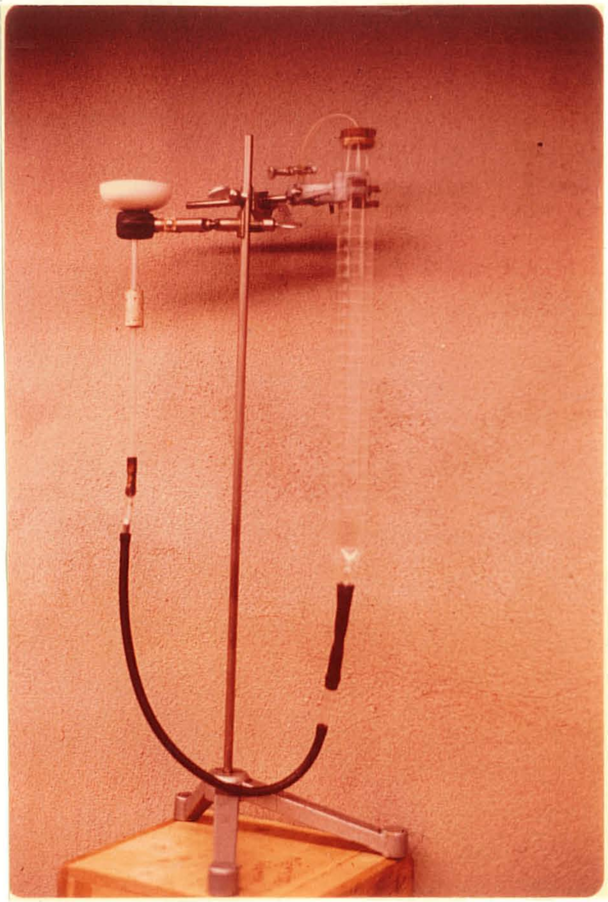


Figure 5. Bellani plate atmometer.

Figure 6. Weather station from the north west corner.

(See Appendix C for instrument installation plan)

NOTES:

No.	Instrument
1	Duplicate black Bellani plate atmometers.
2	U.S.W.B. Class "A" pan.
3	Pyrheliometer.
4	Three cup anemometer 2.00-meter height.
5	Three cup anemometer 1½-foot height.
6	Stevenson screen.
7	Automatic recording rain gauge.

CHAPTER V

PROCEDURES

5.1 Choice of Evaporation Estimation Technique

As already discussed in Chapter II, a considerable amount of research by Wilcox (1963) and Pelton (1964) resulted in the same conclusion that if weather records are used to estimate evapotranspiration, the four weather elements, solar radiation, temperature, wind and humidity should be used. Numerous methods available for estimating potential evapotranspiration from one or several parameters or from instrument readings have already been discussed. To standardize the measurement of evaporation as a climatic factor, Robertson (1955) introduced a modified version of the black Bellani atmometer for the measurement of latent evaporation. Baier and Robertson (1965) developed equations for estimating daily latent evaporation from meteorological observations based on the linear multiple regression technique as briefly discussed in Chapter II. They also tested other more complex approaches such as logarithmic, quadratic, and cubic combinations of the independent variables and found that they did not significantly improve the equation. In their methods, instead of using mean temperature, it appears more logical to use maximum temperature and temperature range. Maximum temperature is considered to be more closely related to the temperature of the evaporating surface while temperature range is considered to be a manifestation of the variation of solar energy and vapour pressure dificit. Energy at the top of the atmosphere was used to replace day length which is considered as a manifestation of the variation of solar energy with latitude. It is available in

Smithsonian Tables (1951). Since these three variables are readily available for all climatological stations, they are considered as first essentials in the empirical formula to be developed.

Additional meteorological factors, for example, wind and solar radiation, are then added for better accuracy of estimation. Because of the simplicity in estimating latent evaporation which will be applied in practical work, this technique was selected for the present study.

5.2 Extraction of Field Data

All the meteorological data obtained from the field described in Chapter IV were extracted for statistical analysis as required by the method of this study during 153 consecutive days, from May 1 to September 30, 1969.

5.2.1 Daily maximum air temperature Daily maximum air temperature in degrees Fahrenheit as recorded in a Stevenson screen.

5.2.2 Daily temperature range Daily temperature range in degrees Fahrenheit which is the difference of the daily maximum and minimum temperature.

5.2.3 Daily vapour pressure deficit Daily vapour pressure deficit in millibars was calculated as follows (all temperatures in degrees Fahrenheit):

1. The dew point temperature was determined at 4:00 pm by using air temperature and relative humidity as recorded by the hygro-thermograph and entered on the psychrometric chart to determine the dew point temperature.

2. The mean daily dew point temperature was determined by calculating the mean value of dew point temperatures at 4:00 pm and at 8:00 am as measured by a sling psychrometer

(Section 4.2).

3. The mean daily air temperature was determined by calculating the mean value of maximum and minimum air temperature $(\frac{\text{maximum} + \text{minimum}}{2})$.

4. Smithsonian Tables (1951) were used to determine vapour pressure at mean air temperature (e_s) and vapour pressure at mean dew point temperature (e_w) from saturation vapour pressure tables and the difference ($e_s - e_w$) expressed in millibars was designated vapour pressure deficit (V.P.D.).

5.2.4 Total daily wind run Total daily wind run in miles as recorded by totalizing cup anemometers at 2.00 meters above the ground.

5.2.5 Total solar radiation Total solar radiation (R_T) in gram-calories per square centimeter per day determined from weekly recording pyrheliometer charts as shown in Appendix B. From the curve trace on the chart, the area under the inked record for each day in square centimeters were determined by using a planimeter. This area is then multiplied by the "chart constant", which is equivalent to 130.5629 gram-calories per square centimeter, per square centimeter of chart (see Appendix B), to obtain total solar radiation in gram-calories per square centimeter per day.

5.2.6 Solar energy at the top of the atmosphere Total solar radiation in calories per square centimeter falling on a horizontal surface at the top of the atmosphere during one day for latitude 50 degrees north (approximate location of Carberry) was obtained from Smithsonian Tables (1951).

All six meteorological variables described above are the same as those of Baier and Robertson (1965) except for solar energy. In their method they used total sky and solar energy on a horizontal surface (Q_S) which is determined from their empirical equation:

$$Q_S = Q_O [0.251 + 0.616(n/N)]$$

where:

Q_O = solar energy at the top of atmosphere in calories per square centimeters per day.

n = duration of bright sunshine in hours which was measured with a Campbell-Stokes sunshine recorder.

N = daylength or duration of daylight, that is, the interval between sunrise and sunset in hours taken from standard Smithsonian Tables (1951).

5.2.7 Evaporation from duplicate black Bellani plate atmometers Evaporation from duplicate black Bellani plate atmometers which is referred to as latent evaporation was determined for mean daily evaporation in cubic centimeters.

5.2.8 Daily evaporation from U.S.W.B. Class A pan Daily evaporation from U.S.W.B. Class A pan in inches measured to the nearest hundredth of an inch was used directly from the field measurements.

5.2.9 Precipitation Precipitation was obtained from an automatic recording rain gauge and was recorded to the nearest hundredth of an inch.

5.3 Estimation of Missing Data

Some of the meteorological observations during the study period of May 1 to September 30 were missing due to malfunctioning of instruments. These missing data were estimated by simple regression techniques between the two sets of observed data, for example, 12 days of latent evaporation were missed. A simple regression equation relating latent evaporation to U.S.W.B. Class A pan evaporation was developed and the equation was used to estimate the missing latent evaporation data.

5.4 Investigation of Past Evaporation Records in Manitoba

Records of weather data obtained from the monthly weather reports published by the Canada Department of Transport were reviewed. Various locations in Manitoba where weather records of monthly evaporation (pan or atmometer) temperature and precipitation are available during the months of May to September for at least five years were selected for this study. For the review, four locations, Baldur, Morden, Riding Mountain Park and Winnipeg were selected. Monthly evaporation data from U.S.W.B. Class A pan were available for the seven-year period of 1963-1969. Some of the evaporation data were missing and they were estimated by a simple regression technique with monthly temperature. The investigated data of mean monthly Class A pan evaporation were shown in Appendix D.

5.5 Selection of Crops and Growing Periods for the Present Study

Crops selected in this study were those currently grown under irrigation as well as some that have a potential as irrigated crops in Manitoba. Four main crops, alfalfa, sugar beets, potatoes and cereals (wheat) were selected. It is difficult to estimate the exact growing period of each crop. The following growing periods of the various crops as shown in Table I were designated for this study.

By comparing with the figure given by Sonmor (1963), the estimated periods of this study are considered to be reasonable.

TABLE I

ESTIMATING GROWING PERIODS OF CROPS

Crops	Growing Period	No. of Days	No. of Days Given by Sonmor (1963)
Alfalfa	May 1 - September 30	153	155 ± 22.7
Potatoes	May 15 - September 15	124	137 ± 6.5
Cereals	May 15 - September 1	110	102 ± 3.8
Sugar beets	May 15 - October 31	170	156 ± 5.0

5.6 Derivation of an Evaporation Equation

Statistical analysis using linear multiple correlation and regression techniques were employed by computing evaporation equations. Daily records of evaporation as a dependent variable were correlated with daily data for several meteorological and astronomical parameters as independent variables. All the dependent and independent variables involved in the computation are listed in Table II and Appendix E.

Two main equations were developed, one is the prediction equation for latent evaporation and the other is the prediction equation for U.S.W.B. Class A pan evaporation.

TABLE II

LIST OF DEPENDENT AND INDEPENDENT VARIABLES

Dependent Variables	Abbreviations
latent evaporation (evaporation from atmometer)	E_L
U.S.W.B. Class A pan evaporation	E_{pan}
Independent Variables	
maximum temperature	Max
temperature range	Range
vapour pressure deficit	V.P.D.
wind	Wind
solar energy at the top of atmosphere	Q_o
total solar radiation	R_T

5.6.1 Model of equation Linear multiple regression models of the type below were employed.

$$Y = a + b_1X_1 + b_2X_2 + \ldots\ldots\ldots b_iX_i$$

where:

Y = dependent variable

X = independent variable

a = constant

$b_1, b_2 .. b_i$ = regression coefficients

Eight versions of the same model were developed with the number of independent variables involved in the computation varying from a minimum of three to a maximum of six. See Table III for detail.

TABLE III

LIST OF METEOROLOGICAL VARIABLES INVOLVED IN EACH METHOD

Method	Meteorological Variables (independent variables)
I	Max, Range, Q_O
II	Max, Range, Q_O, R_T
III	Max, Range, Q_O, V.P.D.
IV	Max, Range, Q_O, Wind
V	Max, Range, Q_O, R_T, V.P.D.
VI	Max, Range, Q_O, R_T, Wind
VII	Max, Range, Q_O, V.P.D., Wind
VIII	Max, Range, Q_O, R_T, Wind, V.P.D.

5.6.2 Computation of equations Statistical analyses of the above model were solved by computer (IBM 360) with the use of a linear multiple regression program from "statistical package number 18", at the University of Manitoba Computer Centre (September, 1969).

5.6.3 Types of equations Three types of equations were developed based on the estimated growing period of each crop as shown below:

Alfalfa:	based on number of observations for 153 days
Potatoes:	based on number of observations for 124 days
Cereals:	based on number of observations for 110 days
Sugar beets:	no equation was developed because there were no evaporation records within the period of October 1-31.

5.7 Testing of Equations

The Baier and Robertson (1965) equations and all the developed equations obtained from this study were tested by the following procedure.

5.7.1 Testing the applicability of Baier and Robertson (1965) equations Equations as developed by Baier and Robertson (1965) were used to calculate the latent evaporation from the available meteorological variables as listed in Table III. Statistical paired 't' tests between calculated and actual latent evaporation at Carberry were applied.

5.7.2 Testing the difference between the derived equations of latent evaporation for Carberry and the equations of Baier and Robertson (1965) Statistical 't' tests of the significance of the difference between regression coefficients of corresponding variables were tested by using the formula

$$t = \frac{b_c - b_B}{S_{bc}}$$

where:

t = statistical 't' value

b_c = regression coefficient of the Carberry equation

b_B = regression coefficient of the Baier and Robertson (1965) equation

S_{bc} = standard error of estimate of regression coefficient of the Carberry equation

5.7.3 Testing the significant difference among the regression coefficients of the three equations for alfalfa, potatoes and cereals The 't' test was also applied by using the formula

$$t = \frac{b_1 - b_2}{\sqrt{(Sb_1)^2 + (Sb_2)^2}}$$

where:

t = statistical 't' value

b_1 = regression coefficient from the alfalfa equation

b_2 = regression coefficient from the potato equation

Note: b_1 and b_2 correspond to the same variable

$(Sb_1)^2$ = variance of b_1

$(Sb_2)^2$ = variance of b_2

Comparisons were made with critical 't' values at the one percent level with the degrees of freedom equal to $(n-k-1)_1 + (n-k-1)_2$.

n = number of observations

k = number of independent variables

5.8 Estimation of Seasonal Consumptive Use

Seasonal consumptive use of the four crops was estimated from evaporation calculated from the best prediction equation of latent evaporation and U.S.W.B. Class A pan evaporation.

5.8.1 Estimates from Vauxhall coefficients (Sonmor, 1963) Seasonal latent evaporation and U.S.W.B. Class A pan evaporation were multiplied by the ratio of consumptive use to evaporation as given by Sonmor (1963) to give predicted values of seasonal consumptive use.

CHAPTER VI

RESULTS AND DISCUSSION

6.1 Correlation Analysis

The results of simple correlation analysis between evaporimeters and meteorological variables are presented in the form of a correlation matrix in Table IV.

TABLE IV

CORRELATION COEFFICIENT MATRIX OF DEPENDENT AND INDEPENDENT VARIABLES

Variables	Pan	Plate	Max	Range	V.P.D.	Wind	R_T	Q_o
Pan	1.000							
Plate	.677**	1.000						
Max	.434**	.551**	1.000					
Range	.414**	.721**	.549**	1.000				
V.P.D.	.472**	.697**	.632**	.542**	1.000			
Wind	.207*	.038	-.252**	-.232**	-.101	1.000		
R_T	.606**	.809**	.426**	.583**	.541**	-.146	1.000	
Q_o	.361**	.314**	.124	.114	.062	.228**	.426**	1.000

** Significant at the one percent level.
 * Significant at the five percent level.

The simple correlation coefficient indicates the gross relationship between two variables regardless of how many intermediate variables may be involved.

6.1.1 Simple correlation between evaporimeters and meteorological variables Evaporimeter correlation coefficients in Table IV were all significant at the one percent level except for daily wind travel. Evaporation from the Class A pan correlated better with maximum temperature than with temperature range. The opposite observation was indicated by the black Bellani plate. Evaporation from the two evaporimeters were correlated highly to each other and each showed the highest correlation coefficients with daily total solar radiation. The coefficient for wind against evaporation from the Class A pan although it was statistically significant at the five percent level, indicated that less than five percent (r^2) of the evaporation from this instrument can be attributed to the effects of wind alone. Correlation coefficients involving radiation, temperature and vapour pressure deficit were not greatly different as shown by the Class A pan but were considerably different as indicated by the black Bellani plate. The data from the Bellani plate appeared to correlate better with each of these meteorological factors than those from the Class A pan except for the correlation between the solar energy at the top of atmosphere and evaporation from the Class A pan.

6.1.2 Simple correlation between individual meteorological variables From Table IV, the correlation coefficient between vapour pressure deficit and maximum temperature was the highest. This is physically reasonable because air temperature formed the basis of one of the vapour pressure components. The radiation terms were significantly correlated with each other. Total solar radiation was correlated with temperature and vapour pressure deficit as expected. Wind showed a correlation with solar energy at the top of atmosphere but was negatively correlated with each of the other meteorological variables. This undoubtedly accounts for the low simple correlations between wind and evaporation from each of the Class A pan and the black Bellani plate.

