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ESTIMATING EVAPO-TRANSPIRATION LOSSES IN THE DOMINION OF CANADA FROM METEOROLOGICAL DATA

A THESIS

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by

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ABSTRACT

Mean annual evapo-transpiration losses are estimated from meteorological and hydrological records using the water budget equation. The effect of changes in storage are diminished by taking the difference between the total precipitation and the total runoff for a six year period. Values of losses so determined are correlated with values of losses predicted by a graph (Appendix I, figure 2) developed by Butler(1) from work by Langbein and others(20). The measured losses are plotted on a map of Canada and lines of equal losses are drawn to show the regional variations.

In Appendix II, the use of various methods of estimating potential evapo-transpiration are illustrated for an example drainage area on the valley of the Thames River, Ontario. The methods used are based mainly on energy budget and mass transfer concepts.

In a future study, such methods could be used to estimate potential losses for the whole country.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

APPENDIX I

APPENDIX II

LIST OF TABLES

Page

APPENDIX I

APPENDIX II

Page

PREFACE

One of Canada's greatest natural resources is its general abundance of water. This resource, probably more than any other, will determine the future economic development of Canada and many parts of the United States during the next few decades. The development of modern household equipment, new industrial processes, and recent farming techniques, have all increased the need for water. In order to properly assess and utilize this natural resource, we must try to accurately analyze each phase of the hydrologic cycle in which it occurs. It is with this idea in mind that the following investigation of evapo-transpiration losses was undertaken.

CHAPTER I

INTRODUCTION

Water losses in a drainage basin may be defined as the difference between the total precipitation and the total runoff from the basin(2). The losses may be subdivided as follows:

1. Interception.
2. Evaporation from free water surfaces.
3. Plant transpiration.
4. Soil or land evaporation.
5. Watershed leakage.

Each of these losses occurs at different rates at different times. Watershed leakage, although quite common, is considered relatively unimportant,and the losses from one basin are frequently balanced by accretions from another. Therefore, neglecting watershed leakage, we may refer to the combination of the other losses as "evapo-transpiration losses" (E_t) or, when referring to a particular type of vegetation, as the "consumptive use".

In a paper by Jensen and Haise(3), the following reasons were given for the need for greater accuracy in determining evapo-transpiration losses: (1) growing competition for limited water supplies, (2) irrigation projects that required the smallest initial cost have been completed and higher construction costs of new projects demand closer tolerances and less leeway in design to make the projects economically feasible, (3) water litigations between irrigation districts, states, upper and lower river basins and, in some cases between countries, are requiring more precise E_t estimates, (4) river basin development for maximum use of water supplies requires long range planning with reliable estimates of E_t, (5) sprinkler irrigation design requires accurate short period estimates for 5 to 10 days to assure adequate but economic capacity to meet peak demands, (6) many drainage problems can be avoided or time of occurrence predicted in advance if accurate E_t estimates are available, and, (7) existing projects can often reduce operational wastes by predicting water deliveries several days in advance.

Competition for our water resources is certain to become more and more keen in the years to come. This increase will occur not only among the various types of uses that exist today but among the new ones that will develop.

CHAPTER II

REVIEW OF LITERATURE

Many investigations have been carried on in the past 70 years in that field of hydrology relating to the determination of water supply and water demand. Most of the research in the North American continent has been conducted in the United States and very little has been done in Canada.

Around the turn of the century, runoff was generally considered and expressed as a percentage of rainfall. As the science developed, it was realized that runoff is the remainder after the various losses are subtracted from precipitation. This fact alone was an important breakthrough and it opened the door on an entirely new field of estimating and measuring water losses.

Numerous studies were conducted on seasonal evapo-transpiration (consumptive use) during the first quarter of the century(3)(Widstoe, 1912; Harris, 1920; Lewis, 1919; Hemphill, 1922; Israelsen and Winsor, 1922; and Briggs and Shantz 1916a, 1916b). An excellent summary of some of these early studies appears in the Progress Report of the Duty of Water Committee of the Irrigation Division, ASCE, "Consumptive Use of Water in Irrigation" presented in 1927 and later published (Anonymous, 1930)(4). Many studies were also carried out in Europe during this period in such countries as Austria, Germany, Poland and Sweden.

Between 1920 and 1950 considerable emphasis was placed on the development of procedures for estimating seasonal evapo-transpiration. Air temperature, being readily available, was the major climatic variable in the various procedures developed(3)(Hedke, 1924; Blaney and Morin, 1942; Lowry and Johnson, 1942; Thornthwaite, 1948; and Blaney and Criddle, 1950).

Many evapo-transpiration studies have been conducted since 1950 and a few of these are mentioned in the list of references. Two theoretical approaches to the problem have been investigated, namely, the mass transfer and the energy balance. The latter approach has received greater acceptance because less refinement in instrumentation is necessary.

(5)Penman (1949) combined the theories of mass transfer and energy balance. The mass transfer theory utilizes concepts of evaporation being related to turbulence, and pressure and temperature gradients , whereas, the energy balance theory involves evaporation as one method of dissipating incoming radiation. The use of the Penman equation, even though evaluated worldwide, has not gained great popularity among engineers because it requires measurements of mean temperature and mean wind velocity over the growing crop.

Some of the more promising estimating methods are compared in Appendix II.

CHAPTER III

THEORETICAL BASIS FOR MEASUREMENT OF LOSSES

As stated earlier, the total evapo-transpiration losses from any drainage basin consist of interception, evaporation from land and water surfaces and transpiration. Ordinarily, these losses for any given drainage basin, can be either measured or estimated more accurately and more easily collectively than separately. (2) The relationship between these collective losses, rainfall, runoff, and storage, is expressed by the hydrologic equation

$$L = P - Q \pm \Delta S \qquad (1)$$

in which L is the total losses for the period, P the total precipitation for the period, Q the total runoff for the period, and ΔS the increment in surface and subsurface storage during the period, the sign being plus for a decrease in storage and minus for an increase. All these quantities are expressed in the dimensions of inches or m.m. depth covering the drainage basin.

Although during the year, there may be fluctuations amounting to several feet or more in storage in the basin, the observed level on October 1 of any year does not ordinarily differ greatly from the long-term average for that date except as a result of unnatural changes or developments made within the basin. Because of this fact, the average annual water loss for any period of 5 years or longer, beginning and ending with October 1, may be determined from equation (1), ignoring ΔS. If the values of P and Q have been accurately determined for the period, the average annual water loss should be correct within no more than 2 inches.

If the water loss for a single year is determined in the same manner, the error will be considerably greater depending upon the value of Δ S for that year. For instance, if the change in ground water level for the year amounted to 18 inches in a soil with an average porosity of $33\frac{1}{3}$ %, the change in subsurface storage alone would amount to 6 inches which, added to changes in surface storage, would probably give a total value for Δ S of 8 or 10 inches.

CHAPTER IV

COMPUTATIONAL PROCEDURE

(a) Sources of Hydrologic Data

As of January, 1964, (6) official meteorological observations were taken and recorded at some 2,230 weather reporting stations in Canada. Records from these stations are published monthly and are available from the Meteorological Branch of the Department of Transport, Toronto, Ontario. Many of these records are now being transferred to punched cards for use in computers. Values of mean monthly temperature and monthly precipitation were taken from these monthly records and used in the computations.

Records of streamflow and runoff are gathered by the Water Resources Branch of the Department of Northern Affairs and National Resources in cooperation with the various provinces. These records are published for each year in 4 separate volumes representing 4 separate drainage areas of Canada: Pacific Drainage; Arctic and Western Hudson Bay Drainage; St. Lawrence and Southern Hudson Bay Drainage, and Atlantic Drainage. These published figures may be obtained from the Water Resources Branch, Department of Northern Affairs and National Resources, Ottawa, Ontario.

(b) Preparation of Map

The map (Appendix I, figure 1) showing lines of mean annual water losses has been based as far as possible on the difference between precipitation and runoff measurements. Not all runoff and precipitation records could be used for this purpose, however. The primary requirements were (1) that the drainage area above the gaging station in question be known, (2) that the flow be not materially affected by diversion or regulation, (3) that the area was adequately represented by a precipitation network and (4) that the records were continuous for the period under study.

Mean annual water losses were computed for the 6 year period from October 1, 1955, to September 30, 1961. This period was chosen because it represents the latest published figures across Canada and embodies the densest available precipitation network in Canada's history.

The drainage basins above each gaging station were outlined on tracing paper laid over Department of Mines and Technical Surveys base maps of Canada. (Scale 1:1,000,000). The meteorological network was then plotted on the same paper and lists were made of the meteorological stations best representing each drainage basin. The base maps used were those showing drainage and topography.

In some cases, where it was felt that the drainage basin included widely varying climatic conditions or where part of the basin was not represented by meteorological coverage, opportunity was taken to calculate runoff from partial basin areas and thus define areal variations in runoff and losses more closely.

The final map was traced from United States Air Force Global Navigation and Planning Chart (GNC-2N). The figures of mean annual water losses were entered within the basin outlines and the lines of mean annual water losses were drawn taking into account the general variation of losses with precipitation, weighted temperature, and terrain.

On the whole, little difficulty was experienced east of the Rockies in determining the losses but, in the Rocky Mountains of British Columbia, it was found that in over 50% of the basins the recorded runoff exceeded the recorded precipitation. Therefore, this area of Canada had to be eliminated from this study. Not enough information was available throughout the northern part of Canada to obtain reliable results, so the lines of mean annual water losses have been estimated in this area from the few values that were available and are plotted on the map as dashed lines.

(c) Data and Computation Sheets

The meteorological data was collected on data sheets such as that shown in Appendix I, figure 3. Values of monthly temperature and precipitation were recorded whenever possible and missing values were replaced by basin averages. The values of precipitation were totalled to give an annual value, and the mean weighted temperature for each year was determined from the equation(1)

$$T_w = \frac{\Sigma(T \times P)}{\Sigma P}$$

where T_w is the mean annual weighted temperature, T is the mean temperature for the month, and P is the total precipitation for the month.