6.2 Latent evaporation

Linear multiple regression equations of latent evaporation on meteorological variables are presented in the following tables:

Table V - Prediction equations based on the growing period of alfalfa (N = 153 days).

Table VI - Prediction equations based on the growing period of potatoes (N = 124 days).

Table VII - Prediction equations based on the growing period of cereals (N = 110 days).

The number of independent variables in each equation followed Methods I to VIII is described in Chapter V. Equations presented in the tables will be of the same form; for example, equation (5.1) will be written as:

$$E_L = -45.62 + 0.362(\text{Max}) + 1.377(\text{Range}) + 0.0326(Q_o)$$

Results from Table V, Table VI and Table VII show multiple correlation coefficients (R) were all highly significant at the one percent level.

Coefficients of determination (R^2), as indicated by equation (5.1), indicated, for example, that approximately 60 percent of the variations of latent evaporation can be explained by variations of three factors (maximum temperature, temperature range and solar energy at the top of the atmosphere).

The standard error of estimate (S_{ee}) was explained by equation (5.1). For equation 5.1, S_{ee} was 12.99cc. This means that 67 percent of the observed values of latent evaporation fell in the range of ± 12.99cc from the predicted values. So the smaller the standard error of estimate the smaller is the error in the prediction.

The 't' values for regression coefficients were used in testing the contribution of each meteorological

TABLE V

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF ALFALFA (153 DAYS)

Equation	Meteorological Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
5.1	Max	-45.62	0.362	0.111	3.261**	R=0.776**
	Range		1.377	0.146	9.458**	R^2=0.602
	Q_o		0.0326	0.0076	4.258**	S_{ee}=12.99
5.2	Max	-29.80	0.242	0.0870	2.783**	R=0.873**
	Range		0.756	0.129	5.856**	R^2=0.762
	Q_o		0.00362	0.00662	0.546	S_{ee}=10.09
	R_T		0.0727	0.0073	9.946**	
5.3	Max	-26.95	-0.0160	0.1088	-0.147	R=0.841**
	Range		1.088	0.132	8.264**	R^2=0.707
	Q_o		0.0345	0.0066	5.230**	S_{ee}=11.19
	V.P.D.		3.280	0.451	7.267**	
5.4	Max	-53.42	0.436	0.108	4.033**	R=0.799**
	Range		1.450	0.141	10.304**	R^2=0.638
	Q_o		0.0245	0.0076	3.210**	S_{ee}=12.44
	Wind		0.0516	0.0135	3.808**	
5.5	Max	-20.56	0.0184	0.0902	0.204	R=0.895**
	Range		0.682	0.119	5.708**	R^2=0.801
	Q_o		0.0101	0.0062	1.639	S_{ee}=9.26
	R_T		0.0594	0.0071	8.307**	
	V.P.D.		2.133	0.398	5.354**	
5.6	Max	-38.66	0.328	0.077	4.274**	R=0.906**
	Range		0.809	0.113	7.113**	R^2=0.821
	Q_o		-0.00919	0.00605	-1.518	S_{ee}=8.79
	R_T		0.0785	0.0064	12.223**	
	Wind		0.0669	0.0096	6.933**	
5.7	Max	-34.20	0.0650	0.108	0.603	R=0.854**
	Range		1.162	0.129	9.008**	R^2=0.729
	Q_o		0.0280	0.0066	4.218**	S_{ee}=10.81
	V.P.D.		3.078	0.440	6.995**	
	Wind		0.0404	0.0119	3.399**	
5.8	Max	-30.24	0.140	0.082	1.705	R=0.919**
	Range		0.737	0.106	6.927**	R^2=0.844
	Q_o		-0.00241	0.00585	-0.413	S_{ee}=8.22
	R_T		0.0672	0.0064	10.396**	
	Wind		0.0586	0.0092	6.364**	
	V.P.D.		1.689	0.360	4.686**	

* Significant at the five percent level.

** Significant at the one percent level.

R = Multiple correlation coefficient.

S_{ee} = Standard error of estimate.

t = Statistical 't' value, test of the difference of each regression coefficient from zero.

TABLE VI

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF POTATOES (124 DAYS)

Equation	Meteorological Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
6.1	Max	-65.07	0.451	0.140	3.207^{**}	$R=0.758^{**}$
	Range		1.517	0.164	9.238^{**}	$R^2=0.574$
	Q_o		0.0428	0.0115	3.705^{**}	$S_{ee}=13.45$
6.2	Max	-50.26	0.338	0.109	3.109^{**}	$R=0.866^{**}$
	Range		0.825	0.147	5.611^{**}	$R^2=0.750$
	Q_o		0.0151	0.0093	1.613	$S_{ee}=10.34$
	R_T		0.0745	0.0081	9.178^{**}	
6.3	Max	-44.11	0.0790	0.138	0.576	$R=0.822^{**}$
	Range		1.204	0.153	7.876^{**}	$R^2=0.707$
	Q_o		0.0435	0.0101	4.293^{**}	$S_{ee}=11.81$
	V.P.D.		3.0333	0.499	6.076^{**}	
6.4	Max	-74.36	0.552	0.137	4.026^{**}	$R=0.785^{**}$
	Range		1.589	0.158	10.059^{**}	$R^2=0.616$
	Q_o		0.0340	0.0113	3.006^{**}	$S_{ee}=12.84$
	Wind		0.0534	0.0149	3.571^{**}	
6.5	Max	-39.07	0.116	0.112	1.043	$R=0.888^{**}$
	Range		0.731	0.137	5.314^{**}	$R^2=0.788$
	Q_o		0.0199	0.0087	2.273^{*}	$S_{ee}=9.57$
	R_T		0.0629	0.0079	7.938^{**}	
	V.P.D.		1.951	0.427	4.567^{**}	
6.6	Max	-60.90	0.457	0.096	4.771^{**}	$R=0.903^{**}$
	Range		0.867	0.1273	6.811^{**}	$R^2=0.815$
	Q_o		0.00204	0.00836	0.244	$S_{ee}=8.94$
	R_T		0.0798	0.0071	11.287^{**}	
	Wind		0.0672	0.0105	6.409^{**}	
6.7	Max	-52.86	0.186	0.138	1.350	$R=0.835^{**}$
	Range		1.285	0.150	8.536^{**}	$R^2=0.697$
	Q_o		0.0368	0.0101	3.653^{**}	$S_{ee}=11.43$
	V.P.D.		2.783	0.491	5.673^{**}	
	Wind		0.0403	0.0135	2.985^{**}	
6.8	Max	-51.22	0.277	0.1029	2.692^{**}	$R=0.914^{**}$
	Range		0.792	0.122	6.469^{**}	$R^2=0.835$
	Q_o		0.00724	0.00805	0.899^{**}	$S_{ee}=8.48$
	R_T		0.0705	0.0071	9.859^{**}	
	Wind		0.0587	0.0102	5.760^{**}	
	V.P.D.		1.457	0.388	3.754^{**}	

* Significant at the five percent level.
** Significant at the one percent level.

TABLE VII

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION BASED ON THE GROWING PERIOD OF CEREALS (110 DAYS)

Equation	Meteorological Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
7.1	Max	-69.52	0.444	0.159	2.794^{**}	$R=0.770^{**}$
	Range		1.623	0.177	9.139^{**}	$R^2=0.593$
	Q_o		0.0454	0.0186	2.438^{*}	$S_{ee}=13.45$
7.2	Max	-69.50	0.369	0.122	3.029^{**}	$R=0.874^{**}$
	Range		0.860	0.161	5.322^{**}	$R^2=0.764$
	Q_o		0.0321	0.0143	2.241^{*}	$S_{ee}=10.29$
	R_T		0.0742	0.0085	8.728^{**}	
7.3	Max	-50.52	0.103	0.154	0.669	$R=0.826^{**}$
	Range		1.289	0.169	7.613^{**}	$R^2=0.682$
	Q_o		0.0465	0.0165	2.812^{**}	$S_{ee}=11.95$
	V.P.D.		2.995	0.553	5.418^{**}	
7.4	Max	-79.45	0.558	0.154	3.619^{**}	$R=0.798^{**}$
	Range		1.715	0.171	10.053^{**}	$R^2=0.637$
	Q_o		0.0356	0.0179	1.994^{*}	$S_{ee}=12.78$
	Wind		0.0541	0.0153	3.544^{**}	
7.5	Max	-58.25	0.178	0.126	1.415	$R=0.890^{**}$
	Range		0.774	0.154	5.019^{**}	$R^2=0.792$
	Q_o		0.0347	0.0135	2.562^{*}	$S_{ee}=9.72$
	R_T		0.0633	0.0085	7.398^{**}	
	V.P.D.		1.774	0.479	3.704^{**}	
7.6	Max	-81.80	0.505	0.106	4.764^{**}	$R=0.911^{**}$
	Range		0.920	0.138	6.663^{**}	$R^2=0.830$
	Q_o		0.0191	0.0124	1.542	$S_{ee}=8.78$
	R_T		0.0794	0.0073	10.880^{**}	
	Wind		0.0670	0.0105	6.351^{**}	
7.7	Max	-59.99	0.224	0.154	1.451	$R=0.841^{**}$
	Range		1.392	0.167	8.338^{**}	$R^2=0.707$
	Q_o		0.0389	0.0161	2.409^{*}	$S_{ee}=11.53$
	V.P.D.		2.708	0.542	4.997^{**}	
	Wind		0.0416	0.0140	2.975^{**}	
7.8	Max	-72.94	0.363	0.115	3.156^{**}	$R=0.918^{**}$
	Range		0.856	0.136	6.306^{**}	$R^2=0.843$
	Q_o		0.0220	0.0120	1.841	$S_{ee}=8.51$
	R_T		0.0715	0.0076	9.381^{**}	
	Wind		0.0602	0.0105	5.727^{**}	
	V.P.D.		1.200	0.431	2.784^{**}	

* Significant at the five percent level.
** Significant at the one percent level.

TABLE VIII

SUMMARY OF THE SIGNIFICANT 't' VALUES FOR REGRESSION COEFFICIENTS FROM THE PREDICTION EQUATIONS FOR LATENT EVAPORATION

Method	Equation	R^2	Significant 't' Values for Regression Coefficients					
			Max	Range	Q_o	V.P.D.	Wind	R_T
I	5.1	0.602	**	**	**	-	-	-
	6.1	0.574	**	**	**	-	-	-
	7.1	0.593	**	**	*	-	-	-
II	5.2	0.762	**	**	No	-	-	**
	6.2	0.750	**	**	No	-	-	**
	7.2	0.764	**	**	*	-	-	**
III	5.3	0.707	No	**	**	**	-	-
	6.3	0.676	No	**	**	**	-	-
	7.3	0.682	No	**	**	**	-	-
IV	5.4	0.638	**	**	**	-	**	-
	6.4	0.616	**	**	**	-	**	-
	7.4	0.637	**	**	*	-	**	-
V	5.5	0.801	No	**	No	**	-	**
	6.5	0.788	No	**	*	**	-	**
	7.5	0.792	No	**	*	**	-	**
VI	5.6	0.821	**	**	No	-	**	**
	6.6	0.815	**	**	No	-	**	**
	7.6	0.830	**	**	No	-	**	**
VII	5.7	0.729	No	**	**	**	**	-
	6.7	0.697	No	**	**	**	**	-
	7.7	0.707	No	**	**	**	**	-
VIII	5.8	0.844	No	**	No	**	**	**
	6.8	0.835	**	**	No	**	**	**
	7.8	0.843	**	**	No	**	**	**

* Significant at the five percent level.
** Significant at the one percent level.

variable to the regression of prediction equations.

All results are discussed on the basis of the types of equations in the following section.

6.2.1 Equations of three meteorological variables

These three variables are minimum temperature, temperature range and solar energy at the top of the atmosphere as shown by equations (5.1), (6.1) and (7.1) in Tables V, VI and VII respectively. Multiple correlation coefficients were significant at the one percent level and had almost the same value of 0.77. Equation (6.1) shows the lowest correlation coefficient of 0.758 of the three equations. The 't' values for the regression coefficients of the three independent variables were all significant at the one percent level. This indicates that all three variables significantly contributed to the regression.

There is a strong statistical justification for choosing these three meteorological variables as the basic variables of the derived equations.

6.2.2 Equations of four meteorological variables

One more variable was added to the basic three-variable equations:

1. The addition of total solar radiation (R_T) as shown by equations (5.2), (6.2) and (7.2) was examined. Correlation coefficients were almost the same, about 0.87 and a lower value of standard error of estimate in the range 10.09 to 10.34cc was obtained. The 't' values for the regression coefficients were all significant at the one percent level except for Q_o. The 't' values of Q_o in equation (7.2) was significant at the five percent level and was not significant for equations (5.2) and (6.2).

This indicates that Q_o did not make any significant contribution to the regression in equations (5.2) and (6.2) and should be eliminated from these equations. The variables R_T and Q_O were the only solar energy terms involved in the equations. The higher regression coefficients for total solar energy indicate the major contribution of solar energy to the regression. For this reason Q_O has been retained as an important independent variable in these equations.

2. The addition of vapour pressure deficit (V.P.D.) as shown by equations (5.3), (6.3) and (7.3) was studied. The highest correlation coefficient was about 0.84 as indicated by equation (5.3). All correlation coefficients were lower than those obtained by adding total solar radiation but they were still highly significant. The standard error of estimate was in the range 11.81 to 11.99cc for these three equations. Regression coefficients were all positive except for maximum temperature in equation (5.3) in which the 't' value was slightly negative. This means the increase in maximum temperature tended to decrease the latent evaporation which is not reasonable. An examination of the regression coefficient of temperature range reveals that it was approximately 70 times greater than that of maximum temperature. Consequently, the lack of significant 't' values for maximum temperature seems to be compensated by the highly significant 't' values of temperature range.

3. The addition of wind as shown by equations (5.4), (6.4) and (7.4) indicates that the values of R were less than the values of R in the equations including total

solar radiation by about 8.5 to 9.4 percent. Correlation coefficients and 't' values were significant at the one percent level except for the 't' value of Q_o of equation (7.4) which was significant only at the five percent level. This means all variables made a significant contribution to the regression, even though the correlation coefficients were lower than those obtained from equations including total solar energy (Method II) and vapour pressure deficit (Method III).

6.2.3 Equations of five meteorological variables

Two more variables were added to the basic equations of three variables.

1. The addition of total solar radiation and vapour pressure deficit as shown by equations (5.5), (6.5) and (7.5) was examined. Correlation coefficients were all significant at the one percent level and had values very close to 0.89 which represents an improvement over those equations with four variables. The standard error of estimate decreased to 9.26cc in equation (5.5). The 't' values of temperature range, vapour pressure deficit, and total solar radiation were all significant at the one percent level. It is interesting to look at equations (5.2), (6.2) and (7.2). With total solar radiation considered the 't' values of solar energy at the top of the atmosphere were not significant. Examining equations (5.3), (6.3) and (7.3), inclusion of vapour pressure deficit instead of total solar radiation resulted in 't' value for maximum temperature which were not significant. Equations (5.5), (6.5) and (7.5) which included both total solar radiation and vapour pressure deficit had 't' values for both solar energy at the top of the atmosphere and for maximum temperature which were not significant.

2. The addition of total solar radiation and wind

as shown by equations (5.6), (6.6) and (7.6) was investigated. Correlation coefficients were improved to about 0.91 and all were highly significant for all three equations. The standard error of estimate decreased to 8.78cc in equation (7.6). The 't' values were all significant at the one percent level except for the regression coefficients of solar energy at the top of the atmosphere. The regression coefficients of total solar energy were much higher than those of total solar energy at the top of the atmosphere. This appears to represent the contribution of solar energy terms to the regression.

3. The addition of vapour pressure deficit and wind as shown by equations (5.7), (6.7) and (7.7) was studied. Correlation coefficients were lower than those of the other five-variable equations, but all were significant at the one percent level. Similar to other equations which included vapour pressure deficit, none of the 't' values of maximum temperature was significant. The 't' values of the other variables were significant at the one percent level. The standard errors of estimate and correlation coefficients indicated no improvement of these equations as compared to the previous equations of five variables.

6.2.4 Equation of six meteorological variables All meteorological variables were included in the regression as shown by equations (5.8), (6.8) and (7.8). As expected, the correlation coefficients were the highest of all the developed equations based on the same growing periods, and also were highly significant. The lowest standard errors of estimate were obtained from these equations. If the minimum value of 8.22cc in equation (5.8) is compared with the maximum value of 13.45cc in equations (6.1) and (7.1), the standard error of estimate decreased by approximately forty percent. All the 't' values for the regression coefficients were significant at the one percent level except that the 't' value of maximum temperature in equation (5.8) and those of the solar energy at the top of the atmosphere of equations (5.8), (6.8) and (7.8) were not significant at all. The higher regression coefficients of total solar energy were considered to be the major factor for the solar energy terms not contributing more to the regression.

6.2.5 Summary From the results of equations with three variables to six variables it can be concluded that, when only three basic meteorological variables (max, range, Q_O) were involved, the multiple correlation coefficient was approximately 0.77. The inclusion of one of solar energy, vapour pressure deficit, or wind increased the correlation coefficient to approximately 0.87. If any two of these variables were included the correlation coefficient increased to approximately 0.91 and with all six variables together the correlation coefficient was 0.92. This means that approximately 85 percent of the latent evaporation could be explained by variations of the six factors involved. Judging from the statistical results with the highest correlation coefficient and the lowest standard error of estimate, which is about 20 percent of the mean daily observed latent evaporation, the equation with six variables was considered to be the most accurate prediction equation for latent evaporation.

It is interesting to look at some results in Table VIII, the 't' values for regression coefficients of temperature range, vapour pressure deficit, wind and total solar energy at the top of the atmosphere were alwyas significant at the one percent level. This indicates that these four variables made a significant contribution to the prediction equations of evaporation. This result agrees with previous research which has demonstrated that, in the use of weather records in predicting evaporation, the four variables, temperature, radiation, humidity and wind, should be used even though wind itself is not correlated with latent evaporation.

6.3 Evaporation from the U.S.W.B. Class A Pan

Linear multiple regression equations of Class A pan evaporation on meteorological variables are presented in the following tables:

Table IX - Prediction equations based on the growing period of alfalfa (N = 153 days).

Table X - Prediction equations based on the growing period of potatoes (N = 124 days).

Table XI - Prediction equations based on the growing period of cereals (N = 110 days).

The results show that the correlation coefficients are all significant at the one percent level but much lower than those obtained from latent evaporation. Discussion of the equations will be the same as in section 6.2.

6.3.1 Equations of three meteorological variables

As shown by equation (9.1), (10.1) and (11.1), the coefficient of determination of equation (11.1) was 0.172, the lowest of all equations. This means that only 17.2 percent of the daily evaporation from Class A pan can be explained by maximum temperature, temperature range and Q_o. The 't' values for regression coefficients indicated a significant contribution by these three variables to the regression in equation (9.1) and (10.1). Equation (11.1) was not acceptable.

TABLE IX

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF ALFALFA (153 DAYS)

Equation	Meteoro-logical Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
9.1	Max	-0.268	0.00272	0.00082	3.328**	R=0.567**
	Range		0.00308	0.00107	2.871**	R^2=0.321
	Q_o		0.00025	0.00006	4.415**	S_{ee}=0.096
9.2	Max	-0.198	0.00219	0.00076	2.859**	R=0.649**
	Range		0.00031	0.00114	0.271	R^2=0.421
	Q_o		0.00012	0.00006	2.055*	S_{ee}=0.089
	R_T		0.00032	0.00006	5.056**	
9.3	Max	-0.199	0.00131	0.00090	1.458	R=0.606**
	Range		0.00200	0.00109	1.835	R^2=0.367
	Q_o		0.00026	0.00005	4.683**	S_{ee}=0.093
	V.P.D.		0.01221	0.00374	3.262**	
9.4	Max	-0.334	0.00334	0.00078	4.267**	R=0.633**
	Range		0.00370	0.00102	3.620**	R^2=0.401
	Q_o		0.00018	0.00006	3.264**	S_{ee}=0.090
	Wind		0.00044	0.00010	4.430**	
9.5	Max	-0.168	0.00148	0.00086	1.725	R=0.658**
	Range		0.00007	0.00113	0.062	R^2=0.433
	Q_o		0.00014	0.00006	2.381*	S_{ee}=0.088
	R_T		0.00028	0.00007	4.159**	
	V.P.D.		0.00675	0.00379	1.782	
9.6	Max	-0.265	0.00284	0.00070	4.041**	R=0.726**
	Range		0.00065	0.00103	0.631	R^2=0.527
	Q_o		0.00002	0.00006	0.405	S_{ee}=0.080
	R_T		0.00037	0.00006	6.275**	
	Wind		0.00051	0.00009	5.745**	
9.7	Max	-0.270	0.00211	0.00088	2.405*	R=0.657**
	Range		0.00274	0.00105	2.605**	R^2=0.432
	Q_o		0.00019	0.00005	3.549**	S_{ee}=0.088
	V.P.D.		0.0102	0.00359	2.848**	
	Wind		0.00040	0.00010	4.110**	
9.8	Max	-0.250	0.00250	0.00081	3.108**	R=0.728**
	Range		0.00053	0.00104	0.513	R^2=0.530
	Q_o		0.00003	0.00006	0.604	S_{ee}=0.080
	R_T		0.00035	0.00006	5.505**	
	Wind		0.00049	0.00009	5.466**	
	V.P.D.		0.00302	0.00353	0.855	

* Significant at the five percent level.
** Significant at the one percent level.
R = Multiple correlation coefficient.
S_{ee} = Standard error of estimate.
t = Statistical 't' value, test of the difference of each regression coefficient from zero.

TABLE X

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF POTATOES (124 DAYS)

Equation	Meteoro- logical Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
10.1	Max	-0.285	0.00253	0.00108	2.332**	R=0.446**
	Range		0.00361	0.00127	2.849**	R^2=0.199
	Q_o		0.00027	0.00009	3.053**	S_{ee}=0.104
10.2	Max	-0.220	0.00203	0.00102	1.993*	R=0.555**
	Range		0.00055	0.00138	0.399	R^2=0.308
	Q_o		0.00015	0.00009	1.705	S_{ee}=0.097
	R_T		0.00033	0.00008	4.330**	
10.3	Max	-0.206	0.00111	0.00118	0.943	R=0.495**
	Range		0.00242	0.00131	1.845	R^2=0.245
	Q_o		0.00027	0.00009	3.163**	S_{ee}=0.101
	V.P.D.		0.0115	0.00427	2.701**	
10.4	Max	-0.371	0.00346	0.00103	3.355**	R=0.557**
	Range		0.00428	0.00119	3.597**	R^2=0.310
	Q_o		0.00019	0.00008	2.238*	S_{ee}=0.097
	Wind		0.00049	0.00011	4.383**	
10.5	Max	-0.183	0.00128	0.00112	1.142	R=0.567**
	Range		0.00023	0.00138	0.169	R^2=0.321
	Q_o		0.00017	0.00009	1.884	S_{ee}=0.096
	R_T		0.00029	0.00008	3.639**	
	V.P.D.		0.00656	0.00429	1.527	
10.6	Max	-0.308	0.00302	0.00093	3.246**	R=0.670**
	Range		0.00090	0.00124	0.728	R^2=0.449
	Q_o		0.00004	0.00008	0.507	S_{ee}= 0.087
	R_T		0.00037	0.00007	5.436**	
	Wind		0.00056	0.00010	5.482	
10.7	Max	-0.304	0.00231	0.00115	2.011*	R=0.580**
	Range		0.00332	0.00125	2.648**	R^2=0.336
	Q_o		0.00020	0.00008	2.375*	S_{ee}=0.095
	V.P.D.		0.00875	0.00409	2.141*	
	Wind		0.00045	0.00011	4.018**	
10.8	Max	-0.295	0.00278	0.00106	2.629**	R=0.671**
	Range		0.00080	0.00126	0.636	R^2=0.450
	Q_o		0.00005	0.00008	0.582	S_{ee}=0.087
	R_T		0.00036	0.00007	4.912**	
	Wind		0.00055	0.00010	5.220**	
	V.P.D.		0.00197	0.00398	0.494	

* Significant at the five percent level.
** Significant at the one percent level.

TABLE XI

MULTIPLE CORRELATION ANALYSIS OF METEOROLOGICAL VARIABLES ON CLASS A PAN EVAPORATION BASED ON THE GROWING PERIOD OF CEREALS (110 DAYS)

Equation	Meteoro-logical Variables	Constant (a)	Regression Coeff. (b)	Std. Error of Regress. Coeff. (S_b)	't' Values for Regress. Coeff.	Other Stat. Values
11.1	Max	-0.102	0.00196	0.00126	1.557	R=0.415**
	Range		0.00433	0.00140	3.083**	R^2=0.172
	Q_o		0.00011	0.00015	0.723	S_{ee}=0.106
11.2	Max	-0.102	0.00165	0.00119	1.385	R=0.513**
	Range		0.00124	0.00158	0.786	R^2=0.263
	Q_o		0.00005	0.00014	0.375	S_{ee}=0.101
	R_T		0.00030	0.00008	3.599**	
11.3	Max	-0.0268	0.00060	0.00134	0.449	R=0.467**
	Range		0.00300	0.00147	2.040*	R^2=0.218
	Q_o		0.00011	0.00014	0.771	S_{ee}=0.104
	V.P.D.		0.0119	0.00481	2.474*	
11.4	Max	-0.197	0.00305	0.00119	2.570*	R=0.549**
	Range		0.00521	0.00131	3.971**	R^2=0.301
	Q_o		0.00001	0.00014	0.099	S_{ee}=0.098
	Wind		0.00052	0.00012	4.401**	
11.5	Max	-0.0582	0.00091	0.00130	0.698	R=0.526**
	Range		0.00091	0.00159	0.571	R^2=0.277
	Q_o		0.00006	0.00014	0.449	S_{ee}=0.100
	R_T		0.00026	0.00009	2.912**	
	V.P.D.		0.00693	0.00495	1.401	
11.6	Max	-0.207	0.00282	0.00109	2.593*	R=0.648**
	Range		0.00176	0.00142	1.244	R^2=0.420
	Q_o		-0.00006	0.00013	-0.459	S_{ee}=0.090
	R_T		0.00034	0.00007	4.607**	
	Wind		0.00057	0.00011	5.294**	
11.7	Max	-0.135	0.00199	0.00130	1.527	R=0.569**
	Range		0.00418	0.00141	2.975**	R^2=0.324
	Q_o		0.00002	0.00014	0.176	S_{ee}=0.097
	V.P.D.		0.00860	0.00456	1.886	
	Wind		0.00048	0.00012	4.046**	
11.8	Max	-0.196	0.00263	0.00122	2.158*	R=0.648**
	Range		0.00168	0.00144	1.164	R^2=0.420
	Q_o		-0.00005	0.00013	-0.424	S_{ee}=0.090
	R_T		0.00033	0.00008	4.129**	
	Wind		0.00056	0.00011	5.048**	
	V.P.D.		0.00156	0.00458	0.340	

* Significant at the five percent level.
** Significant at the one percent level.

TABLE XII

SUMMARY OF ALL THE 't' VALUES FOR REGRESSION COEFFICIENTS FROM THE PREDICTION EQUATIONS FOR CLASS A PAN EVAPORATION

Method	Equation	R^2	Significant 't' Values for Regression Coefficients					
			Max	Range	Q_o	V.P.D.	Wind	R_T
I	9.1	.321	**	**	**	-	-	-
	10.1	.199	**	**	**	-	-	-
	11.1	.172	No	**	No	-	-	-
II	9.2	.421	**	No	*	-	-	**
	10.2	.308	*	No	No	-	-	**
	11.2	.263	No	No	No	-	-	**
III	9.3	.367	No	No	**	**	-	-
	10.3	.245	No	No	**	**	-	-
	11.3	.218	No	*	No	*	-	-
IV	9.4	.401	**	**	**	-	**	-
	10.4	.310	**	**	*	-	**	-
	11.4	.301	*	**	No	-	**	-
V	9.5	.433	No	No	*	No	-	**
	10.5	.321	No	No	No	No	-	**
	11.5	.277	No	No	No	No	-	**
VI	9.6	.527	**	No	No	-	**	**
	10.6	.449	**	No	No	-	**	**
	11.6	.420	*	No	No	-	**	**
VII	9.7	.432	*	**	**	**	**	-
	10.7	.336	*	**	*	*	**	-
	11.7	.324	No	**	No	No	**	-
VIII	9.8	.530	**	No	No	No	**	**
	10.8	.450	**	No	No	No	**	**
	11.8	.420	*	No	No	No	**	**

* Significant at the five percent level.
** Significant at the one percent level.

6.3.2 Equations of four meteorological variables

1. The addition of total solar radiation (R_T) as shown by equations (9.2), (10.2) and (11.2) was investigated. The correlation coefficient was about 0.65 in equation (9.2). The 't' values of equations (9.2) and (10.2) show that maximum temperature and total solar energy made a significant contribution to the regression. Equation (11.2) shows that only total solar energy made a contribution to the regression.

2. The addition of vapour pressure deficit as shown by equations (9.3), (10.3) and (11.3) was considered. The correlation coefficients were lower than those obtained from equations when total solar radiation was involved. Only the regression coefficients for vapour pressure deficit and Q_O showed 't' values which were significant at the one percent level. None of the temperature terms made a contribution to the regression, so these three equations are of questionable validity.

3. The addition of wind as shown by equations (9.4), (10.4) and (11.4) was studied. The correlation coefficients were approximately the same as those obtained when total solar radiation was involved. The 't' values for regression coefficients were all significant except for Q_O in equation (11.4). Even though more variables made a significant contribution to the regression than those in equations (9.2), (10.2) and (11.2), the correlation coefficients were not improved. This indicates that total solar radiation made more contribution to the regression than vapour pressure deficit.

6.3.3 Equations of five meteorological variables

The number of variables was increased to five.

1. The addition of total solar radiation and vapour pressure deficit as shown by equations (9.5), (10.5) and (11.5) was examined. Only the 't' values of total solar radiation were significant at the one percent level and the 't' value for Q_o of equation (9.5) was significant at the five percent level. The correlation coefficients were improved even though the 't' values for the regression coefficients of temperature terms and vapour pressure deficit were not significant.

2. The addition of total solar radiation and wind as shown by equations (9.6), (10.6) and (11.6) was investigated. All the 't' values were highly significant except for those of temperature range and Q_o . The correlation coefficients were all improved and the standard errors of estimate decreased to 0.08 inches in equation (9.6). This means that wind made a greater contribution to the regression than vapour pressure deficit in the preceding equations.

3. The addition of vapour pressure deficit and wind as shown by equations (9.7), (10.7) and (11.7) was considered. The correlation coefficients were not appreciably higher than those obtained from equations with terms for vapour pressure deficit and total solar radiation even though the 't' values for regression coefficient of all variables in equations (9.7) and (10.7) indicated that they all made a significant contribution to the regression. This means that vapour pressure deficit did not make much contribution to this type of equation.