Other columns were left for possible future studies in this field although it is probable that most future work would be more easily done on a computer.

On the data sheets of the type shown in Appendix I, figure 4, the values of annual runoff, annual precipitation, and mean annual weighted temperature were recorded for each basin for each of 6 years from October 1, 1955, to September 30, 1961. These values were then averaged to find mean annual precipitation and runoff for the period and then the mean annual water losses were determined and recorded as the difference between these two values. Mean annual weighted temperature for the period was also determined and recorded. The meteorological stations used in each basin were listed in the upper righthand corner opposite the name of the river. When a runoff value was adjusted for partial areas, the basins which were subtracted from the runoff values are shown listed below the column headed "year" and the corrected drainage area is listed beside them. The corrected values of runoff are shown above the stroked-out values.

A list of results for all basins is shown in Appendix I, Table 1.

CHAPTER V

DISCUSSION OF RESULTS

It was found that for the water year 1955-56 runoff exceeded precipitation in most of the Pacific Drainage. The runoff and/or precipitation data in this area is obviously (see Appendix I, Table 2) not representative and reasons for this are discussed under the heading "Sources of Error". Throughout the other major drainages, fairly reasonable results were obtained (see Appendix I, Table 1) except in areas where the precipitation network was sparse. The most reliable results were obtained throughout the Prairies and Ontario and these results were subjected to the following analysis.

The measured values of mean annual water losses were compared with the results as expected from the graph(1) in Appendix I, figure 2 using mean annual precipitation and mean annual weighted temperature to find the losses. Graphical correlation(7) is shown in Appendix I, figure 2. The averages of groups of values within certain abscissa ranges were taken and plotted in blocks as in the figure 2. The line of $T_w = 43^oF$. was then plotted to fit these points and the estimate is observed to follow quite well the original lines in both directions and position.

A numerical analysis was also carried out onthese data. The measured results were correlated with the graphical results yielding a correlationcoefficient of 0.926 for 47 observations. This comparison is shown graphically in Appendix I, figure 5.

It appears, then, that reasonable correlation exists and that the graph in Appendix I, figure 2, may be used to estimate actual mean annual evapo-transpiration in the Prairies and Ontario with a reasonable degree of accuracy.

The remaining portion of eastern Canada is influenced by mountainous regions and coastal climates and until more representative data is obtained for these watersheds, no accurate correlation can be made.

CHAPTER VI

FACTORS AFFECTING ACTUAL EVAPO-TRANSPIRATION LOSSES

Actual evapo-transpiration losses are dependent upon many factors, the most important of which are as follows:

(a) Radiation

Energy is consumed in the evapo-transpiration process and the ultimate source of this energy is the sun's radiation. Therefore, the rate of evapo-transpiration varies directly with the amount of solar radiation.

(b) Daylight Hours

Transpiration virtually ceases at night and therefore the amount of evapo-transpiration is dependent on the percentage of daylight hours.

(c) Temperature

As with radiation, temperature is concerned with energy and is in fact a measure of the amount of energy available. Thus, the higher the temperature, the more energy available and, therefore, the higher the potential rate of evapo-transpiration.

(d) Wind

Wind acts as a transporting agent for water vapor. It has a relatively minor effect on the total amount of evapo-transpiration but due to increased turbulence, it may increase the rate for a short time.

(e) Humidity

Since water vapor in the air moves towards points of lower moisture content, the humidity gradient is therefore of importance in determining the rate of evapo-transpiration.

(f) Precipitation

Precipitation limits the amount of moisture available for evapo-transpiration and thus the actual losses may be less than the potential losses.

(g) Type of Vegetation

Different types of vegetation use different amounts of water in plant development and transpire water at different rates. The structure of the plant (i.e. the height and amount of surface area) is also important in determining how much of the precipitation will be intercepted and evaporated during a rainfall.

CHAPTER VII

SOURCES OF ERROR

(a) Streamflow Records

Stage-discharge relations are usually established at all gaging stations. This relationship can be subject to considerable error under certain conditions either because of unsteady flow or variable backwater conditions due to channel obstructions. The equation of flow is $Q = V A$ where Q is the rate of flow in cubic feet per second, V is the velocity in feet per second, and A is the cross-sectional area in square feet. If there is no ice or aquatic growth at the gaging site, the area is related to the stage but if the station is subjected to ice or aquatic growth, the stage-area relationship will vary with the time of year and cannot be depended on for accurate results. Velocity V is related to slope as well as depth and therefore the streamflow Q is subject to error dependent on the change in slope of the water surface.

Gaging stations(8) should always be located on a backwater profile upstream of a point of critical velocity (weir or ledge of rock) called a "station control". In other cases, it is governed by the channel features such as shape, slope and frictional resistance, known as "channel control".

A control is said to be "permanent" if with steady flow and no submergence (i.e. no backwater from downstream), there is a fixed stage-discharge relation. If the control is subject to scour or fill of the channel bottom, it is called a "shifting control".

Various factors may temporarily destroy the stage-discharge relationship at a station control under steady flow conditions. The control may become submerged by backwater from discharging tributaries downstream or the control may become clogged with ice or debris. Measurements of stage under either of these conditions would tend to overestimate discharge as determined from the established stage-discharge relationship.

Loop ratings(8) have often been found to occur under conditions of changing rate of discharge. During increasing discharge, the values will plot to the right, and for falling stages to the left of the normal steady-flow stage-discharge curve. This loop rating can be caused either by change in storage between the control and the gage, or by variable slopes at constant stage during the passage of a flood wave.

Flow over some sort of permanent station control where flow is related to discharge alone is most desirable and eliminates errors due to changing slope. These permanent controls are usually hard to find and usually must be created by installation of a low level weir or dam at considerable expense.

For each gaging station listed in the records, there is a corresponding drainage area given for the basin. These areas have been subject to some revision and sometimes have been revised by as much as 10%. Any error in the drainage area is reflected in the runoff values and thus affects the estimate of water losses.

Watershed leakage is normally of little significance except perhaps in mountainous areas where the geology may be such that water infiltrating the ground in one basin may follow the strata and appear as runoff in an adjoining basin. This is very hard to detect unless adequate values of mean areal precipitation and runoff are available for adjoining basins.

The accuracy(9) of streamflow data depends on (1) the stability of the stage-discharge relation, or if the control is unstable, the frequency of discharge measurements, and (2) the accuracy of observations of stage, measurements of rate of discharge and interpretation of records.

In order to give some indication of the quality of the currently published records in Canada, the probable accuracy of the daily record is indicated in the description of the station under "Remarks" as "excellent", "good", "fair", or "poor". The records of yearly streamflow are, in general, more accurate than the daily records. In this study, only values of yearly runoff were used and the stations marked "poor" were not considered.

(b) Meteorological Observations

(i) Precipitation

In the(10) Canadian Meteorological Branch, rainfall is measured in a rain gauge which has a cross-sectional area of 10 square inches, while snowfall is taken as the depth of freshly fallen snow (measured with a ruler) in an area free from drifting. Precipitation is taken to be the rainfall plus one-tenth the snowfall. The rainfall equivalent of snowfall varies with the density of the snow but is about one-tenth on the average.

In many areas of Canada, the precipitation network is not dense enough and for various reasons cannot be used as representative of the drainage basin. The most serious errors occur in the mountainous regions of British Columbia. In this area, most of the climatological stations are located in the inhabited valley floors and very few are located on the mountain tops. Since lifting(7) of air masses accounts for almost all precipitation in mountainous topography, amounts and frequency are generally greater on the windward side of mountain barriers. Conversely, since downslope motion of air results in decreased relative humidity, the lee sides of barriers usually experience relatively light precipitation.

The variation in precipitation with topographic features is quite varied and presents great difficulties in establishing a representative network to define mean areal precipitation.

As mentioned earlier, due to lack of correlation between precipitation and streamflow in British Columbia, no attempt was made to estimate the mean annual water losses in this area.

(ii) Temperature

Temperatures(10) in Canada are observed at a height of about 4 feet above the ground in a standard louvred screen which protects them from the effect of radiation.

Values of temperature are more uniform than precipitation and therefore the temperature network need not be as great. In the mountainous regions, however, the temperature experiences a lapse rate of about - 5.4°F. per 1000 feet rise in elevation in dry adiabatic conditions and about - 3.0°F. per 1000 feet rise in elevation in saturated adiabatic conditions. The average(19) lapse rate is considered to be about - 3.3°F. per 1000 feet rise in elevation. This, therefore, illustrates the need for more temperature readings at higher elevations to find the mean basin temperature.

CHAPTER VIII

CONCLUSIONS

Values of mean annual evapo-transpiration losses were determined for as many basins as possible in Canada using the water budget equation. The values were then compared with the losses predicted by the graph in Appendix I, figure 2, using the mean annual weighted precipitation and mean annual weighted temperature. Satisfactory correlation was found for the Prairies and Ontario and it is felt that figure 2 may be used with a reasonable degree of accuracy in those regions.

It was observed that the data in the mountainous regions of Canada is not representative and it is recommended that efforts be made to coordinate and improve the work in these areas. One method of accomplishing this goal would be to have one agency responsible for both meteorological observations and streamflow observations. The network could then be better and more efficiently organized to give representative values of runoff and precipitation. Such merging of effort occurred in some European countries after World War II under the title of Hydro-Meteorological Institutes. In view of some of the recent proposals for water development in North America (i.e. North American Water and Power Alliance. NAWAPA), it is becoming more important that Canada know more accurately the extent and nature of its water resources.

More time and money should be directed towards improving the network in the sparsely populated regions of Canada to gather the basic hydrologic data necessary for a comprehensive water resources inventory.

APPENDIX I

TABLE 1 Results of Computations 1955-61.

Station No.	Precipitation (inches)	Losses (measured)	Losses (1) (from graph)	T_w (F.)
Pacific				
$9AH_1$	16.57	6.33	9.2	28.8
Arctic and Western Hudson Bay				
$7SA_3$	12.61	8.37	7.0	26.8
$7SB_3$	12.61	9.00	7.0	26.8
$7BE_1$	19.64	16.13	15.8	43.6
$6EA_2$	16.93	12.86	13.7	40.3
$6AD_6$	17.27	14.63	14.6	44.1
$5PB_{14}$	28.89	21.23	19.1	42.7
$5QA_1$	30.26	20.38	18.3	40.5
$5QD_6$	26.09	18.41	18.5	43.3
$5OD_1$	19.59	17.02	16.2	46.3
$5OF_6$	19.59	18.24	16.2	46.3
$5OE_1$	19.59	17.36	16.2	46.3
$5MJ_1$	14.35	13.92	12.9	44.6
$5OH_6$	19.59	17.30	16.2	46.3
$5LM_1$	17.08	15.82	14.1	42.4
$5KJ_1$	14.12	11.90	12.5	42.8
$5AD_8$	34.02	16.05	17.3	38.7
$5GG_1$	15.04	14.58	13.1	44.3
St. Lawrence and Southern Hudson Bay				
$4GB_1$ & $2AD_9$	30.03	18.97	17.1	38.6
$4JD_{2\&3}$	29.27	16.91	17.0	38.6
$4JC_2$	33.19	20.91	16.9	38.1
$4JC_3$	33.19	19.48	16.9	38.1
$4JA_2$	33.19	17.19	16.9	38.1
$4LG_1$	31.26	16.65	18.0	39.7
$4ME_2$	30.97	13.89	18.3	40.4
$2AB_6$	31.04	21.32	19.0	41.4
$2BD_2$	33.17	17.66	18.0	39.6
$2BD_3$	33.06	15.88	16.9	38.0
$2BE_2$	33.98	16.95	18.5	40.3

TABLE 1 (continued)

Station No.	Precipitation (inches)	Losses (measured)	Losses (1) (from graph)	T_w (°F.)
2CC$_7$	30.40	17.31	18.8	41.2
2CE$_1$	30.88	18.27	19.8	43.5
2DD$_4$	35.94	18.88	20.5	43.6
2DB$_5$	32.07	17.92	20.2	44.2
2EB$_6$	39.96	21.05	19.7	41.6
2EC$_3$	32.38	21.49	21.2	45.8
2ED$_3$	31.99	22.53	21.8	47.0
2FC$_1$	37.38	22.00	21.0	44.1
2FE$_4$	33.81	18.63	20.3	43.7
2FF$_2$	41.48	28.74	21.8	44.9
2GG$_2$	35.03	21.37	21.0	44.5
2GE$_3$	33.90	20.71	22.0	46.9
2GB$_1$	34.99	22.62	22.0	46.1
2HB$_2$	30.93	20.03	21.2	46.9
2HC$_3$	29.28	21.37	20.8	46.5
2HD$_2$	33.38	15.50	21.0	45.1
2HK$_2$	32.61	21.26	20.5	44.3
2HL$_1$	34.70	22.56	21.2	45.2
2HM$_1$	33.87	21.60	20.7	44.3
2JE$_{12}$	37.66	18.35	19.1	41.1
2KB$_1$	35.47	21.43	20.8	43.9
2KE$_5$	30.43	18.29	20.0	44.3
2KF$_6$	28.62	18.51	-	-
2LA$_2$	30.99	21.63	20.3	44.9
2LH$_8$	38.70	17.87	20.3	42.9
2LF$_2$	43.20	22.47	19.7	41.6
2LD$_1$	38.14	20.78	19.9	42.1
2LB$_5$	33.28	24.61	21.5	44.5
2LC$_7$	38.11	13.61	19.8	41.9

TABLE 1 (continued)

Station No.	Precipitation (inches)	Losses (measured)	Losses (1) (from graph)	T_w (F.)
2LC$_8$	43.41	19.90	20.3	42.8
2OA$_1$	34.15	20.13	19.8	42.4
2OB$_2$	36.63	16.24	19.9	42.2
2OC$_2$	32.64	11.60	–	–
2OF$_2$	41.02	19.23	19.5	41.6
2NG$_1$	38.23	17.80	19.0	40.6
2PA$_3$	38.80	13.70	18.5	39.9
2PB$_2$	48.39	14.29	19.0	40.8
2PJ$_5$	38.66	15.18	19.1	41.0
2PE$_1$	38.87	8.92	18.3	39.6
2PH$_1$	42.20	13.30	20.1	42.6
2PG$_2$	36.21	12.35	19.4	41.5
2PG$_1$	39.89	18.81	15.8	36.9
2RH$_2$	36.19	6.42	19.1	41.1
2QA$_1$	35.48	15.13	17.8	38.9
2QA$_2$	32.41	15.83	16.9	38.1
2QA$_4$	39.11	11.79	14.6	35.2
2QC$_1$	37.13	10.79	16.4	37.2
1BH$_2$	34.33	9.65	15.7	36.1
Atlantic				
3OE$_1$	31.61	5.41	13.1	33.1
2YM$_1$	34.18	7.15	17.9	39.1
2YO$_1$	38.09	12.96	17.0	38.0
1BE$_1$	40.89	20.27	17.9	39.0
1BJ$_1$	35.32	7.13	18.0	39.2
1BK$_3$	37.50	13.49	18.4	39.8
1BP$_1$	40.20	11.15	18.0	39.2
1AD$_2$	38.55	16.55	18.4	39.7

TABLE 1 (continued)

Station No.	Precipitation (inches)	Losses (measured)	Losses (1) (from graph)	T_w (F.)
1AF$_2$	39.52	19.44	18.5	39.9
1AJ$_1$	39.98	18.21	19.2	40.9
1AK$_2$	31.91	10.71	18.7	40.7
1AD$_3$	32.83	14.20	16.6	37.7
1AH$_4$	40.72	18.05	19.0	40.7
1AK$_1$	40.83	12.70	18.0	39.3
1AQ$_1$	52.27	13.52	17.0	38.4
1AQ$_2$	45.70	14.14	18.0	39.3
1AR$_4$	44.49	20.80	17.4	38.6
1AR$_3$	45.26	18.83	18.8	40.2
1AD$_1$	36.70	16.11	17.0	38.4
1EO$_1$	49.53	11.57	18.1	39.4
1EK$_1$	46.32	7.53	19.2	40.9
1EH$_3$	55.52	20.06	18.1	39.4
1EF$_1$	48.04	12.10	19.3	41.0
1EE$_2$	52.23	16.58	19.9	41.8
1EE$_1$	53.56	14.86	20.0	42.1
1ED$_3$	52.38	16.96	20.0	42.1
1EC$_1$	52.68	11.01	19.2	41.2
1EA$_3$	51.70	13.59	–	–
1DG$_3$	52.30	13.65	20.0	42.0
1FB$_3$	54.19	14.47	19.9	41.8
1FH$_1$	48.25	8.72	20.2	42.6

TABLE 2 Results of Computations for Pacific Drainage 1955-56

Station	Precipitation (inches)	Runoff (inches)	Losses (inches)
8HA$_1$	74.56	58.69	15.87
8HA$_2$	99.26	104.61	- 5.35
8HB$_{14}$	116.03	147.17	-31.14
8NA$_{45}$	19.41	17.29	2.12
8NA$_2$	21.36	22.75	- 1.39
8ND$_{11}$	30.68	44.04	-13.36
8ND$_6$	48.00	46.80	1.20
8NE$_{49}$	30.82	33.82	- 3.00
8NA$_{11}$	19.64	32.89	-13.25
8NE$_1$	35.47	65.61	-30.14
8NE$_8$	48.77	39.21	9.56
8NE$_{77}$	25.95	26.68	- 0.73
8NG$_{53}$	18.64	25.79	- 7.15
8NG$_5$	16.78	11.51	5.27
8NG$_{42}$	30.36	15.33	15.03
8NH$_{o.21}$	27.15	26.24	0.91
8NG$_{46}$	21.51	42.43	-20.92
8NG$_2$	33.21	34.75	- 1.54
8NK$_5$	34.41	28.14	6.27
8NH$_{34}$	25.79	21.45	4.34
8NH$_{0.06}$	34.06	26.24	7.82
8NH$_{0.32}$	20.23	40.23	-20.00
8NH$_4$	23.94	46.81	-22.87
8NH$_1$	32.94	60.00	-27.06
8NH$_7$	32.94	51.16	-18.22
8NJ$_{14}$	41.57	43.37	- 1.80
8NJ$_{13}$	30.24	36.77	- 6.53
8NP$_1$	34.41	35.45	- 1.04
8NE$_{74}$	28.87	38.63	- 9.76
8NE$_{39}$	30.34	24.32	6.02
8NM$_{50}$	16.19	4.20	11.99

TABLE 2 (continued)

Station No.	Precipitation (inches)	Runoff (inches)	Losses (inches)
$8NL_7$	30.57	27.80	2.77
$8NL_{24}$	49.67	24.76	24.91
$8NL_4$	43.63	13.55	30.08
$8MH_{50}$	62.14	41.73	20.41
$8MH_{20}$	56.68	43.79	12.89
$8KA_7$	24.35	34.27	- 9.92
$8KA_4$	28.32	27.15	1.17
$8KB_1$	25.94	27.60	- 1.66
$8KD_3$	32.19	14.22	17.97
$8JB_2$	15.12	4.07	11.05
$8JB_3$	15.03	3.55	11.48
$8JE_1$	17.95	7.88	10.07
$8KH_1$	27.50	23.18	4.32
$8LF_{51}$	21.27	25.19	- 3.92
$8LA_1$	18.84	24.03	- 5.19
$8LE_{20}$	13.35	3.98	9.37
$8LC_{19}$	19.94	22.80	- 2.86
$8LD_1$	30.13	20.13	10.00
$8MG_{13}$	65.67	68.01	- 2.34
$8MH_{29}$	60.75	31.15	29.60
$8MH_1$	72.90	70.30	2.60
$8MH_{38}$	121.01	156.05	-35.04
$8MH_{41}$	128.68	175.94	-47.26