<u>6.3.4 Equations of six meteorological variables</u> All six variables were included as shown by equations (9.8), (10.8) and (11.8). Correlation coefficients and standard errors of estimate were not much improved as might be expected. Their values were exactly the same as those obtained

from equations without vapour pressure deficit. Judging from the 't' values for regression coefficients, only three variables, maximum temperature, wind and total solar radiation, made a significant contribution to the regression.

6.3.5 Summary The highest multiple correlation coefficients were obtained from the alfalfa equations (N = 153 days). When only three basic meteorological variables were involved, the multiple correlation coefficient was approximately 0.57. The inclusion of one of solar energy, vapour pressure deficit, or wind increased the correlation coefficient to not more than 0.65. If any two of these variables were included the correlation coefficient increased to not more than 0.73 and with all six variables together the correlation coefficient was 0.73. This means that approximately 53 percent of the evaporation from a Class A pan can be explained by the six variables involved.

The significance of the 't' values for the regression coefficients of all variables involved in each equation is summarized in Table XII. Only wind and total solar energy indicated 't' values for regression coefficients which were all significant at the one percent level whereas those of maximum temperature and vapour pressure deficit were not all significant. This is unexpected because the simple correlation coefficients in Table IV showed that these two variables were correlated to Class A pan evaporation next only to total solar energy. Prediction equations of evaporation from Class A pan data did not show results which agreed with the previous studies because the total solar radiation and wind were the only two factors in the present study which significantly contributed to the prediction equations.

6.4 Comparison Between Prediction Equations of Latent Evaporation and Class A Pan Evaporation

The summaries of 6.2.5 and 6.3.5 clearly show that all the coefficients of determination obtained from the prediction equations for latent evaporation were much higher than those for Class A pan evaporation. Equations for latent evaporation agreed with past research in that temperature, vapour pressure, solar energy and wind significantly contributed to the prediction equations, whereas equations for Class A pan evaporation did not. Results from the black Bellani plate, in all respects, were much more reliable than from the Class A pan in predicting the evaporation from meteorological observations. For this reason the prediction equations for latent evaporation were selected for further studies.

6.5 Testing of Equations

6.5.1 Testing the equations of Baier and Robertson (1965) for the meteorological data of the present study

The prediction equations of Baier and Robertson (1965) for latent evaporation as shown in Table XIII are similar to the prediction equations of this study. They suggested that their equations would be applicable to parts of Canada. In their equations, all independent variables were the same as in the equations of the present study except for total solar radiation as already described in 5.2.6, so only the equations of Methods I, III, IV and VII of Table XIII are of real interest. The latent evaporation values were calculated from the eight equations by using the corresponding meteorological variables at Carberry. Statistical paired 't' tests between calculated values from eight methods, and the observed values are presented in Table XIV. Results indicated

TABLE XIII

MULTIPLE CORRELATION AND REGRESSION COEFFICIENTS OF METEOROLOGICAL VARIABLES ON LATENT EVAPORATION (AFTER BAIER AND ROBERTSON, 1965)

Method	Meteorological Variables	Constant	Regression Coefficient	Correlation Coefficient	Standard Error of Estimate (cm)^3
I	Max	-87.03	0.928	0.680	18.90
	Range		0.933		
	Q_o		0.0486		
II	Max	-55.60	0.687	0.750	16.90
	Range		0.284		
	Q_o		0.00913		
	Q_s		0.0685		
III	Max	-42.28	-0.0228	0.760	16.70
	Range		1.090		
	Q_o		0.0506		
	V.P.D.		2.990		
IV	Max	-108.80	1.130	0.760	16.70
	Range		0.920		
	Q_o		0.0359		
	Wind		0.131		
V	Max	-26.69	0.0232	0.800	15.50
	Range		0.557		
	Q_o		0.0196		
	Q_s		0.0531		
	V.P.D.		2.410		
VI	Max	-78.68	0.897	0.800	15.40
	Range		0.340		
	Q_o		0.00166		
	Q_s		0.0613		
	Wind		0.118		
VII	Max	-69.30	0.350	0.810	14.90
	Range		1.040		
	Q_o		0.0403		
	V.P.D.		2.310		
	Wind		0.101		
VIII	Max	-53.39	0.337	0.840	14.20
	Range		0.531		
	Q_o		0.0107		
	Q_s		0.0512		
	Wind		0.0977		
	V.P.D.		1.770		

For $P = 0.01$ and two independent variates, $R = 0.30$.
For $P = 0.01$ and six independent variates, $R = 0.40$.

TABLE XIV

STATISTICAL PAIRED 't' TEST FOR LATENT EVAPORATION COMPARING OBSERVED VALUES AT CARBERRY AND CALCULATED VALUES USING THE METHODS OF BAIER AND ROBERTSON (1965)

Method	Meteorological Variables	Statistical Paired 't' Test
I	Max, Range, Q_o	-1.120
II	Max, Range, Q_o, Q_s	3.526**
III	Max, Range, Q_o, V.P.D.	2.895**
IV	Max, Range, Q_o, Wind	-2.237
V	Max, Range, Q_o, Q_s, V.P.D.	2.829**
VI	Max, Range, Q_o, Q_s, Wind	1.712*
VII	Max, Range, Q_o, V.P.D., Wind	0.828
VIII	Max, Range, Q_o, Q_s, Wind, V.P.D.	4.691**

* Significant difference at the five percent level.
** Significant difference at the one percent level.

TABLE XV

STATISTICAL 't' TESTS OF THE DIFFERENCE BETWEEN REGRESSION COEFFICIENTS FOR BAIER AND ROBERTSON'S EQUATIONS AND THOSE OF EACH OF THE DERIVED EQUATIONS FOR LATENT EVAPORATION AT CARBERRY

Method	Equation	Statistical 't' Values for the Difference Between Regression Coefficients					
		Max	Range	Q_o	V.P.D.	Wind	R_T
I	5.1	-5.102**	3.051**	-2.094*	-	-	-
	6.1	-3.390**	3.556**	-0.504	-	-	-
	7.1	3.047**	3.886**	0.173	-	-	-
II	5.2	-5.111**	3.658**	-0.832	-	-	0.572
	6.2	-3.207**	3.680**	0.638	-	-	0.740
	7.2	2.610**	3.564**	1.603	-	-	0.674
III	5.3	0.063	-.018	-2.439*	0.643	-	-
	6.3	0.741	0.749	0.701	0.087	-	-
	7.3	2.145*	1.177	0.248	0.010	-	-
IV	5.4	-6.403**	3.768**	-1.495	-	-5.860**	-
	6.4	4.200**	4.230**	0.172	-	5.180**	-
	7.4	-3.706**	4.661**	-0.014	-	-5.039**	-
V	5.5	-.0461	1.044	-1.524	-.696	-	0.882
	6.5	0.835	1.266	0.031	-1.075	-	1.242
	7.5	1.231	1.409	1.114	1.327	-	1.191
VI	5.6	-7.403**	4.096**	-1.793	-	-5.292**	2.674**
	6.6	1.348	0.512	1.343	-	0.026	0.188
	7.6	-3.690**	4.201**	1.408	-	-4.830**	2.486**
VII	5.7	2.644**	0.950	1.842	1.746	-5.103**	-
	6.7	0.879	0.814	0.866	-0.601	0.004	-
	7.7	0.815	2.109*	-0.0087	0.735	-4.240**	-
VIII	5.8	-2.389*	1.935	-2.241*	-0.224	-4.247**	2.477*
	6.8	-0.582	2.131*	-0.430	-0.800	-3.820**	2.699**
	7.8	0.223	2.396*	0.953	-1.322	-3.563*	2.668**

* Significant at the five percent level.
** Significant at the one percent level.

no significant difference for Methods I, IV and VII and equations including the radiation term, Q_s were all significantly different as expected (see 5.2.6 for the difference between Q_s and R_T). This means that only equations I, IV and VII gave predicted results very close to the observed values of the present study.

6.5.2 Testing the difference between the regression coefficients of Baier and Robertson equations (1965) and those of each of the derived equations for latent evaporation at Carberry Statistical 't' tests for the significant difference between regression coefficients of corresponding variables are presented in Table XV. Only equations (6.3), (5.5), (6.5), (7.5) (6.6) and (6.7) indicated no difference between the regression coefficients of the corresponding variables for the Carberry equations and those of Baier and Robertson's equations. This represents only twenty-five percent of the derived equations. This is reasonable because the equations of this study were developed from experimental data from the local area. The derived equations for Carberry certainly indicated higher correlation coefficients and lower standard errors of estimate which means that the error is smaller in the predicted values. The regression coefficients of Q_o indicated that they were all not significantly different except for those of equations (5.1), (5.3) and (5.8) which were significantly different at the five percent level. Another interesting thing is the regression coefficients for vapour pressure deficit in equations indicated no significant difference. This means that the contribution of average daily vapour pressure deficit calculated from measuring data at 8:00 a.m. and 4:00 p.m. was almost the same as in the methods of Baier and Robertson. Comparing these results with those in section 6.5.1, we can conclude that only equation VII of Baier and Robertson (1965) is applicable to the Carberry area.

6.5.3 Testing the significant difference among the regression coefficients of the three quations for alfalfa, potatoes and cereals Statistical 't' values are presented in Table XVI, all 't' values indicated no difference among the regression coefficients of the derived equations except for one which was different at the five percent level. This is quite understandable because all the equations were derived from the same source of independent variables for periods which were not quite coincidental.

6.6 Selection of Prediction Equations in Estimating Seasonal Consumptive Use

Estimation of latent evaporation from all the prediction equations for the growing periods of alfalfa, potatoes and cereals are presented in Table XVII. Prediction equations for alfalfa were also used to estimate the latent evaporation for the growing periods of potatoes and cereals. Results indicated that some estimated values were equal to and some were slightly greater than the observed values. Latent evaporation estimated from the alfalfa equations but for the growing periods of potatoes and cereals was slightly greater than from equations developed expressly for potatoes and cereals. However, it is more preferable to overestimate than to underestimate. The tests in 6.5.3 indicated no difference among the regression coefficients of these three equations, so it appears that it is more practical to select one prediction equation for all crops.

TABLE XVI

THE 't' VALUES FROM TESTS OF SIGNIFICANCE OF THE DIFFERENCE AMONG THE REGRESSION COEFFICIENTS OF THE THREE EQUATIONS

Prediction Equations	Method	Statistical 't' Values					
		Max	Range	Q_o	Q_s	Wind	V.P.D.
Alfalfa Vs. Potatoes	I	-.497	-.638	-.736	-	-	-
	II	-.689	-.352	-1.001	-.165	-	-
	III	-.545	-.574	-.746	-	-	-.367
	IV	-.667	-.657	-.697	-	-.0892	-
	V	-.680	-.140	-.914	-.321	-	.312
	VI	-1.049	-.341	-1.082	-.136	-.021	-
	VII	-.691	-.620	-.729	-	.0055	.447
	VIII	-.661	-.340	-.976	-.340	-.0073	.438
Alfalfa Vs. Cereals	I	-.423	-1.071	-.636	-	-	-
	II	-.848	-.503	-1.805	-.134	-	-
	III	-.631	-.937	-.693	-	-	.399
	IV	-.651	1.198	-.571	-	-.122	-
	V	-1.030	-.441	-1.652	-.342	-	.576
	VI	-1.352	-.622	-2.047*	-.092	-.007	-
	VII	-.844	-1.090	-.624	-	.065	.530
	VIII	-1.579	-.689	-.331	-.430	-.111	.871
Potatoes Vs. Cereals	I	.033	-.438	-.119	-	-	-
	II	-.190	-.160	-.993	-.025	-	-
	III	-.116	-.373	-.158	-	-	.051
	IV	-.029	-.542	-.076	-	.033	-
	V	-.368	-.208	-.918	-.034	-	-.276
	VI	-.336	-.282	-1.139	-.039	-.013	-
	VII	-.183	-.476	-.110	-	-.067	.102
	VIII	-.881	-.350	.363	-.095	.099	.443

* Significant at the five percent level.
** Significant at the one percent level.

TABLE XVII

ESTIMATION OF SEASONAL LATENT EVAPORATION (cc)

Method	ALFALFA (May 1 - Sept. 30)		POTATOES (May 15 - Sept. 15)			CEREALS (May 15 - Sept. 1)		
	Observed	Predicted	Observed	Predicted by Alfalfa Equation	Predicted by Potatoe Equation	Observed	Predicted by Alfalfa Equation	Predicted by Cereals Equation
	6095		5272			4769		
I		6105		5323	5272		4786	4769
II		6111		5431	5277		4832	4776
III		6101		5315	5272		4783	4769
IV		6101		5313	5272		4776	4769
V		6095		5321	5273		4809	4771
VI		6115		5337	5280		4827	4779
VII		6099		5307	5272		4776	4769
VIII		6184		5328	5272		4818	4817

As already discussed, temperature range, vapour pressure deficit, wind and total solar radiation were the only four variables contributing significantly to the regression of the prediction equations. The two variables, maximum temperature and Q_o were then eliminated from equations (5.8), (6.8) and (7.8) and new equations were derived. The results indicated that the 't' values for the regression coefficients were all significant at the one percent level and the new equation (5.9), derived from (5.8), was selected to be the best. The equation is:

$$\text{Latent evaporation} = -23.77 + 0.787\ (\text{Range}) + 1.997\ (\text{V.P.D.}) + 0.0546\ (\text{Wind}) + 0.0658\ (R_T)$$

$$(R = 0.917,\ S_{ee} = 8.25) \qquad (5.9)$$

The 't' values for the regression coefficients of this equation are 7.68, 6.44, 6.39 and 11.73 respectively, and this equation was used in the estimation of seasonal consumptive use for alfalfa, potatoes, cereals (wheat) and sugar beets.

The meteorological data during the period of October 1 - 31, 1969 were not observed at the weather station. The growing period of sugar beets was estimated to be the period May 15 to October 31. The evaporation during the period October 1 - 31 was predicted by using equation (5.1) for latent evaporation. The temperature data for use in equation (5.1) were obtained from the Department of Transport for the Carberry weather station (see Appendix E). The estimation of latent evaporation for the month of October, 1969 was 235 cubic centimeters; this figure was also used to estimate the evaporation from the Class A pan from the regression equation.

$$E_{pan} = 0.0575 + 0.0038 \ (E_L) \ , \ r = 0.677$$

The Class A pan evaporation for October was 0.95 inch. These values are somewhat questionable because the temperature data were not measured right at the experiment station. However, by comparing these results with the much larger values of evaporation for May to September, one can conclude that they did not have much effect on the seasonal evaporation for the growing season of sugar beets.

6.7 Estimation of Seasonal Consumptive Use

Evaporation during the growing periods of each crop were presented in Table XVIII.

TABLE XVIII

SEASONAL EVAPORATION

Crops	Length of Season (Days)	Latent Evaporation (cc)		Class A pan (inches)	
		Actual	Predicted[1]	Actual	Predicted[2]
Alfalfa	153	6095	6107	32.05	32.07
Sugar Beets	170	5798	5822	30.77	30.40
Potatoes	124	5272	5305	28.47	28.19
Cereals	110	4769	4799	26.42	25.83

[1] Predicted from equation (5.9).

[2] Predicted from equation (9.8).

6.7.1 Transferability of Hobbs and Krogman's (1968) curves and Vauxhall coefficients to Manitoba

In the Sixth Hydrology Symposium on Soil Moisture, Baier (1967) discussed the transferability of the Vauxhall coefficients to other areas. One of the points made in the discussion of Baier's paper was recorded in the symposium proceedings as follows: "Dr. Baier agreed with Mr. Krogman that the results may be transferable, particularly if the coefficients were determined on some phenological basis." To study the transferability of Vauxhall coefficients and the AE/PE curves of Hobbs and Krogman (1968) to an area in Manitoba, previous research at Brandon by Ferguson (1965) was examined (see Appendix G). The latent evaporation was converted to potential evapotranspiration by using a conversion factor of 0.0034 (in/cc) after Holmes and Robertson (1957). Weekly consumptive use values were calculated from the AE/PE curve of Hobbs and Krogman (1968) for wheat in Appendix H. These results were compared with measured consumptive use; statistical paired 't' tests indicated no significant difference. The calculated consumptive use for wheat was 12.4 inches. The measured consumptive use for non-irrigated wheat at Brandon was 9.6 inches. The difference between calculated and observed values was likely a reflection of the assumed stress-free growth condition for the calculated values which were not in fact realized in this field study. It should also be recognized here that neither of these values should be considered as representative of the consumptive use for the entire growing season of wheat, having been determined only for the 10-week period from May 22 to July 29.

6.7.2 Estimates from the Vauxhall coefficients

Ratios of consumptive use to evaporation for both the Bellani plate and the Class A pan for various crops as shown in Appendix F were used to convert the evaporation data in Table XVIII to consumptive use values, as presented in Table XIX.

TABLE XIX

SEASONAL CONSUMPTIVE USE FROM THE VAUXHALL COEFFICIENTS

	Black Bellani Plate		Class A Pan	
	$\frac{CU}{E_L}$, in/cc	CU* (in.)	$\frac{CU}{E_{pan}}$, in/in	CU* (in.)
Alfalfa	0.00300	18.3	0.659	21.1
Sugar Beets	0.00250	14.5	0.542	16.6
Potatoes	0.00254	13.4	0.556	15.8
Wheat	0.00297	14.2	0.658	17.4

*Estimate from actual evaporation.

Seasonal consumptive use for the four crops estimated from each of the evaporimeters did not agree. The values estimated from the Class A pan were considerably higher than from the black Bellani plate.

6.7.3 Estimates from curves of Hobbs and Krogman (1968) Unfortunately, the consumptive use of water could not be measured from the experimental plots by the soil moisture depletion technique because of the unpredictable precipitation patterns and consequent unmeasured deep percolation losses beginning in late July and continuing almost to the end of the season. The available data for daily latent evaporation, precipitation and irrigation water application were used to estimate the consumptive use of potatoes which was selected as the main irrigated crop of this study. The growing period of potatoes for this study was from May 15 to September 15. The daily potential evapotranspiration values were calculated by multiplying the daily latent evaporation by the conversion factor 0.0034 (in/cc) after Holmes and Robertson (1957). The daily consumptive use of potatoes was estimated by assuming that the daily consumptive use factors AE/PE of this study followed the curve of Hobbs and Krogman (1968) in Appendix H. The curve was adjusted to match the growing period of potatoes, May 15 to September 15. At the beginning of the experiment the soil moisture condition was assumed to be at field capacity with a total storage capacity of 9.00 inches in the 4-foot profile of soil. The amount of deep-percolated water was estimated by assuming that after each irrigation the soil was at field capacity. So whenever the precipitation was greater than the estimated consumptive use since the last time the soil was at field capacity the excess water was considered. to be deep-percolated. From computations shown in Appendix I, the estimated seasonal consumptive use of irrigated potatoes was 13.33 inches. The figure 13.22 inches calculated from daily plate evaporation using Holmes and Robertson's coefficient of 0.0034 in/cc for converting latent evaporation to potential evapotranspiration and Hobbs' AE/PE ratios for estimating consumptive use seems to agree with the value of 13.40 inches as calculated using Sonmor's Vauxhall ratio for calculating seasonal consumptive use directly from Bellani plate evaporation data. These observations indicate the transferability of the Vauxhall coefficients.

The same procedures as above were used to estimate the seasonal consumptive use of alfalfa, sugar beets and wheat from consumptive use factor curves in Appendix H. Calculations are presented in Appendix I, and the seasonal consumptive use values for alfalfa, sugar beets and wheat were 22.33, 15.56 and 10.50 inches respectively.

In the development of the curves of Hobbs and Krogman (1968), potential evapotranspiration was calculated from the method of Jensen and Haise (1963), presented in Chapter II. The equation is: $PE = (.014\ T - .37) R_s$ where:

PE = potential evapotranspiration, in/day

T = mean air temperature, $^{\circ}F$

R_s = solar radiaion, in/day, which is a linear function of $R_T (gm\text{-}cal/cm^2)$.

This equation was also used to calculate the daily potential evapotranspiration from the available data of the present study. Results were compared with those calculated from the conversion factor of 0.0034 in/cc of Holmes and Robertson (1957). The statistical paired 't' test value was 1.061 based on 153 pairs indicating no significant difference but the results from Jensen and Haise (1963) seem to be slightly higher.

6.7.4 Estimates of consumptive use at Brandon by the method of Coligado et al. (1968) The irrigation requirements for four crops were estimated from the tables of Coligado et al. (1968) under the condition of a storage capacity of 6.00 inches for a 4-foot depth of sandy loam. It was assumed that the irrigation would be applied when the soil water reached the 50-percent level. The seasonal irrigation requirements were estimated on a 50-percent-risk basis using average consumptive use factors for alfalfa, sugar beets, potatoes and wheat of approximately 1.00, 0.75, 0.75 and 0.75 respectively from the curves of Hobbs and Krogman (1968). Precipitation within the growing period of these four crops was estimated from a table of long-term average weekly precipitation, Coligado et al. (1968). Seasonal consumptive use of each crop was estimated by adding the precipitation to the irrigation requirements. Results are presented in Table XX.

TABLE XX

SEASONAL CONSUMPTIVE USE AT BRANDON BY THE METHOD OF COLIGADO ET AL. (1968)

Crops	Growing Period	Average CU Factor	Precipitation (in.)[1]	Irrigation Requirement[2] (in.)	Consumptive Use (in.)
Alfalfa	May 1-Sept. 30	1.00	12.5	7.8	20.3
Sugar Beets	May 15-Oct. 31	0.75	12.6	3.2	15.8
Potatoes	May 15-Sept. 15	0.75	11.0	3.2	14.2
Cereals	May 15-Sept. 1	0.75	10.1	3.2	13.3

[1] Table 2, Coligado et al. (1968).
[2] Table 19 and 20, Coligado et al. (1968).

6.7.5 Comparison of estimated results Seasonal consumptive use from the three methods is presented in Table XXI.

TABLE XXI

SEASONAL CONSUMPTIVE USE BY VARIOUS METHODS

Crops	Consumptive Use in Inches				
	Black Bellani Plate	Class A Pan	$\frac{CU}{PE}$ curves	Mean at Carberry	Brandon
Alfalfa	18.3	21.1	22.3	20.6	20.3
Sugar Beets	14.5	16.6	15.6	15.6	15.8
Potatoes	13.4	15.8	13.2	14.1	14.2
Cereals	14.2	17.4	10.5	14.0	13.3

Comparing the results of each method with mean values, Bellani plate evaporation combined with the appropriate Vauxhall coefficients seems to slightly underestimate consumptive use for alfalfa and sugar beets but is quite satisfactory for potatoes and cereals. Results from the Class A pan are preferable for estimating alfalfa. Judging from the mean values, the estimated seasonal consumptive use of the four crops, in inches, is as follows: 20.6 for alfalfa, 15.6 for sugar beets, 14.1 for potatoes and 14.0 for cereals. These figures are considerably lower than the values reported for Vauxhall by Sonmor (1963). This was probably due in part to the cool climate of the 1969 summer months at Carberry. Comparing the 1969 Class A pan evaporation at Carberry to the mean seasonal pan evaporation values for each growing period in Appendix D, the pan evaporation values at Carberry for 1969 were all less than those at Baldur, Morden and Winnipeg but greater than those at Riding Mountain Park. So the seasonal consumptive use values estimated at Carberry in 1969 would apparently be slightly low if they were applied to areas further south and east of Carberry. These results agree very well, however, with those estimates at Brandon which is about fifteen miles west of Carberry.

CHAPTER VII

CONCLUSIONS

The conclusions resulting from this study are as follows:

1. The black Bellani plate atmometer responded better than the U.S.W.B. Class A pan to total solar radiation, temperature range, maximum temperature and vapour pressure deficit, but the Class A pan showed slightly better response to the total solar energy at the top of the atmosphere and to wind.

2. Multiple regression analyses indicated that, at the best, 85 percent of the latent evaporation can be accounted for by the linear combination of the six meteorological variables whereas, at the best, the corresponding figure is only 53 percent for the Class A pan.

3. The prediction equations for daily latent evaporation were all reliable. The predicted values for the 1969 growing periods of the four crops extrapolated from the alfalfa equations were slightly higher than those from potatoes and cereals. The most accurate prediction equation was:

$$\begin{aligned}\text{Latent evaporation} = & -23.77 + 0.787\ (\text{temperature range}) \\ & + 1.997\ (\text{vapour pressure deficit}) \\ & + 0.0546\ (\text{wind}) + 0.0658\ (\text{total solar radiation})\end{aligned}$$

The results also agreed with the several past research studies which demonstrated that temperature, vapour pressure, wind and solar radiation are the four main meteorological factors required for the prediction of evaporation.

4. The equations of Method VII as given by Baier and Robertson (1965) were the only ones that could be applied safely to the Carberry area.

5. The examination of the other research investigations and the present study indicated that the consumptive use evaporation ratios at Vauxhall by Sonmor (1963) are transferable to Manitoba.

6. Potential evapotranspiration values calculated by the method of Jensen and Haise (1963) were slightly lower than the results from the method of Holmes and Robertson (1957) but the statistical test indicated no significant difference.

7. In predicting consumptive use of the four crops, alfalfa, sugar beets, potatoes and cereals (wheat), the estimated values were 20.6, 15.6, 14.1 and 14.0 inches respectively. Evaporation data from the black Bellani plate indicated reliable results for potatoes and cereals but better results were obtained from the Class A pan data for alfalfa. The plate and the pan were equally satisfactory for predicting the consumptive use of sugar beets.

CHAPTER VIII

RECOMMENDATIONS

Recommendations for further studies are as follows:

1. Results from this study were based on one year's record, 1969, and were conducted at only one location, Carberry. Weather records from the other parts of Manitoba, for example, Winnipeg, Baldur and Morden, should be taken into the analysis to obtain representative results of the whole agricultural area of Manitoba.

2. For more reliable results, the consumptive use of the four crops should be measured from field plots by the soil moisture depletion technique to confirm the predicted values. Lysimeters are recommended for their measurement.

REFERENCES

1. Baier, W. and G.W. Robertson. 1965. Estimation of latent evaporation from simple weather observations. Can. J. Plant Sci. 45:276-284.

2. Baier, W. and G.W. Robertson. 1967. Estimating supplemental irrigation water requirements from climatological data. Can. Agric. Eng. 9(1):46-50.

3. Baier, W. 1967. Relationships between soil moisture, actual and potential evapotranspiration. Proc. Hydrology Symposium. 6:204.

4. Blaney, H.F. and W.D. Criddle. 1950. Determining water requirement in irrigated area from climatological and irrigation data. U.S.D.A., Soil Conserv. Serv. Tech. Pub. 96.

5. Blaney, H.F. and W.D. Criddle. 1962. Determining consumptive use and irrigation water requirements. Tech. Bul. 1275. U.S.D.A. 59 pp.

6. Bloemen, G.W. 1964. Hydraulic device for weighing large lysimeters. Trans. A.S.A.E. 7(3):297-299.

7. Carder, A.C. 1960. Atmometer assemblies, a comparison. Can. J. Plant Sci. 40:700-706.

8. Carder, A.C. 1961. Rate of evaporation from a free water surface as influenced by exposure. Can. J. Plant Sci. 41:199-203.

9. Coligado, M.C., W. Baier and K. Sly Wilbur. 1968. Risk analyses of weekly climatic data for agricultural and irrigation planning, Brandon, Manitoba. Canada Department of Agriculture. Tech. Bul. 34: Table 19, 20.

10. Computer Centre (September 1969). Statistical Package Part "B", The University of Manitoba.

11. Denmead, O.T. and R.H. Shaw. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54:385-390.

12. Eagleman, Joe R. 1967. Pan evaporation, potential and actual evaporation. J. Appl. Meteorol. 6(3):482-488.

13. Ferguson, W.S. 1965. Relationship between evapotranspiration by wheat and the stage of crop development, Bellani-plate evaporation and soil moisture content. Can. J. Soil Sci. 45:33-38.

14. Geiger, R. 1959. The climate near the ground. Amplified 2nd Ed. Harvard University Press, Massachusetts.

15. Halkias, N.A. 1963. Evaluating water defficiency of plants with variations of climate. Trans. A.S.A.E. 6(4):338-339.

16. Hammon, A.J. and W.E. Code. 1954. An irrigation guide for Colorado. Colo. Agr. and Mech. College Bul. 432-A.

17. Harrold, L.L. 1955. Evapotranspiration rates for various crops. Agric. Eng. 36:669-672.

18. Harrold, L.L. and F.R. Dreibelbis. 1958. Evaluation of agricultural hydrology by monolith lysimeters. U.S.D.A. Tech. Bul. 1179.

19. Hobbs, E.H., K.K. Krogman and L.G. Sonmor. 1963. Effects of levels of minimum available soil moisture on crop yields. Can. J. Plant Sci. 43:441-446.

20. Hobbs, E.H. and K.K. Krogman. 1966. A comparison of measured and calculated evapotranspiration for alfalfa in Alberta. Can. Agric. Eng. 8:9-11.

21. Hobbs, E.H. and K.K. Krogman. 1966. Evapotranspiration from alfalfa as related to evaporation and other meteorological variables. Can. J. Plant Sci. 46: 271-277.

22. Hobbs, E.H. and K.K. Krogman. 1968. Observed and estimated evapotranspiration in Southern Alberta. Trans. A.S.A.E. 11(4):502-503 and 507.

23. Holmes, R.M. and G.W. Robertson. 1958. Conversion of latent evaporation to potential evapotranspiration. Can. J. Plant Sci. 38:164-172.

24. Holmes, R.M. 1961. Estimation of soil moisture content using evaporation data. Proc. of Hydrology Symposium No. 2, Evaporation. 184-196. Queen's Printer, Ottawa.

25. Holmes, R.M. and G.W. Robertson. 1963. Application of the relationship between actual and potential evapotranspiration in dry land agriculture. Trans. A.S.A.E. 6:65-67.

26. Jensen, M.C., J.E. Middleton and W.O. Pruitt. 1961. Scheduling irrigation from pan evaporation. Wash. Agr. Exp. Stn. Cir. 386.

27. Jensen, Marvin E. and Howard R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. and Drain. Div., Proc. A.S.C.E., 89(1R4) Part 1, 15-41.

28. Krogman, K.K. and E.H. Hobbs. 1965. Evapotranspiration by irrigated alfalfa as related to season and growth stage. Can. J. Plant Sci. 45:309-313.

29. Mukammal, E.I. and J.P. Bruce. 1960. Evaporation measurements by pan and atmometer. Cir. 3300/Tech. 315, Meteor. Br., Canada Dept. of Transport, Ottawa.

30. Pelton, W.L. 1961. The use of lysimetric methods to measure evapotranspiration. Proc. of Hydrology Symposium No. 2, Evaporation. Queen's Printer, Ottawa. 106-121.

31. Pelton, W.L. 1964. Evaporation from atmometers and pans. Can. J. Plant Sci. 44:397-404.

32. Pelton, W.L. and H.C. Korven. 1969^1. Evapotranspiration estimates in a semiarid climate. Can. Agr. Eng. 11(2):50-53, 61.