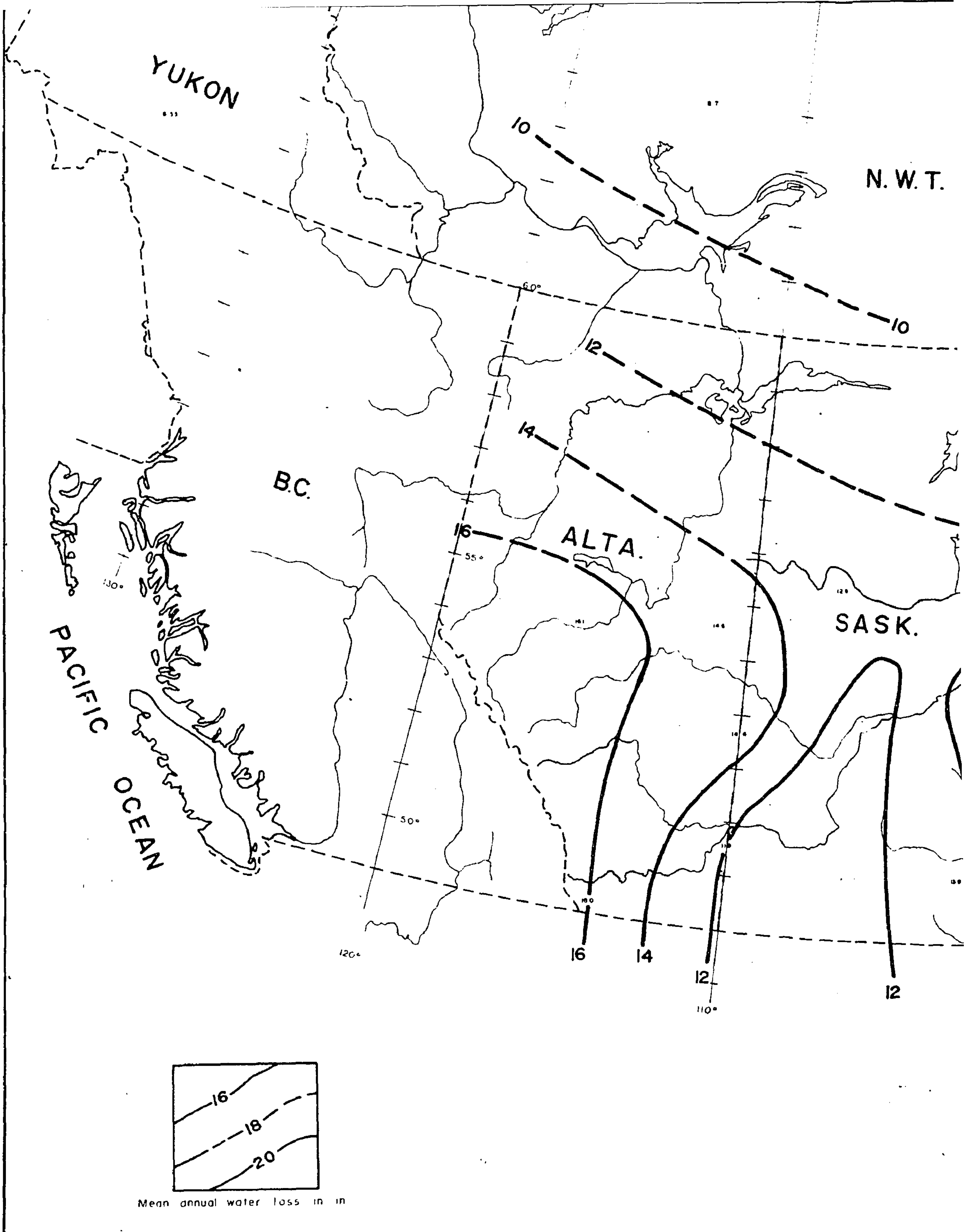
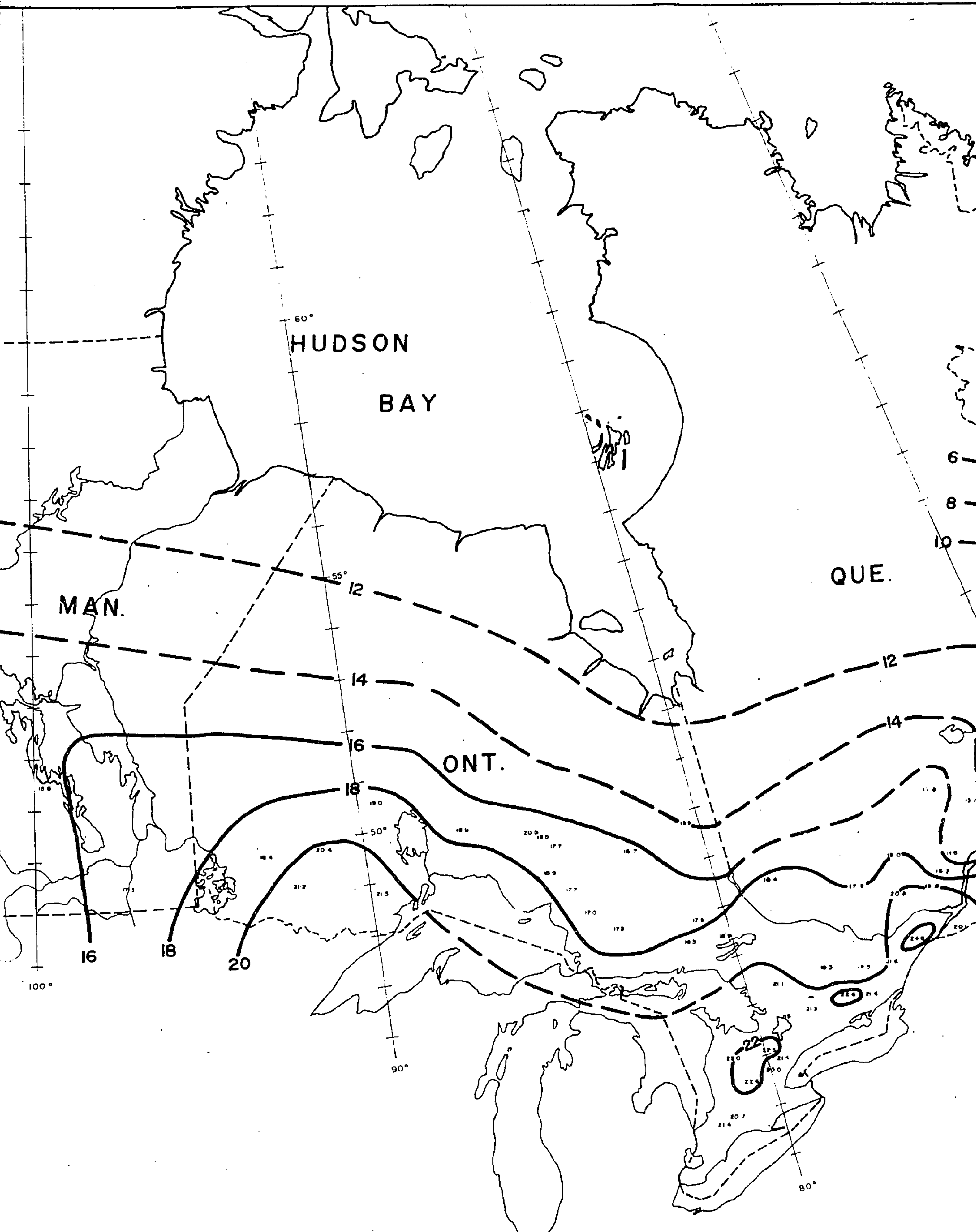
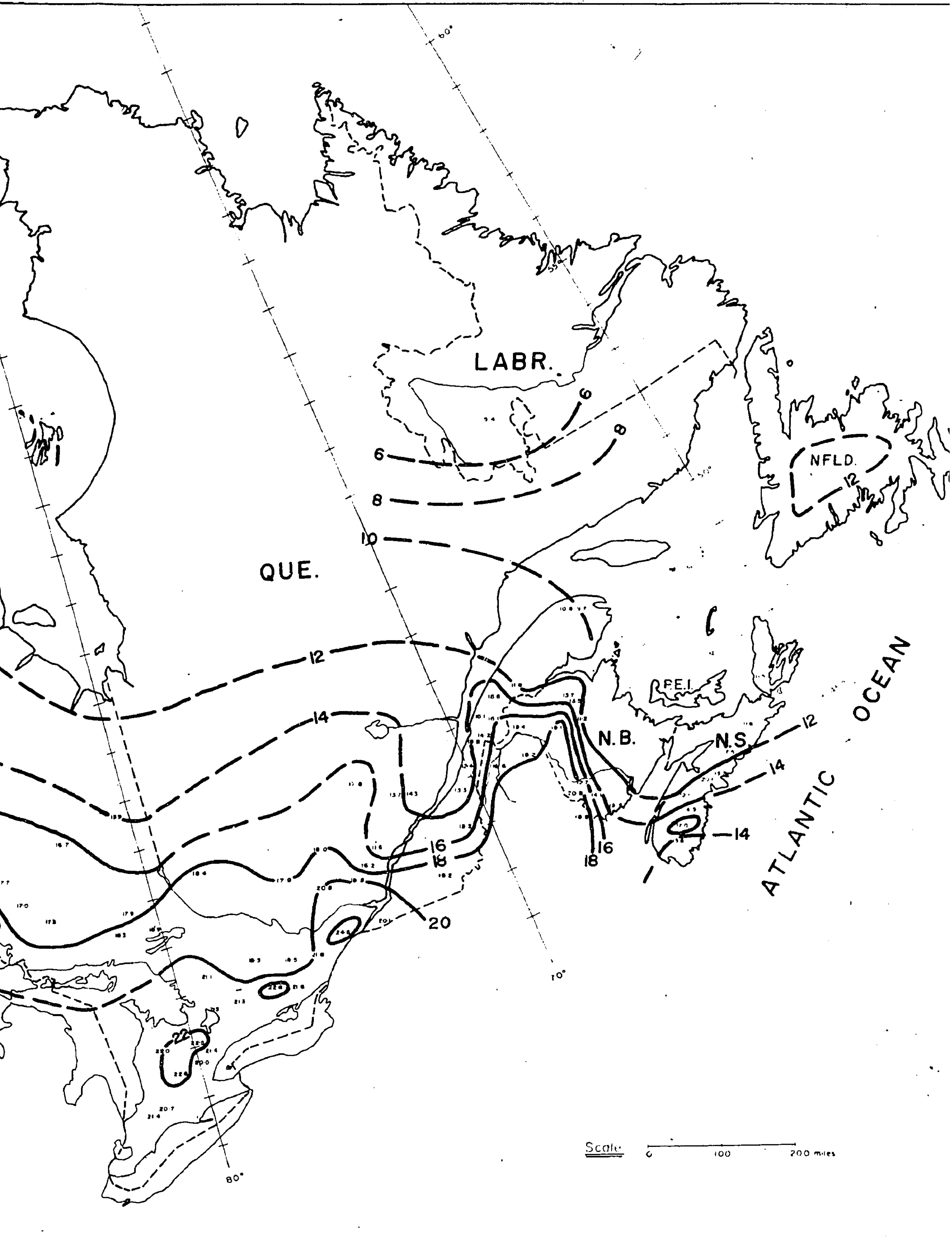


Figure I. Map of Canada showing lines of mean annual w


HUDSON
BAY
MAN.
ONT.
QUE.
60°
55°
50°
100°
90°
80°
6
8
10
12
12
14
14
16
16
18
18
20

losses.


60°
LABR.
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QUE.
P.E.I.
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14
N.B.
N.S.
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ATLANTIC OCEAN
16
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14
16
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10°
22
80°
Scale
0
100
200 miles

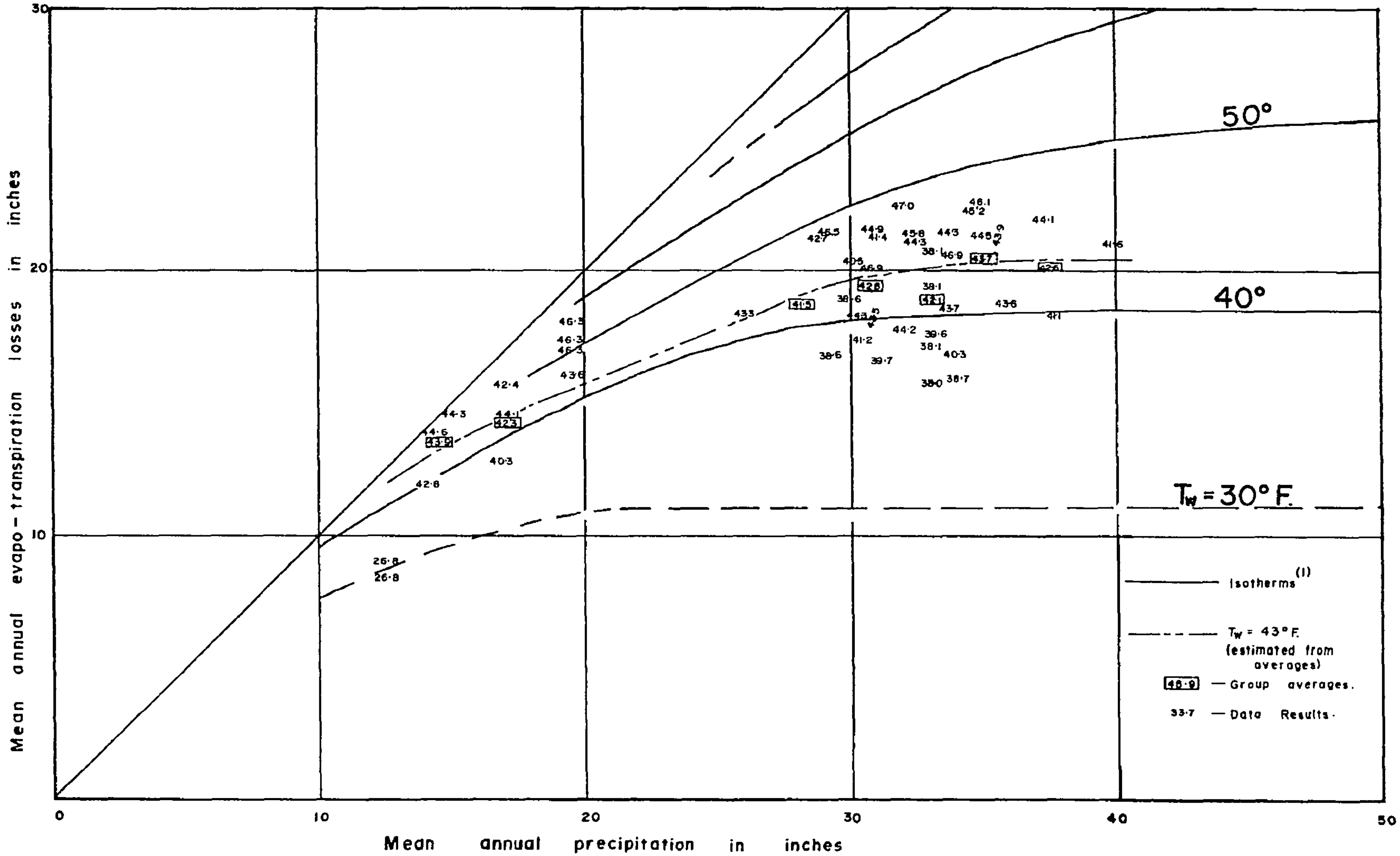


Fig. 2 Evapo-transpiration in relation to precipitation and temperature (1)

Fig. 3 Data and Computation Sheet.

STATION --- London (A)
LAT. N. --- 43° 02
LONG. W. --- 81° 09
ELEV. ----- 912

Month & Year	Mean Temp. (°F.)	Mean Dew Pt. (°F.)	Daily Sun (hrs.)	Mean Solar Rad. (langleys)	Precip. (in.)				
1955-56									
Oct.	51.5				5.32				
Nov.	35.4				3.61				
Dec.	23.2				3.64				
Jan.	22.7				1.33				
Feb.	23.6				2.62				
Mar.	28.1				2.86				
Apr.	41.3				4.34				
May	52.0				4.25				
June	65.2				2.31				
July	67.4				5.39				
Aug.	67.7				5.49				
Sept.	56.5				2.59				
T_W	47.8				43.75				
1956-57									
Oct.	52.3				1.21				
Nov.	38.4				3.48				
Dec.	31.1				2.66				
Jan.	16.4				2.48				
Feb.	25.3				2.49				
Mar.	33.8				1.96				
Apr.	46.5				3.10				
May	53.8				2.87				
June	66.4				4.52				
July	68.9				2.28				
Aug.	65.6				2.27				
Sept.	60.2				4.61				
					33.93				

Fig. 4 Data and Computation Sheet.

RIVER ------------------ Thames

STATION NO. ------------ 2GE3

DRAINAGE AREA (SQ. MI.) ---- 1,660

Fullarton
Glencoe
Lambeth
London (A)
London S.D.
Mitchell
Mount Brydges

Prospect Hill
Stratford
Woodstock

Ridgetown
Talbotville

YEAR	RUNOFF (in.)	PRECIP. (in.)	LOSSES (in.)	T_w (°F)			
1954-55							
1955-56	18.10	44.32		47.1			
1956-57	12.45	34.84		48.6			
1957-58	10.51	31.15		47.8			
1958-59	12.57	33.98		44.0			
1959-60	17.89	36.70		43.5			
1960-61	7.62	32.43		50.3			
1961-62							
Ave.	13.19	33.90	20.71	46.9			