33. Pelton, W.L. and H.C. Korven. 1969^2. Evapotranspiration estimates from atmometers and pans. Can. J. Plant Sci. 49:615-621.

34. Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London (A), 193:120-145.

35. Penman, H.L. 1952. The physical bases of irrigation control. 13th International Hort. Congress Report and Proc. 11:913-924.

36. Penman, H.L. 1956. Evaporation: an introductory survey. Netherlands J. Agr. Sci. 4:9-29.

37. Pohjakas, K., D.W.L. Read and H.C. Korven. 1967. Consumptive use of water by crops at Swift Current, Saskatchewan. Can. J. Soil Sci. 47:131-138.

38. Pruitt, W.O. and D.E. Augus. 1960. Large weighing lysimeter for measuring evapotranspiration. Trans. A.S.A.E. 3(2):13-18.

39. Robertson, G.W. 1954. Latent evaporation: its concept, measurement and application. Processed Bul., Canada Dept. Agric., Ottawa.

40. Robertson, G.W. and R.M. Holmes. 1959. Estimating irrigation water requirements from meteorlogical data. Pub. 1054, 303. Canada Dept. Agric., Ottawa.

41. Rohwer, C. 1934. Evaporation from different types of pans. Proc. A.S.C.E. Part 2, 60(8): 673-703.

42. Rose, C.W. 1966. Agricultural physics. 1st Ed., 22-26, 69-73. Pergamon Press.

43. Skidmore, E.L., H.S. Jacobs and W.L. Powers. 1968. Potential evapotranspiration as influenced by wind. Agron. J. 61: 543-546.

44. Smithsonian Institute. 1951. Smithsonian meteorological tables. 6th Ed. Washington, D.C.

45. Sonmor, L.G. 1963. Seasonal consumptive use of water by crops grown in southern Alberta and its relationship to evaporation. Can. J. Soil Sci. 43:287-297.

46. Taylor, Sterling A. and C.S. Slater. 1955. When to irrigate and how much to apply. U.S.D.A. Yearbook of Agriculture.

47. Thornthwaite, C.W. 1948. An approach toward a rational classification of climate. Geog. Review 38:85-94.

48. Thornthwaite, C.W. and J.R. Mather. 1955. The water balance. Publ. Climatol. (Drexel Inst. Tech.) 8:1-104.

49. Veihmeyer, F.J. and A.H. Hendrickson. 1950. Soil moisture in relation to plant growth. Ann. Rev. Plant Physiol. 1:284-303.

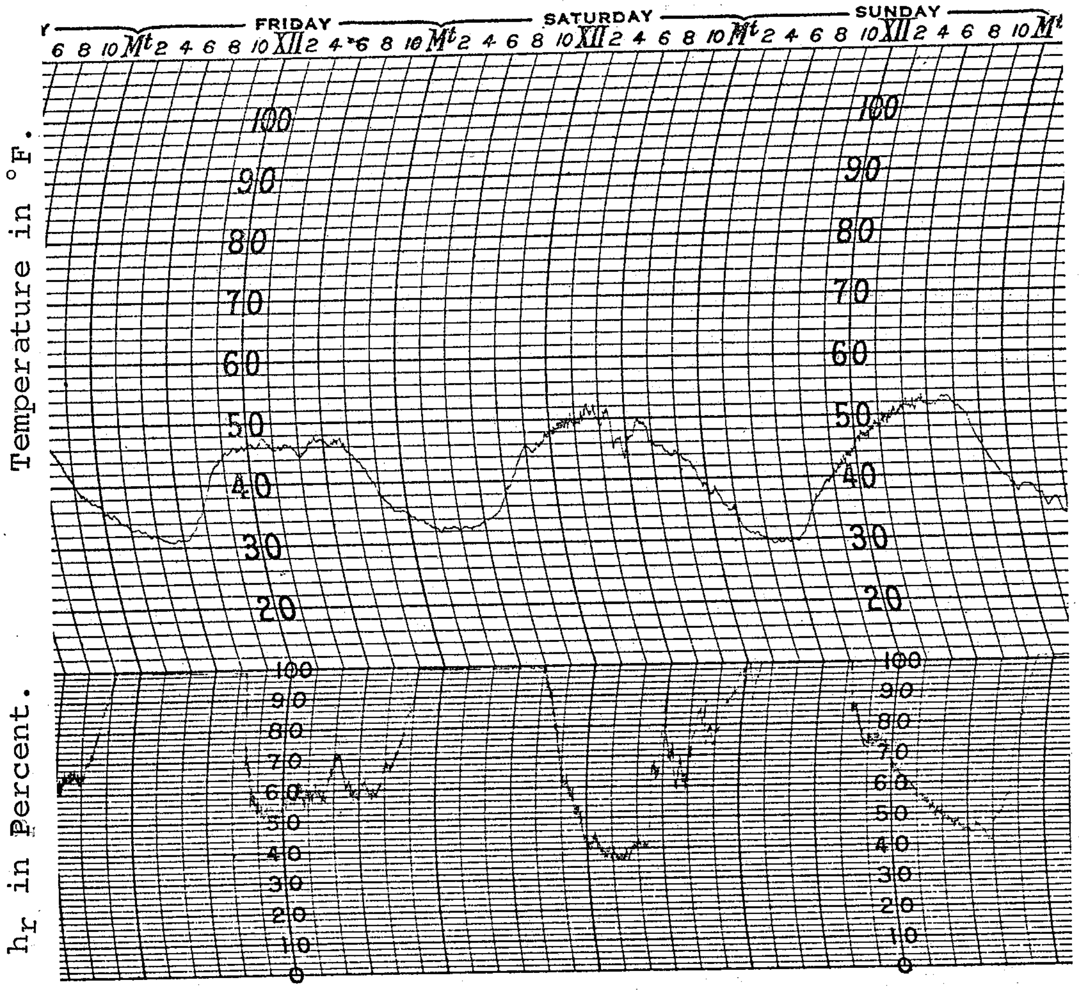
50. Veihmeyer, F.J. and A.H. Hendrickson. 1955. Does transpiration decrease as the soil moisture decreases? Trans. Am. Geophys. Union. 26:425-448.

51. Wilcox, J.C. 1963. Effects of weather on evaporation from Bellani plates and evapotranspiration from lysimeters. Can. J. Plant Sci. 43:1-11.

52. World Meteorological Organization. 1966. International Meteorological Vocabulary No. 182. TP. 91. World Meteorological Organization, Geneva, Switzerland. 276 pp.

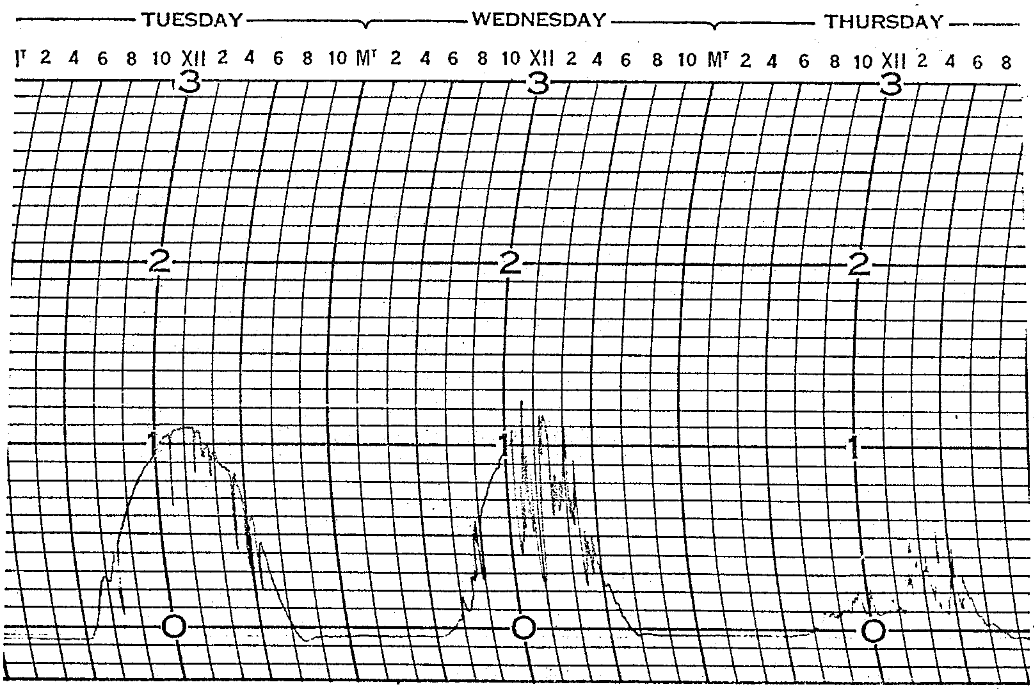
APPENDIX A

TYPICAL HYGRO-THERMOGRAPH CHART


FRIDAY
SATURDAY
SUNDAY
6 8 10 Mt 2 4 6 8 10 XII 2 4 6 8 10 Mt 2 4 6 8 10 XII 2 4 6 8 10 Mt 2 4 6 8 10 XII 2 4 6 8 10 Mt
Temperature in °F.
100
90
80
70
60
50
40
30
20
h_r in Percent.
100
90
80
70
60
50
40
30
20
10
0

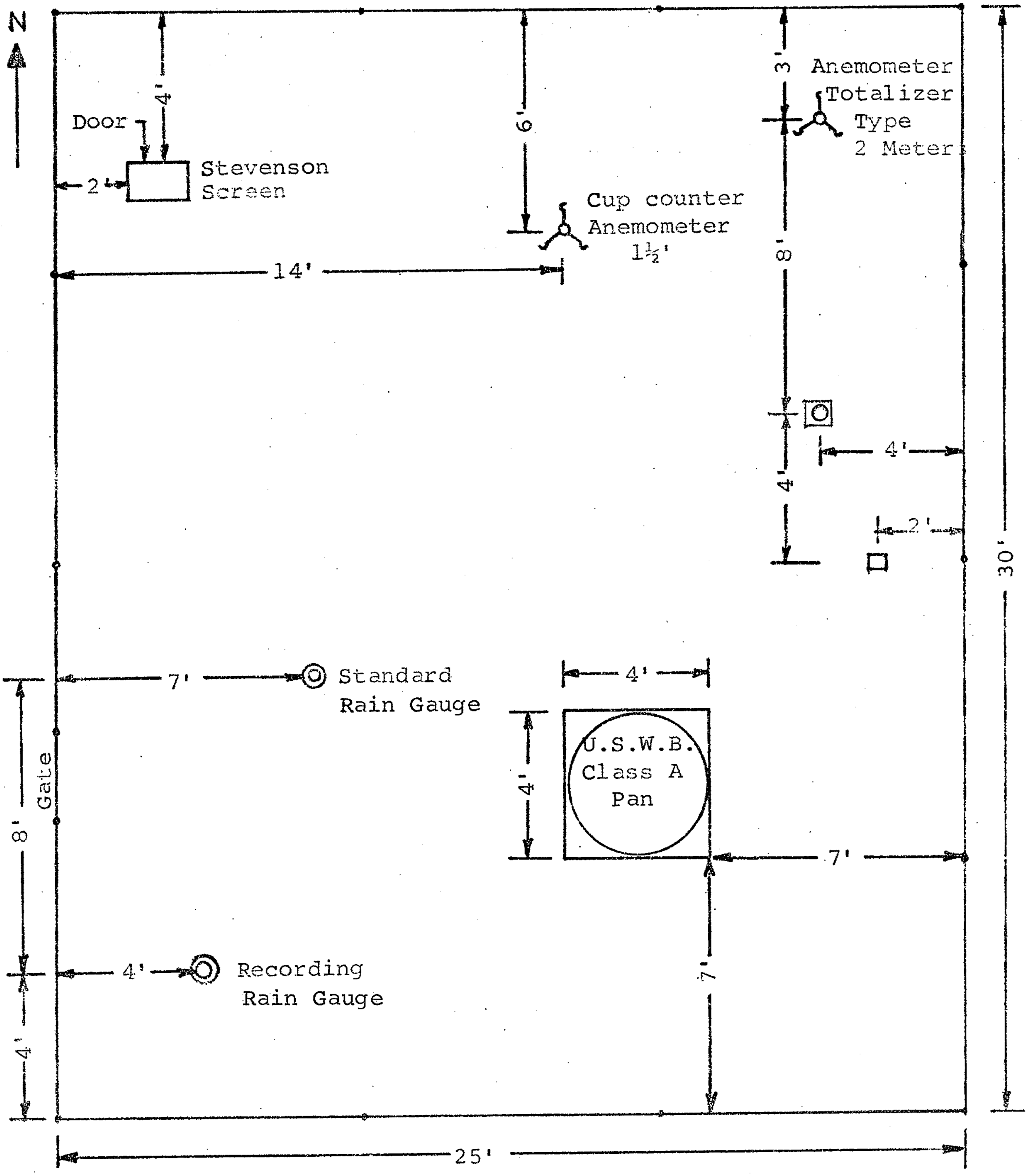
APPENDIX B

TYPICAL PYRHELIOGRAPH CHART


TUESDAY
WEDNESDAY
THURSDAY
Iᵀ 2 4 6 8 10 XII 2 4 6 8 10 Mᵀ 2 4 6 8 10 XII 2 4 6 8 10 Mᵀ 2 4 6 8 10 XII 2 4 6 8
3
2
1
0

APPENDIX C

INSTRUMENT INSTALLATION PLAN
CARBERRY WEATHER STATION 1969


N
Door
4'
2'
Stevenson Screen
6'
Cup counter Anemometer 1½'
14'
3'
Anemometer Totalizer Type 2 Meter
8'
4'
4'
2'
30'
7'
Standard Rain Gauge
Gate
8'
4'
4'
U.S.W.B. Class A Pan
4'
7'
7'
4'
Recording Rain Gauge
25'

Scale 1" = 4'

APPENDIX D

SEASONAL EVAPORATION FROM
U.S.W.B. CLASS A PAN
AT
BALDUR
MORDEN, C.D.A.
WINNIPEG INTERNATIONAL AIRPORT
RIDING MOUNTAIN PARK
1963-1969

SEASONAL EVAPORATION FROM U.S.W.B. CLASS A PAN (INCHES)
(FROM MONTHLY RECORDS, METEOROLOGICAL BRANCH, DEPT. OF TRANSPORT)

Crop	Growing Period	Location	Year							Mean
			1963	1964	1965	1966	1967	1968	1969	
Alfalfa	May 1 to Sept. 1	Baldur	38.9	35.4	32.5	37.6	35.8	28.0	30.5	34.1
		Morden	32.0	35.2	31.6	33.0	38.4	32.0	34.5	33.8
		Winnipeg	37.6	40.3	36.9	35.1	39.2	35.3	34.8	37.0
		Riding Mtn.	20.0	23.5	18.9	18.9	23.2	16.1	17.9	19.8
		Carberry	----	----	----	----	----	----	32.0	
Sugar Beets	May 15 to Oct. 31	Baldur	43.8	37.3	34.7	40.6	38.7	31.0	----	37.7
		Morden	35.0	36.7	34.2	34.9	40.4	33.9	33.6	35.5
		Winnipeg	40.6	39.6	37.1	36.0	40.1	35.6	33.7	37.5
		Riding Mtn.	----	----	----	----	----	----	----	----
		Carberry	----	----	----	----	----	----	30.4	----
Potaotes	May 15 to Sept. 15	Baldur	33.8	30.5	29.2	33.5	31.9	24.5	26.6	30.0
		Morden	28.3	30.7	28.8	29.4	34.4	28.0	30.3	29.9
		Winnipeg	33.3	36.2	33.1	31.9	35.2	31.5	30.6	33.1
		Riding Mtn.	17.9	20.6	16.7	16.7	20.4	14.4	16.1	17.5
		Carberry	----	----	----	----	----	----	28.2	
Cereals	May 15 to Sept. 1	Baldur	28.6	26.9	27.2	29.1	27.1	21.1	22.7	26.1
		Morden	24.7	27.4	26.9	25.4	29.4	23.9	26.8	26.4
		Winnipeg	29.3	31.7	30.6	28.1	29.2	28.7	27.4	29.3
		Riding Mtn.	15.9	18.7	15.8	15.0	18.2	13.0	14.9	15.9
		Carberry	----	----	----	----	----	----	25.8	

Notes: Evaporation for May 15-31 estimated as 2/3 of May value.