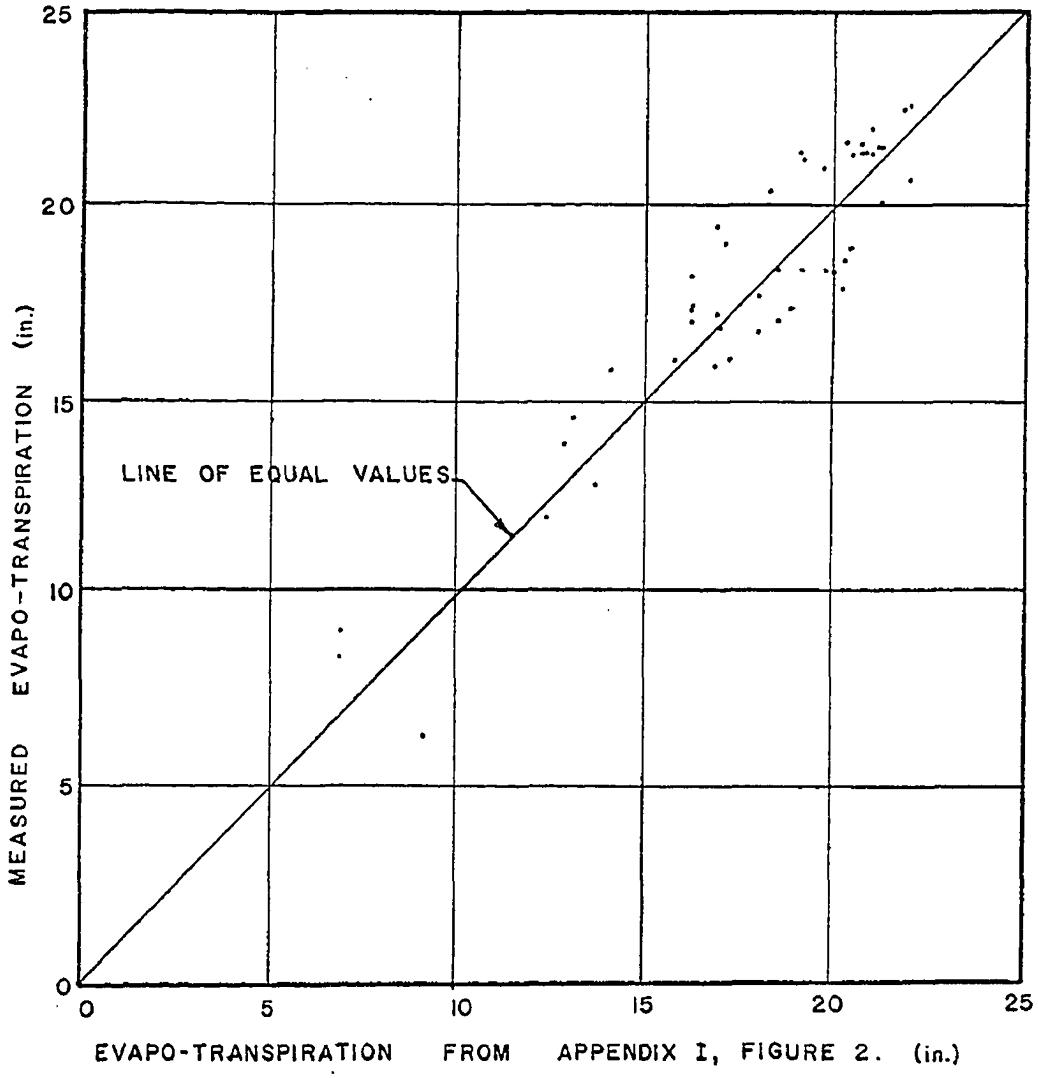
RIVER ------------------

STATION NO. ------------

DRAINAGE AREA (SQ. MI.) ----

YEAR	RUNOFF (in.)	PRECIP. (in.)	LOSSES (in.)	T_w (°F)			
1954-55							
1955-56							
1956-57							
1957-58							
1958-59							
1959-60							
1960-61							
1961-62							

Figure 5 Comparison of computed and estimated average annual evapo-transpiration losses.



APPENDIX II

METHODS OF ESTIMATING POTENTIAL EVAPO-TRANSPIRATION

Potential evapo-transpiration is that which will occur when the supply of moisture is not limiting.

Many methods have been developed to estimate potential evapo-transpiration. In the following, seven of the more common methods are used to estimate the potential evapo-transpiration for the drainage basin above station $2GE_3$ on the Thames River in southwestern Ontario. Appendix II, figure 1, shows the basin outline and locates the principal climatological stations used in the study. The latitude is taken as 43°N. for use in the computations.

(i) Lowry-Johnson Method(11)(12)

This method is used to estimate consumptive use for agriculture based on a linear relationship between "Effective heat" (the accumulation, in day degrees, of maximum daily growing season temperature above 32°F.) and consumptive use.

The approximate relationship $U = 0.8 + 0.156\ F$ is used where

U = Consumptive use in acre-feet per acre.

F = Effective heat in thousands of day degrees.

The mean(13) annual maximum temperature at London, Ontario, is about 54°F. Thus, the effective heat would be $(54-32)365 = 8030°F$. Therefore, the average consumptive use for the basin is

$$\begin{aligned} U &= 0.8 + 0.156\ (8.030) \\ &= 2.053 \text{ feet} \\ &= 24.64 \text{ inches} \end{aligned}$$

(ii) Thornthwaite Method(11)(14)

Monthly values of heat index are related to monthly temperatures by the equation $i = (\frac{t}{5})^{1.514}$ where t is the monthly temperature in ^{o}C. This relationship is used to determine the seasonal heat index value I shown in Appendix II, Table 2. This value of 36.31 was plotted on the nomograph of Appendix II, figure 2. A straight line drawn from the "Index point" through this "Heat index point" gives the relationship between temperature and evapo-transpiration for the basin. The uncorrected potential evapo-transpiration (e) is listed in fifth column of Table 2. This potential is corrected for sunlight and days of the month from Appendix II, Table 1, using a latitude of approximately 43^{o}N. The corrected value of E_t is them listed in the seventh column of Appendix II, Table 2, and the total for the year is found to be 61.53 cm. or 24.19 inches.

(iii) Blaney - Criddle Method(11)(15)

The Blaney-Criddle method correlates measured consumptive use of water data with monthly temperatures (t), monthly percentage of day-time hours (p), and the crop's growing period or irrigation season. The coefficients so developed for different crops (see Appendix II, Table 4) are used to translate or transpose consumptive use data from one location to others in which climatological data alone are available.

The equation used by Blaney-Criddle is:

$$U = K F$$

where U is the consumptive use of water by the crop in inches for any period

K is the empirical comsumptive use coefficient (see Appendix II, Table 4)

F is the sum of the monthly comsumptive use factors, $\frac{(t \times p)}{100}$

where t is mean monthly temperature in ^{o}F. and

p is the monthly percentage of day-time hours of the year (see Appendix II, Table 5, for values of p).

The average annual potential consumptive use for the Thames valley above station $2GE_3$ is computed in Appendix II, Table 3, to be 0.70 x 34.60 = 24.22 inches when using an average seasonal coefficient (K) of 0.70 for the 6 month growing period of May 1 to October 31.

(iv) Hargreaves Method(11)(16)

Consumptive use for a specific crop is assumed to vary with the consumptive use potential and can be expressed as:

$$U = K E = \sum k e$$

in which U is the consumptive use of a crop for a given period; E is the sum of the monthly evaporation for the period; and K is an empirical coefficient depending upon the individual crop grown. Monthly values of evaporation and crop coefficients are represented by e and k respectively where e is estimated by the equation

$$e = d\,(0.38 - 0.0038\,h)(t-32)$$

in which d is the monthly day-time coefficient (see Appendix II, Table 7) dependent upon latitude; h is the mean monthly relative humidity at noon(17); and t is the mean monthly temperature in ^{o}F.

Computations of consumptive use by Hargreaves method are illustrated in Appendix II, Table 6, using monthly values of k for alfalfa from Appendix II, Table 8. Total yearly losses by this method are estimated to be 23.83 inches.

(v) Penman Method(11)(5)

The following three formulas are used by Penman in estimating evapo-transpiration:

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

2. $E_a = 0.35\,(e_a - e_d)(1 + 0.0098\ \mu_2)$

3. $E_T = \dfrac{\Delta H - 0.27\ E_a}{\Delta - 0.27}$

where:

H = Daily heat budget at surface in mm. H_2O/day

R_A = Mean monthly extra terrestrial radiation in mm. H_2O/day

r = Reflection coefficient of surface

n = Actual duration of bright sunshine

N = Maximum possible duration of bright sunshine

σ = Boltzman constant = 2.01×10^{-9} mm./day

σT_a^{4} = mm. H_2O/day (see Appendix II, Table 9)

e_d = Saturation vapour pressure at mean dew point (i.e. actual vapour pressure in the air) mm.Hg

E_a = Evaporation in (mm.) H_2O/day

$\Delta = \dfrac{d_{ea}}{dt}$ in mm. Hg/°F.

e_a = Saturation vapour pressure at mean air temperature in mm. H_g

μ_2 = Mean wind speed at 2 meters above the ground (miles/day). Windsmeasurements at other heights can be converted to 2 meters by use of the formula

$$\mu_2 = \mu_1 \times \left(\frac{\log 6.6}{\log h}\right)$$ where μ_1 is the measured wind speed in miles per day at height h in feet.

E_T = Evapo-transpiration in mm. H_2O/day

The computations for the Thames valley are shown in Appendix II, Table 11. From this computation, the annual potential evapotranspiration is shown to be 19.74 inches which appears to be somewhat low when compared with the other methods of estimating and with the actual measured evapo-transpiration of 20.71 inches.

(vi) Jensen and Haise Method(3)

Using an energy balance approach, this method correlates $\left(\frac{E_t}{R_s}\right)_p$ with T in the equation

$$\left(\frac{E_t}{R_s}\right)_p = 0.014\ T - 0.37$$

where E_t = potential evapo-transpiration, inches/day

R_s = solar radiation, inches/day

T = mean air temperature, $^\circ$F.

Where values of solar radiation are not recorded they may be estimated by the equation

$$R_s = R_{so}\ (0.35 + 0.61S)$$

where R_s = solar radiation under existing conditions

R_{so} = solar radiation on cloudless days, (see Appendix II, Table 13)

S = fraction of possible sunshine for time period.

An example of this method is given in Appendix II, Table 12, for the Thames River, Ontario. The mean annual evapo-transpiration is computed to be 29.65 inches.

(vii) Hamon Method(18)

Hamon has formulated a simple computational procedure whereby average daily potential evapo-transpiration is represented as proportional to the product of day-time hours squared and the saturated water vapour concentration at the mean temperature. The day-time factor was determined from a consideration of the disparity between net radiation and temperature, latitudinally, and the fact that transpiration is restricted during darkness since the leaf stomata are closed.

The expression for average potential evapo-transpiration is:

$$P.E. = C\,D^2\,P_t$$

in which P.E. represents the average potential evapo-transpiration in inches per day; D is the possible hours of sunshine in units of 12 hours (see Appendix II, Table 1); P_t is the saturated water vapour density at the daily mean temperature in grams per cubic meter, times 10^{-2} (see Appendix II, figure 5); and C = 0.55

Appendix II, Table 14, illustrates the use of this method for estimating potential evapo-transpiration in the Thames River valley above station $2GE_3$. The total yearly value is estimated to be 22.01 inches.

SUMMARY

Since (11) it is impractical to measure consumptive water requirements of crops under all conditions of climate, soil, water supply, and management practice at all locations, various methods have been devised, utilizing climatic factors to estimate evapo-transpiration under a given set of conditions. The methods outlined in this appendix are in general agreement with each other except for the Penman method which tends to give a low value for potential evapo-transpiration.

METHOD	ANNUAL AVERAGE POTENTIAL EVAPO-TRANS.
(i) Lowry-Johnson	24.64 inches
(ii) Thornthwaite	24.19 inches
(iii) Blaney-Criddle	24.22 inches
(iv) Hargreaves	23.83 inches
(v) Penman	19.74 inches
(vi) Jensen and Haise	29.65 inches
(vii) Hamon	22.01 inches

Actual Measured Losses = 20.71 inches

Estimates of potential evapo-transpiration are becoming vitally important in many parts of Canada and particularly in the Prairie Provinces where many large scale irrigation projects are being developed. Methods such as those outlined in Appendix II are useful in predicting the amount of evapo-transpiration on irrigated land before the irrigation project is actually undertaken.