Evaporation for September 1-15 estimated as 2/3 of September value - no record.

APPENDIX E

SUMMARY OF EVAPORATION
AND
METEOROLOGICAL DATA
USED TO DERIVE EQUATIONS
INCLUDING MEAN AND STANDARD DEVIATION
(MAY - SEPTEMBER, 1969)
CARBERRY, MANTTOBA

Date	Class 'A' Pan Evap. (in.)	Latent Evap. (cc)	Max. Temp. (°F)	Temp. Range (°F)	Vapour Pressure Deficit (mb.)	Wind Height 2.0 m. (miles)	Total Solar Radiation gm-cal-cm^{-2}	Q_o gm-cal-cm^{-2}
May 1	0.08	25.00*	52.00	11.00	1.70	187.02	143.20	865.70
2	0.22	41.00*	63.00	27.00	3.49	151.42	530.67	871.60
3	0.08	25.00*	51.00	16.00	1.51	164.99	353.79	877.60
4	0.12	30.00*	65.00	31.00	2.20	140.35	345.53	881.80
5	0.16	34.00*	67.00	26.00	1.90	178.68	412.75	887.50
6	0.26	60.00	62.00	21.00	3.13	293.39	534.89	893.10
7	0.07	18.00	57.00	15.00	1.48	191.90	311.67	898.80
8	0.15	30.00	51.00	15.00	1.96	180.06	425.37	902.40
9	0.12	31.00	49.00	20.00	0.80	155.39	379.05	907.90
10	0.16	42.00	53.00	22.00	2.57	182.64	496.97	913.30
11	0.15	35.00	54.00	18.00	3.36	114.90	547.51	918.50
12	0.17	42.00	62.00	26.00	5.07	131.32	389.15	921.80
13	0.21	54.00	67.00	34.00	3.52	156.96	610.69	926.70
14	0.28	65.00	79.00	36.00	6.57	290.88	391.69	931.70
15	0.05	6.00	50.00	11.00	2.81	394.90	134.77	936.50
16	0.14	52.00	53.00	21.00	4.31	170.78	670.50	941.20
17	0.30	54.00	61.00	32.00	4.76	152.48	652.81	943.90
18	0.27	40.00	62.00	25.00	4.31	348.09	387.47	948.50
19	0.29	49.00*	45.00	18.00	2.39	196.83	644.39	952.90
20	0.26	46.00*	52.00	25.00	2.36	140.90	501.19	957.30
21	0.26	46.00*	60.00	32.00	4.24	172.35	682.29	961.40
22	0.36	70.00	68.00	32.00	5.31	199.33	530.67	963.50
23	0.42	86.00	74.00	39.00	4.51	277.34	598.06	967.50
24	0.20	44.00	54.00	27.00	2.18	115.94	657.02	971.50
25	0.26	74.00	71.00	37.00	6.87	234.87	475.91	975.10
26	0.35	84.00	93.00	45.00	11.03	133.95	555.94	978.60
27	0.40	82.00	76.00	28.00	1.76	379.25	648.60	980.30
28	0.48	95.00	76.00	33.00	6.87	294.71	694.93	983.70
29	0.43	78.00	75.00	31.00	6.75	263.74	606.48	986.90
30	0.19	45.00	75.00	33.00	3.86	352.66	421.17	990.10
31	0.01	2.00	44.00	3.00	0.18	470.98	172.68	991.30

*Estimated.

Date	Class 'A' Pan Evap. (in.)	Latent Evap. (cc)	Max. Temp. (°F)	Temp. Range (F°)	Vapour Pressure Deficit (mb.)	Wind Height 2.0 m. (miles)	Total Solar Radiation gm-cal-cm^{-2}	Q_o gm-cal-cm^{-2}
June 1	0.38	62.00	60.00	24.00	4.95	274.00	724.41	994.10
2	0.38	54.00	66.00	36.00	4.50	99.80	562.81	994.90
3	0.06	34.00	69.00	23.00	3.45	155.92	290.61	997.50
4	0.27	53.00	73.00	30.00	5.72	136.68	547.52	1000.10
5	0.37	62.00	71.00	20.00	4.84	191.50	690.72	1002.20
6	0.01	2.00	56.00	13.00	0.93	88.45	151.62	1004.60
7	0.25	46.00	61.00	20.00	4.54	156.07	581.21	1006.60
8	0.45	90.00	76.00	38.00	7.11	213.30	682.29	1008.60
9	0.46	100.00	80.00	32.00	9.89	350.68	614.91	1010.40
10	0.13	34.00	55.00	18.00	3.70	234.67	589.64	1010.00
11	0.23	42.00*	67.00	32.00	6.10	253.49	501.19	1011.60
12	0.24	44.00*	59.00	31.00	4.08	159.76	543.31	1013.00
13	0.29	49.00*	63.00	36.00	3.41	132.73	635.97	1014.30
14	0.22	41.00*	68.00	29.00	6.62	104.20	623.33	1015.50
15	0.47	56.00	72.00	36.00	7.11	91.67	501.19	1016.50
16	0.07	45.00	69.00	27.00	2.40	141.53	433.80	1017.30
17	0.28	74.00	71.00	31.00	5.87	181.95	627.54	1018.10
18	0.20	51.00	62.00	13.00	4.80	259.56	442.23	1018.70
19	0.14	33.00	52.00	15.00	1.47	191.71	404.32	1019.10
20	0.26	54.00	61.00	32.00	3.17	127.38	429.59	1017.50
21	0.21	36.00	61.00	21.00	1.37	102.80	438.02	1017.70
22	0.14	30.00	64.00	31.00	0.00	65.55	379.05	1017.70
23	0.27	44.00	74.00	27.00	4.74	88.59	502.03	1017.70
24	0.18	48.00	76.00	33.00	3.33	134.69	564.37	1017.50
25	0.58	1.00	63.00	6.00	0.92	496.02	160.04	1017.10
26	0.29	2.00	62.00	7.00	0.00	453.66	126.35	1016.70
27	0.00	8.00	59.00	10.00	0.51	186.51	202.16	1016.10
28	0.25	33.00	65.00	21.00	1.37	144.53	429.59	1015.30
29	0.06	4.00	55.00	4.00	0.49	235.18	223.22	1014.30
30	0.16	48.00	63.00	23.00	0.88	202.75	602.27	1013.30

*Estimated.

Date	Class 'A' Pan Evap. (in.)	Latent Evap. (cc)	Max. Temp. (°F)	Temp. Range (°F)	Vapour Pressure Deficit (mb.)	Wind Height 2.0 m. (miles)	Total Solar Radiation gm-cal-cm^{-2}	Q_o gm-cal-cm^{-2}
July 1	0.28	32.00	64.00	15.00	1.56	107.91	572.79	1012.10
2	0.33	60.00	72.00	29.00	4.39	139.19	623.33	1011.10
3	0.07	14.00	67.00	16.00	1.18	181.71	219.01	1009.60
4	0.09	4.00	59.00	7.00	0.27	178.11	126.35	1008.00
5	0.23	32.00	61.00	20.00	0.73	128.98	480.13	1006.20
6	0.06	10.00	59.00	13.00	0.24	227.55	189.53	1004.40
7	0.08	5.00	62.00	12.00	0.27	165.96	185.31	1002.40
8	0.25	46.00	72.00	19.00	1.38	215.42	539.10	1000.50
9	0.29	51.00	74.00	19.00	2.07	202.98	572.79	998.30
10	0.20	54.00	81.00	26.00	6.30	126.11	648.60	995.90
11	0.30	75.00	90.00	34.00	5.94	137.12	623.33	993.40
12	0.29	65.00	92.00	24.00	12.60	90.78	627.54	990.80
13	0.44	62.00	82.00	19.00	8.48	117.00	614.91	988.20
14	0.07	27.00	78.00	25.00	2.81	89.27	307.45	985.30
15	0.20	46.00	77.00	19.00	5.56	99.03	501.19	984.00
16	0.23	55.00	75.00	28.00	4.79	117.43	572.79	981.00
17	0.30	50.00	79.00	34.00	5.50	59.89	610.70	977.90
18	0.09	5.00	65.00	9.00	0.32	102.24	172.68	974.50
19	0.16	29.00	73.00	20.00	4.21	56.14	539.10	971.10
20	0.20	35.00	72.00	23.00	1.97	68.37	564.37	967.60
21	0.15	24.00	74.00	17.00	0.81	111.16	357.99	965.70
22	0.26	47.00	73.00	17.00	2.07	174.79	505.40	962.00
23	0.30	52.00	79.00	25.00	5.30	130.79	572.79	958.00
24	0.22	60.00	75.00	22.00	6.40	125.18	631.75	954.10
25	0.22	40.00	75.00	27.00	2.18	135.58	577.00	949.90
26	0.17	30.00	72.00	17.00	4.13	215.35	496.98	945.80
27	0.21	36.00	72.00	16.00	4.89*	106.38	488.56	941.40
28	0.20	78.00	79.00	31.00	1.03	56.05	524.78	936.90
29	0.38	56.00	85.00	30.00	5.22	132.05	602.27	932.60
30	0.62	24.00	74.00	12.00	1.94	117.91	404.32	927.90
31	0.19	34.00	73.00	27.00	2.16	67.33	530.57	923.10

*Estimated.

Date	Class 'A' Pan Evap. (in.)	Latent Evap. (cc)	Max. Temp. (°F)	Temp. Range (°F)	Vapour Pressure Deficit (mb.)	Wind Height 2.0 m. (miles)	Total Solar Radiation gm-cal-cm^{-2}	Q_o gm-cal-cm^{-2}
Aug. 1	0.25	46.00	78.00	20.00	4.06	81.62	598.06	920.20
2	0.25	51.00	86.00	32.00	7.92	94.47	560.15	915.30
3	0.18	40.00	83.00	20.00	4.93	126.27	496.98	910.20
4	0.33	40.00	80.00	20.00	3.74	90.56	484.34	905.10
5	0.37	12.00	74.00	17.00	0.00	114.40	214.80	900.00
6	0.18	39.00	75.00	17.00	6.61	171.23	406.85	894.70
7	0.21	52.00	75.00	23.00	5.45	148.11	589.64	889.20
8	0.25	41.00	82.00	30.00	4.95	64.96	555.94	885.50
9	0.26	48.00	83.00	30.00	3.59	75.74	564.37	880.00
10	0.22	50.00	90.00	33.00	10.67	57.21	555.94	874.50
11	0.21	36.00	86.00	29.00	1.52	68.74	324.30	868.60
12	0.14	36.00	81.00	14.00	3.51	128.88	475.92	862.90
13	0.34	34.00	68.00	7.00	2.50	276.23	307.45	857.00
14	0.28	42.00	73.00	22.00	3.38	139.82	564.37	852.80
15	0.21	36.00	77.00	27.00	4.56	69.04	555.94	846.80
16	0.18	48.00	80.00	25.00	3.98	185.11	526.46	840.70
17	0.50	44.00	68.00	17.00	6.00	159.10	551.73	834.40
18	0.05	16.00	67.00	21.00	0.28	93.74	357.99	828.20
19	0.06	30.00	73.00	23.00	3.22	66.50	438.02	823.50
20	0.20	46.00	81.00	28.00	7.54	99.18	530.67	817.30
21	0.27	52.00	91.00	33.00	6.72	109.71	509.61	810.80
22	0.30	66.00	93.00	29.00	10.02	160.14	522.25	804.30
23	0.31	42.00	81.00	21.00	4.76	124.80	526.46	797.70
24	0.30	42.00	79.00	21.00	6.05	130.61	480.13	792.60
25	0.14	58.00	88.00	31.00	10.50	111.21	450.65	787.70
26	0.24	46.00	84.00	22.00	9.70	109.64	446.44	781.00
27	0.07	27.00	78.00	19.00	3.15	118.16	404.32	774.20
28	0.21	26.00	74.00	22.00	1.01	137.30	408.53	767.40
29	0.26	23.00	80.00	25.00	0.00	160.54	286.39	762.00
30	0.43	52.00	72.00	23.00	7.22	157.12	509.61	755.10
31	0.17	29.00	71.00	22.00	4.66	99.10	450.65	748.10

Date	Class 'A' Pan Evap. (in.)	Latent Evap. (cc)	Max. Temp. (°F)	Temp. Range (°F)	Vapour Pressure Deficit (mb.)	Wind Height 2.0 m. (miles)	Total Solar Radiation gm-cal-cm^{-2}	Q_o gm-cal-cm^{-2}
Sept. 1	0.36	48.00	78.00	34.00	5.28	136.69	345.36	741.10
2	0.04	25.00	70.00	18.00	1.56	139.85	273.76	735.50
3	0.14	46.00	82.00	25.00	6.34	151.78	366.42	728.30
4	0.10	26.00	75.00	16.00	2.59	120.12	235.85	721.20
5	0.16	34.00	72.00	28.00	6.28	101.41	294.82	714.00
6	0.12	22.00	67.00	22.00	2.20	92.28	387.48	708.20
7	0.12	13.00	59.00	18.00	0.62	126.84	286.39	700.90
8	0.07	9.00	57.00	18.00	1.12	47.33	235.85	693.60
9	0.11	34.00	71.00	34.00	2.62	87.01	454.86	686.30
10	0.21	40.00	65.00	23.00	2.36	156.23	496.98	683.30
11	0.24	58.00	79.00	43.00	4.52	176.56	459.07	672.90
12	0.16	36.00	74.00	32.00	1.74	118.62	433.80	665.60
13	0.12	52.00	86.00	42.00	10.99	88.20	416.96	658.20
14	0.27	58.00	83.00	27.00	10.38	162.87	387.48	652.00
15	0.19	50.00	60.00	16.00	6.73	129.94	459.07	644.60
16	0.18	39.00	58.00	23.00	4.66	106.61	446.44	637.10
17	0.12	27.00	60.00	29.00	3.05	90.80	311.66	630.90
18	0.16	40.00	71.00	33.00	4.85	153.16	383.26	623.40
19	0.11	35.00	73.00	32.00	1.16	165.93	252.70	615.90
20	0.14	37.00	72.00	17.00	4.69	253.29	336.93	608.40
21	0.02	4.00	50.00	1.00	0.22	231.36	71.60	602.10
22	0.02	12.00	49.00	6.00	1.32	244.39	248.49	594.60
23	0.03	10.00	43.00	10.00	0.44	110.70	189.53	587.10
24	0.03	13.00	53.00	20.00	0.56	133.66	214.80	580.70
25	0.10	4.00	50.00	9.00	0.00	124.65	101.08	573.20
26	0.10	15.00	54.00	11.00	2.80	57.01	307.45	565.70
27	0.10	22.00	55.00	22.00	2.59	84.51	320.09	560.00
28	0.04	4.00	54.00	23.00	0.03	115.56	151.62	553.60
29	0.17	25.00	53.00	15.00	2.45	167.98	311.66	546.20
30	0.03	4.00	41.00	7.00	0.00	173.04	67.39	538.70