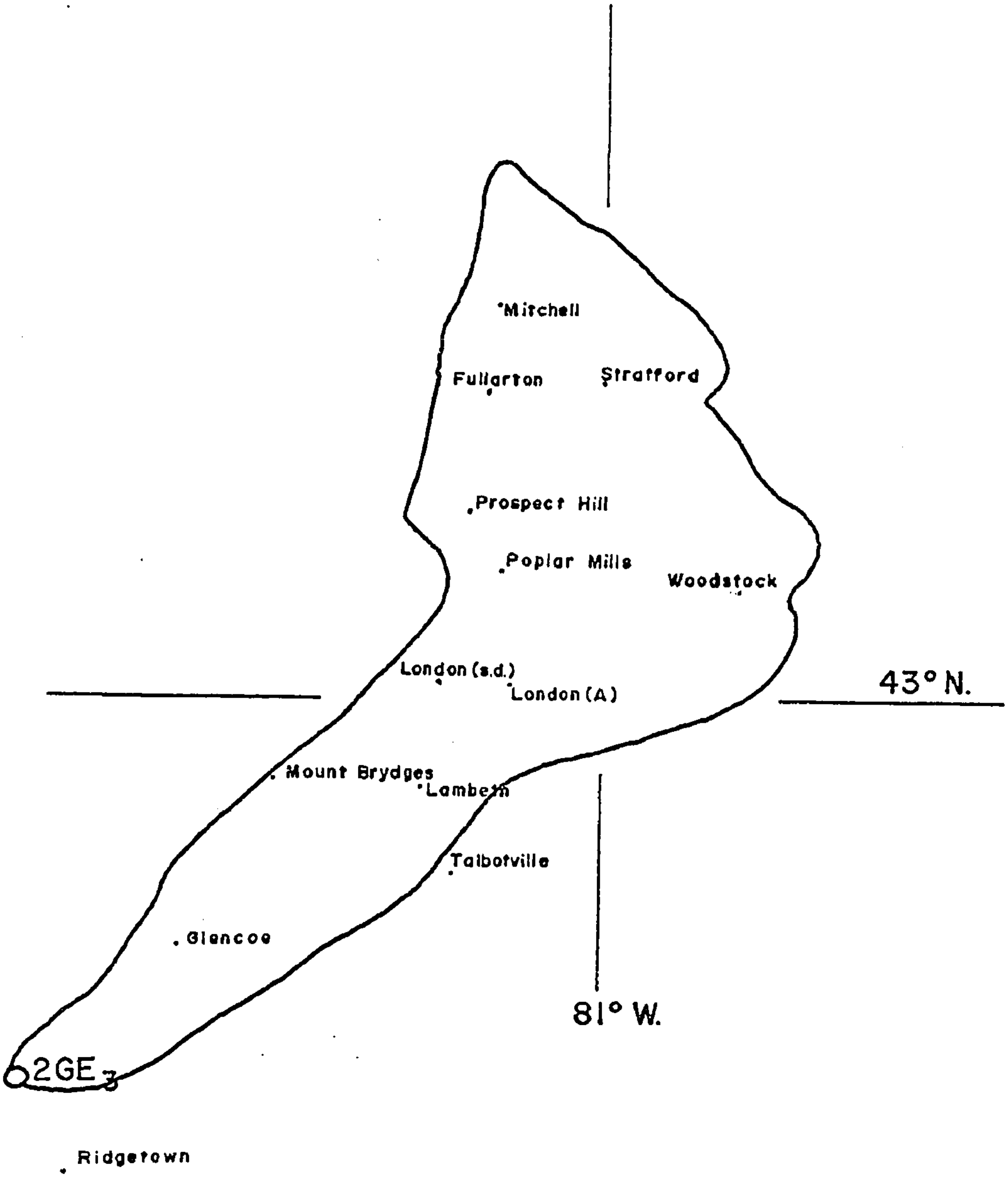


FIGURE I THAMES RIVER BASIN ABOVE STATION $2GE_3$

Figure 2 Nomograph for computing monthly evapo-transpiration. (Thornthwaite Method)

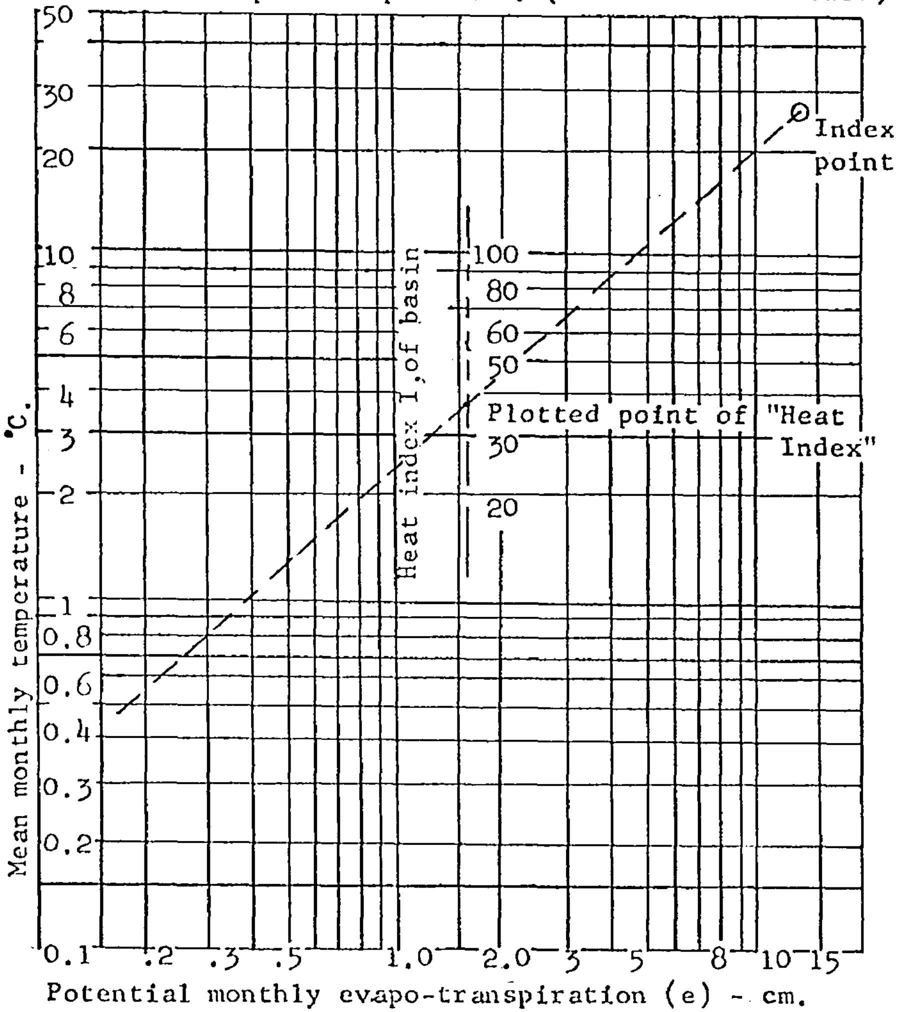


TABLE 1

Mean possible duration of sunlight in the northern and southern hemispheres expressed in units of 30 days of 12 hours each.

N. Lat.	J	F	M	A	M	J	J	A	S	O	N	D
0	1.04	.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10	1.00	.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	.98	.99
20	.95	.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	.93	.94
30	.90	.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	.98	.89	.88
35	.87	.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	.97	.86	.85
40	.84	.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	.96	.83	.81
45	.80	.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04	.94	.79	.75
50	.74	.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	.92	.76	.70

TABLE 2 Calculations (Thornthwaite Method)

Month	Temperature °F.	°C.	Heat Index	(e) (cm.)	Sunlight Coeff.	E_t (cm.)
J	19.7	-6.8	—	—	—	—
F	22.4	-5.3	—	—	—	—
M	29.0	-1.7	—	—	—	—
A	43.5	6.4	1.45	2.9	1.14	3.31
M	53.4	11.9	3.71	5.6	1.31	7.34
J	63.3	17.4	6.30	8.6	1.33	11.44
J	67.9	19.9	8.05	10.0	1.35	13.50
A	67.5	19.7	8.00	10.0	1.23	12.30
S	60.9	16.1	5.60	8.0	1.05	8.40
O	49.7	9.8	2.76	4.6	0.93	4.28
N	37.2	2.9	0.44	1.3	0.77	0.96
D	25.0	-3.9	—	—	—	—
			TOTAL =36.31			TOTAL =61.53 cm. =24.19 in.

TABLE 3 Calculations (Blaney-Criddle Method)

Month	% Daytime hours (p)	Temperature (t)°F.	$f = \frac{txp}{100}$
J	6.55	19.7	–
F	6.63	22.4	–
M	8.30	29.0	–
A	9.03	43.5	–
M	10.20	53.4	5.45
J	10.30	63.3	6.52
J	10.42	67.9	7.08
A	9.66	67.5	6.52
S	8.41	60.9	5.12
O	7.66	49.7	3.81
N	6.55	37.2	–
D	6.30	25.0	–

TOTAL =34.60

TABLE 4 Normal seasonal consumptive-use coefficients.

Item	Length of growing season or period	Consumptive use coefficients Seasonal (K)	Maximum Monthly 1/ (k)
Alfalfa	frost-free	0.85	0.95 – 1.25
Beans	3 months	0.65	0.75 – 0.85
Corn	4 months	0.75	0.80 – 1.20
Cotton	7 months	0.70	0.75 – 1.10
Citrus orchard	7 months	0.60	0.65 – 0.75
Deciduous orchard	frost-free	0.65	0.70 – 0.95
Pasture, grass, hay annuals	frost-free	0.75	0.85 – 1.15
Potatoes	3 months	0.70	0.85 – 1.00
Rice	3 to 4 months	1.00	1.10 – 1.30
Small grains	3 months	0.75	0.85 – 1.00
Sorghum	5 months	0.70	0.85 – 1.10
Sugar beets	5½ months	0.70	0.85 – 1.00

1/ Dependent upon mean monthly temperature and stage of growth of crop.