MEAN AND STANDARD DEVIATION OF EACH VARIABLE

Variable	Units	Mean	Standard Deviation
Pan Evaporation	in.	0.209	0.115
Latent Evaporation	cc.	39.84	20.42
Maximum Temperature	°F	68.80	11.40
Temperature Range	°F	23.10	8.70
Vapour Pressure Deficit	mb	3.76	2.72
Wind	miles/day	158.40	80.70
R_T	gm-cal-cm^{-2}	444.40	155.50
Q_o	gm-cal-cm^{-2}	881.40	139.00

APPENDIX F

CONSUMPTIVE USE FOR VARIOUS CROPS
AT TABER AND VAUXHALL
1950-1961
(AFTER SONMOR, 1963)

CONSUMPTIVE USE FOR VARIOUS CROPS TABER AND VAUXHALL, 1950-61 (AFTER SONMOR, 1963)

Crop	Seasonal Consumptive Use (in.)	Mean Daily Consumptive Use (in.)	Seasonal Ratio of Consumptive Use to Evaporation	
			Black Bellani Plate Atmometer (in./cc)	U.S.W.B. Class A Pan (in./in.)
Perennials (closed seeded)				
Alfalfa	25.5	0.163	0.00300	0.659
Grass, pasture	23.6	0.155	0.00308	0.678
Annuals (closed seeded)				
Soft Wheat	19.4	0.187	0.00302	0.658
Hard wheat	18.2	0.178	0.00293	
Oats	16.1	0.168	0.00276	0.586
Barley	16.1	0.178	0.00281	0.640
Flax	15.2	0.155	0.00256	-
Peas, canning	13.4	0.174	0.00314	-
Annuals (row crops)				
Sugar beets	21.5	0.138	0.00250	0.542
Potatoes	19.9	0.149	0.00254	0.556
Corn, canning	15.2	0.143	0.00223	0.500
Corn, field	14.7	0.124	0.00222	
Tomatoes	14.4	0.140	0.00238	-

APPENDIX G

MEAN WEEKLY EVAPOTRANSPIRATION OF WHEAT AND BELLANI-PLATE EVAPORATION AT BRANDON, 1955-1959

(AFTER FERGUSON, 1965)

MEAN WEEKLY EVAPOTRANSPIRATION OF WHEAT AND BELLANI-PLATE EVAPORATION AT BRANDON (1955-1959), AFTER FERGUSON (1965)

Approximate Date	Approximate Growth Stage	Bellani Plate Evaporation (cc)	Potential Evapotrans. (in.)[1]	$\frac{AE}{PE}$[2]	AE (in.)	Measured Evapotrans. (in.)
May 28	3-leaf	347	1.18	0.46	0.54	0.70
June 3		389	1.32	0.54	0.71	0.84
10	5-leaf	398	1.35	0.65	0.88	0.93
17		395	1.34	0.83	1.11	0.93
24	Shot-blade	372	1.27	0.98	1.24	1.06
July 1	Flowering	367	1.25	1.05	1.31	1.45
8		413	1.41	1.06	1.49	1.19
15	Soft-dough	396	1.31	1.03	1.39	0.91
22		453	1.54	0.96	1.48	1.00
29		485	1.65	0.77	1.27	0.60
Total		4015	13.62		12.42	9.61

---

[1] From conversion factor 0.0034 inches per cubic centimeter of latent evaporation, after Holmes and Robertson (1957).

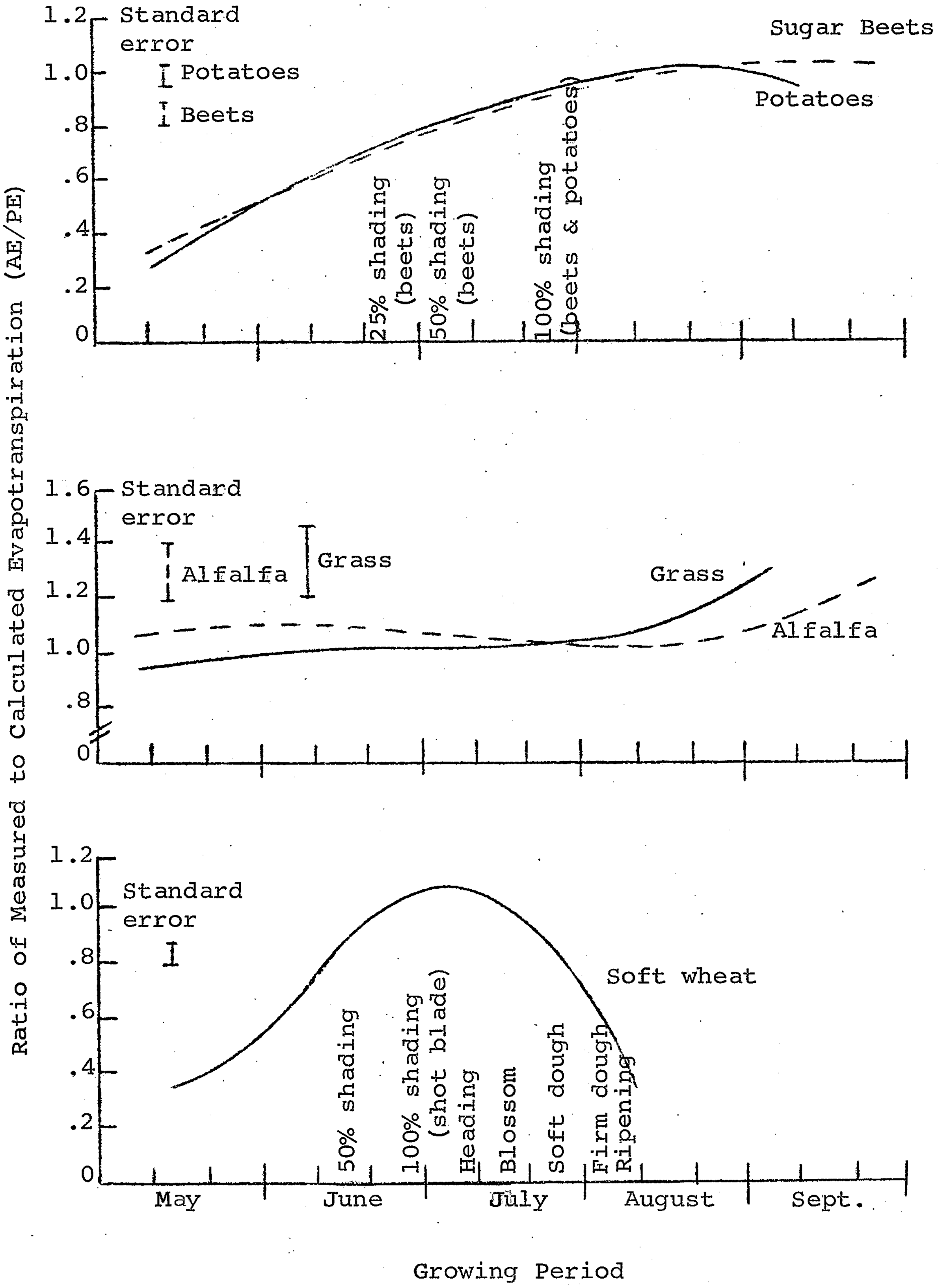
[2] From AE/PE curve of wheat, after Hobbs and Krogman (1968).

A paired 't' test was employed to test the difference between measured and estimated evapotranspiration. The statistical 't' value was 1.91 indicating no significant difference.

APPENDIX H

RATIO OF MEASURED EVAPOTRANSPIRATION TO CALCULATED EVAPOTRANSPIRATION IN SOUTHERN ALBERTA

(AFTER HOBBS AND KROGMAN, 1968)


Ratio of Measured to Calculated Evapotranspiration (AE/PE)
1.2
1.0
.8
.6
.4
.2
0
Standard error
Potatoes
Beets
Sugar Beets
Potatoes
25% shading (beets)
50% shading (beets)
100% shading (beets & potatoes)
1.6
1.4
1.2
1.0
.8
0
Standard error
Alfalfa
Grass
Grass
Alfalfa
1.2
1.0
.8
.6
.4
.2
0
Standard error
Soft wheat
50% shading
100% shading (shot blade)
Heading
Blossom
Soft dough
Firm dough
Ripening
May
June
July
August
Sept.
Growing Period

APPENDIX I

ESTIMATION OF SEASONAL CONSUMPTIVE USE FROM FIELD DATA FOR

POTATOES
ALFALFA
SUGAR BEETS
CEREALS (WHEAT)

ESTIMATION OF SEASONAL CONSUMPTIVE USE FROM FIELD DATA OF THE FOUR CROPS

POTATOES: (irrigated), May 15 - September 15

Date	$\frac{CU}{PE}$	E_L (cc)	PE (in)	CU (in)	Precip. (in)	Irrig. (in)	Deep Perco. (in)	Remarks
May 15-31	0.36	953	3.240	1.166	0.24			
June 1-10	0.51	537	1.820	0.928	0.27			
11-19	0.60	435	1.480	0.888	-			
20	0.65	54	0.184	0.120	-			
21-24	0.67	158	0.538	0.360	-	0.40		F.C.
25	0.70	1	0.003	0.002	1.76		1.398	
26	0.70	2	0.007	0.005	1.44		1.435	
27	0.71	8	0.027	0.019	0.10		0.081	
28	0.72	33	0.112	0.081	0.65		0.569	
29	0.73	4	0.014	0.010	0.19		0.180	
30	0.73	48	0.163	0.119	-			
July 1-2	0.75	92	0.313	0.235	-			
3	0.76	14	0.047	0.036	0.57		0.180	
4	0.77	4	0.014	0.011	0.66		0.649	
5	0.78	32	0.109	0.085	-			
6	0.78	10	0.034	0.026	0.44		0.329	
7	0.80	5	0.017	0.014	0.53		0.516	
8	0.81	46	0.156	0.126	-			
9	0.82	51	0.173	0.142	0.06			
10	0.82	54	0.184	0.151	-			
11-16	0.83	330	1.120	0.930	-			
17	0.84	50	0.170	0.143	0.83			
18	0.85	5	0.017	0.014	0.14			
19	0.86	29	0.098	0.084	-			
20	0.87	35	0.119	0.103	-			
21	0.87	24	0.082	0.071	0.12			
22-24	0.88	159	0.540	0.475	-			
25	0.90	40	0.136	0.122	0.02			
26	0.90	30	0.102	0.092	0.12			
27-28	0.91	114	0.387	0.352	-			
29	0.92	56	0.190	0.175	0.43	1.06		F.C.

POTATOES: (irrigated), May 15 - September 15 (continued)

Date	$\frac{CU}{PE}$	E_L (cc)	PE (in)	CU (in)	Precip. (in)	Irrig. (in)	Deep Perco. (in)	Remarks
July 30	0.93	24	0.082	0.076	0.03			
31	0.93	34	0.115	0.107	-			
August 1	0.93	46	0.156	0.145	-			
2	0.94	51	0.173	0.163	0.10			
3-4	0.95	80	0.272	0.258	-			
5	0.95	12	0.041	0.039	1.20	1.06		F.C.
6	0.96	39	0.132	0.127	0.06			
7-10	0.97	191	0.650	0.630	-			
11	0.97	36	0.122	0.118	0.01	1.70		F.C.
12	0.98	36	0.122	0.119	1.00		0.881	
13	0.98	34	0.116	0.114	0.34		0.226	
14-15	0.99	78	0.265	0.262	-			
16	0.99	48	0.163	0.161	0.43		0.007	
17	1.00	44	0.150	0.150	0.06			
18	1.00	16	0.054	0.054	0.11			
19-20	1.00	76	0.258	0.258	-			
21-24	1.00	202	0.687	0.687	-			
25	1.00	58	0.197	0.197	0.10			
26	1.00	46	0.156	0.156	-	0.80		F.C.
27	1.00	27	0.092	0.092	0.21		0.118	
28	1.00	26	0.088	0.088	0.31		0.222	
29	1.00	23	0.078	0.078	0.11		0.032	
30-31	1.00	81	0.275	0.275	-			
Sept. 1-5	0.99	179	0.610	0.604	-			
6	0.99	22	0.075	0.046	0.25			
7	0.98	13	0.043	0.042	0.02			
8	0.97	9	0.031	0.030	-	1.06		F.C.
9-15	0.96	328	1.110	1.060	-			$\Delta M=1.06$
Total		5272	17.909	13.221	13.01	6.08	6.823	

CU = Precipitation + Irrigation - Deep percolation + Change in soil moisture storage
= 13.01 + 6.08 - 6.82 + 1.06
= 13.33 inches
CU from Vauxhall coefficient = (0.00254)(5272) = 13.40 inches
CU from AE/PE curve = 13.22 inches
All three values are very close and are considered to be reliable.

ALFALFA: May 1 - September 30

Date	$\frac{CU}{PE}$	E_L (cc)	PE (in.)	CU (in.)	Remarks
May 1-10	1.05	336	1.142	1.199	Consumptive Use Factors $\left[\frac{CU}{PE}\right]$ obtained from Appendix H.
11-20	1.08	443	1.506	1.626	
21-31	1.10	706	2.400	2.640	
June 1-10	1.10	537	1.826	2.008	
11-20	1.10	489	1.663	1.829	
21-31	1.08	254	0.864	0.933	
July 1-10	1.06	308	1.047	1.110	
11-20	1.05	449	1.527	1.603	
21-31	1.03	481	1.635	1.684	
Aug. 1-10	1.02	419	1.425	1.453	
11-20	1.02	368	1.251	1.276	
21-31	1.05	463	1.574	1.653	
Sept. 1-10	1.10	297	1.010	1.111	
11-20	1.17	432	1.469	1.718	
21-31	1.28	113	0.384	0.491	
Total		6095		22.334	

CEREALS (wheat): May 15 - September 1

Date	$\frac{CU}{PE}$	E_L (cc)	PE (in.)	CU (in.)	Remarks
May 15-20	0.37	247	0.840	0.311	Consumptive Use Factors $\left(\frac{CU}{PE}\right)$ obtained from Appendix H.
21-25	0.43	320	1.088	0.468	
26-31	0.50	386	1.312	0.656	
June 1-10	0.64	537	1.826	1.168	
11-15	0.82	232	0.789	0.647	
16-20	0.91	257	0.874	0.795	
21-25	0.99	159	0.541	0.535	
26-30	1.04	95	0.323	0.336	
July 1-5	1.06	142	0.483	0.512	
6-10	1.05	166	0.564	0.592	
11-20	1.00	449	1.526	1.526	
21-25	0.88	223	0.758	0.667	
26-31	0.77	258	0.877	0.675	
Aug. 1-5	0.61	189	0.643	0.392	
6-10	0.42	230	0.782	0.328	
11-15	0.30	184	0.625	0.187	
16-31	0.30	647	2.200	0.660	
Sept. 1	0.30	48	0.163	0.049	
Total		4769		10.504	

SUGAR BEETS: May 15 - October 31

Date	$\frac{CU}{PE}$	E_L (cc)	PE (in.)	CU (in.)	Remarks
May 15-20	0.41	247	0.840	0.344	Consumptive Use Factors $\left(\frac{CU}{PE}\right)$ obtained from Appendix H.
21-31	0.46	706	2.400	1.104	
June 1-10	0.55	537	1.826	1.004	
11-20	0.63	489	1.663	1.048	
21-30	0.71	254	0.864	0.613	
July 1-10	0.80	308	1.047	0.837	
11-20	0.85	449	1.527	1.298	
21-31	0.90	481	1.635	1.471	
Aug. 1-10	0.95	419	1.425	1.354	
11-20	0.98	368	1.251	1.226	
21-31	1.00	463	1.574	1.574	
Sept. 1-10	1.02	297	1.010	1.030	
11-20	1.02	432	1.469	1.498	
21-30	1.00	113	0.384	0.384	
Oct. 1-31	0.97	235	0.799	0.775	
Total		5798		15.560	