TABLE 5 Monthly percentage of daytime hours of the year.

	Latitudes in Degrees North of Equator													
Month	24	26	28	30	32	34	36	38	40	42	44	46	48	50
January	7.58	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17	5.98
February	7.17	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42	6.32
March	8.40	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27	8.25
April	8.60	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18	9.25
May	9.30	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53	10.69
June	9.20	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71	10.93
July	9.41	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80	10.99
August	9.05	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89	10.00
September	8.31	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44	8.44
October	8.09	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51	7.43
November	7.43	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22	6.07
December	7.46	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86	5.65
Annual	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 6

Calculations (Hargreaves Method)

Month	Temperature °F.	Humidity (h) %	(c) ☆	(d)	e	(k)	(ke) (in.)
J	19.7	82	0.08	0.79	–	–	–
F	22.4	79	0.10	0.80	–	–	–
M	29.0	70	0.13	1.00	–	–	–
A	43.5	61	0.17	1.09	2.13	0.70	1.49
M	53.4	61	0.17	1.22	4.44	0.64	2.84
J	63.3	61	0.17	1.24	6.60	0.67	4.42
J	67.9	58	0.18	1.25	8.08	0.74	5.98
A	67.5	58	0.18	1.16	7.41	0.67	4.96
S	60.9	62	0.16	1.01	4.67	0.64	2.99
O	49.7	65	0.15	0.92	2.44	0.40	0.98
N	37.2	77	0.10	0.78	0.41	0.41	0.17
D	25.0	80	0.09	0.76	–	–	–

☆ $C = 0.38 - 0.0038h$

TOTAL = 23.83 in.

TABLE 7

Calculated monthly daytime coefficients, (d) for Hargreaves Formula.

North Latitude in Degrees	January	February	March	April	May	June	July	August	September	October	November	December
5	1.01	0.91	1.02	0.99	1.03	1.00	1.03	1.03	0.98	1.02	0.98	1.00
10	0.98	0.89	1.02	1.01	1.05	1.03	1.06	1.05	0.99	1.00	0.95	0.97
15	0.96	0.88	1.01	1.01	1.08	1.06	1.08	1.06	0.99	0.99	0.93	0.95
20	0.93	0.87	1.01	1.02	1.10	1.08	1.11	1.08	0.99	0.98	0.91	0.92
25	0.91	0.86	1.01	1.03	1.12	1.11	1.13	1.09	1.00	0.97	0.89	0.89
30	0.88	0.84	1.00	1.05	1.14	1.14	1.16	1.11	1.00	0.96	0.86	0.86
35	0.85	0.83	1.00	1.06	1.17	1.17	1.19	1.12	1.00	0.94	0.84	0.82
40	0.81	0.81	1.00	1.08	1.20	1.21	1.23	1.14	1.01	0.93	0.81	0.78
45	0.77	0.79	0.99	1.09	1.24	1.26	1.27	1.17	1.01	0.91	0.77	0.74
50	0.72	0.76	0.99	1.11	1.28	1.32	1.32	1.20	1.01	0.89	0.73	0.68

TABLE 8

Consumptive-use coefficients for use in the Hargreaves Formula.

	MONTHLY CONSUMPTIVE USE COEFFICIENTS "k" a/									
CROP	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	SEASONAL COEFFICIENT "k"
Alfalfa	0.41	0.70	0.64	0.67	0.74	0.67	0.64	0.40	0.41	0.59
Almonds	0.16	0.36	0.34	0.52	0.48	0.34	0.29	0.48	0.21	0.36
Asparagus	0.16	0.11	0.12	0.18	0.46	0.81	0.84	0.99	0.51	0.46
Beans (Lima				0.41	0.51	0.61	0.32			0.46
Beans				0.15	0.28	0.66	0.51			0.40
Cantaloupes			0.24	0.31	0.37	0.61	0.38			0.48
Carrots	0.16	0.18	0.19	0.52	0.64	0.28				0.33
Celery				0.15	0.14	0.25	0.45	0.70	0.85	0.42
Citrus	0.41	0.36	0.44	0.43	0.44	0.41	0.41	0.64	0.41	0.44
Corn				0.12	0.38	0.42	0.26	0.10		0.26
Fruit (deciduous)	0.14	0.45	0.49	0.74	0.71	0.55	0.43	0.36		0.48
Grain sorghums			0.07	0.30	0.39	0.30	0.15			0.24
Grain and Hay	0.50	0.75	0.58	0.12						0.49
Grapes (Muscat)		0.13	0.24	0.26	0.31	0.26	0.26	0.18		0.23
Hops		0.07	0.12	0.31	0.61	0.61	0.38			0.35
Ladino Clover	0.50	0.81	0.55	0.77	0.83	0.76	0.70	0.44		0.67
Onions (early)	0.28	0.45	0.30							0.34
Onions (late)	0.28	0.45	0.30	0.31	0.28					0.32
Pasture	0.11	0.25	0.29	0.33	0.31	0.32	0.32	0.22	0.14	0.25
Peaches	0.22	0.45	0.43	0.46	0.51	0.51	0.38	0.60	0.41	0.44
Peas	0.28	0.36	0.49	0.31						0.36
Potatoes (early)	0.55	0.72	0.73	0.62						0.66
Prunes	0.17	0.34	0.34	0.50	0.48	0.32	0.42	0.48	0.24	0.37
Rice		0.32	1.34	1.42	1.40	1.44	0.51			1.07
Sudan Grass			0.24	0.33	0.37	0.35	0.28	0.24		0.30
Sugar Beets	0.19	0.27	0.55	0.87	0.69	0.36	0.15	0.10	0.03	0.36
Tomatoes				0.32	0.41	0.71	0167	0.81		0.58
Walnuts		0.36	0.43	0.57	0.67	0.63	0.26	0.36	0.24	0.44
Watermelons				0.15	0.18	0.25	0.51			0.27

a/ Based upon consumptive use date for Davis, California, published in "Suggested Subject Matter for Presentation at Irrigation Meetings" by L. J.Booher, 1948, College of Agricultural Extension Service, Davis, California.

TABLE 9

Values of σT_a^4 for various temperatures when computing evapo-transpiration by Penman method.

Temperature	σT_a^4	Temperature	σT_a^4
° Abs.	mm H_2O/ day	°F.	mm H_2O/day
270	10.73	35	11.48
275	11.51	40	11.96
280	12.40	45	12.45
285	13.20	50	12.94
290	14.26	55	13.45
295	15.30	60	13.96
300	16.34	65	14.52
305	17.46	70	15.10
310	18.60	75	15.65
315	19.85	80	16.25
320	21.15	85	16.85
325	22.50	90	17.46
		95	18.10
		100	18.80

Note: Heat of vaporization was assumed to be constant at 590 cal./gm of H_2O.

TABLE 10

Mid monthly intensity of solar radiation (R_A) on a horizontal surface in m.m. of water evaporated per day. 1/

	Northern Hemisphere										Southern Hemisphere								
	90°	80°	70°	60°	50°	40°	30°	20°	10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Jan.	—	—	—	1.3	3.6	6.0	8.5	10.8	12.8	14.5	15.8	16.8	17.3	17.3	17.1	16.6	16.5	17.3	17.6
Feb.	—	—	1.1	3.5	5.9	8.3	10.5	12.3	13.9	15.0	15.7	16.0	15.8	15.2	14.1	12.7	11.2	10.5	10.7
Mar.	—	1.8	4.3	6.8	9.1	11.0	12.7	13.9	14.8	15.2	15.1	14.6	13.6	12.2	10.5	8.4	6.1	3.6	1.9
Apr.	7.9	7.8	9.1	11.1	12.7	13.9	14.8	15.2	15.2	14.7	13.8	12.5	10.8	8.8	6.6	4.3	1.9	—	—
May	14.9	14.6	13.6	14.6	15.4	15.9	16.0	15.7	15.0	13.9	12.4	10.7	8.7	6.4	4.1	1.9	0.1	—	—
June	18.1	17.8	17.0	16.5	16.7	16.7	16.5	15.8	14.8	13.4	11.6	9.6	7.4	5.1	2.8	0.8	—	—	—
July	16.8	16.5	15.8	15.7	16.1	16.3	16.2	15.7	14.8	13.5	11.9	10.0	7.8	5.6	3.3	1.2	—	—	—
Aug.	11.2	10.6	11.4	12.7	13.9	14.8	15.3	15.3	15.0	14.2	13.0	11.5	9.6	7.5	5.2	2.9	0.8	—	—
Sept.	2.6	4.0	6.8	8.5	10.5	12.2	13.5	14.4	14.9	14.9	14.4	13.5	12.1	10.5	8.5	6.2	3.8	1.3	—
Oct.	—	0.2	2.4	4.7	7.1	9.3	11.3	12.9	14.1	15.0	15.3	15.3	14.8	13.8	12.5	10.7	8.8	7.1	7.0
Nov.	—	—	0.1	1.9	4.3	6.7	9.1	11.2	13.1	14.6	15.7	16.4	16.7	16.5	16.0	15.2	14.5	15.0	15.3
Dec.	—	—	—	0.9	3.0	5.5	7.9	10.3	12.4	14.3	15.8	16.9	17.6	17.8	17.8	17.5	18.1	18.9	19.3

1/ Computed from "Manual of Meteorology" by Napier Shaw, Vol. II, Comparative Meteorology, 2nd Edition, Cambridge University Press, 1936, pp. 4 and 5.

Note: Values from the table by Shaw multiplied by 0.86 and divided by 59 gives the radiation in mm. of water per day.

Figure 3 Temperature VS. Saturated Vapor Pressure.

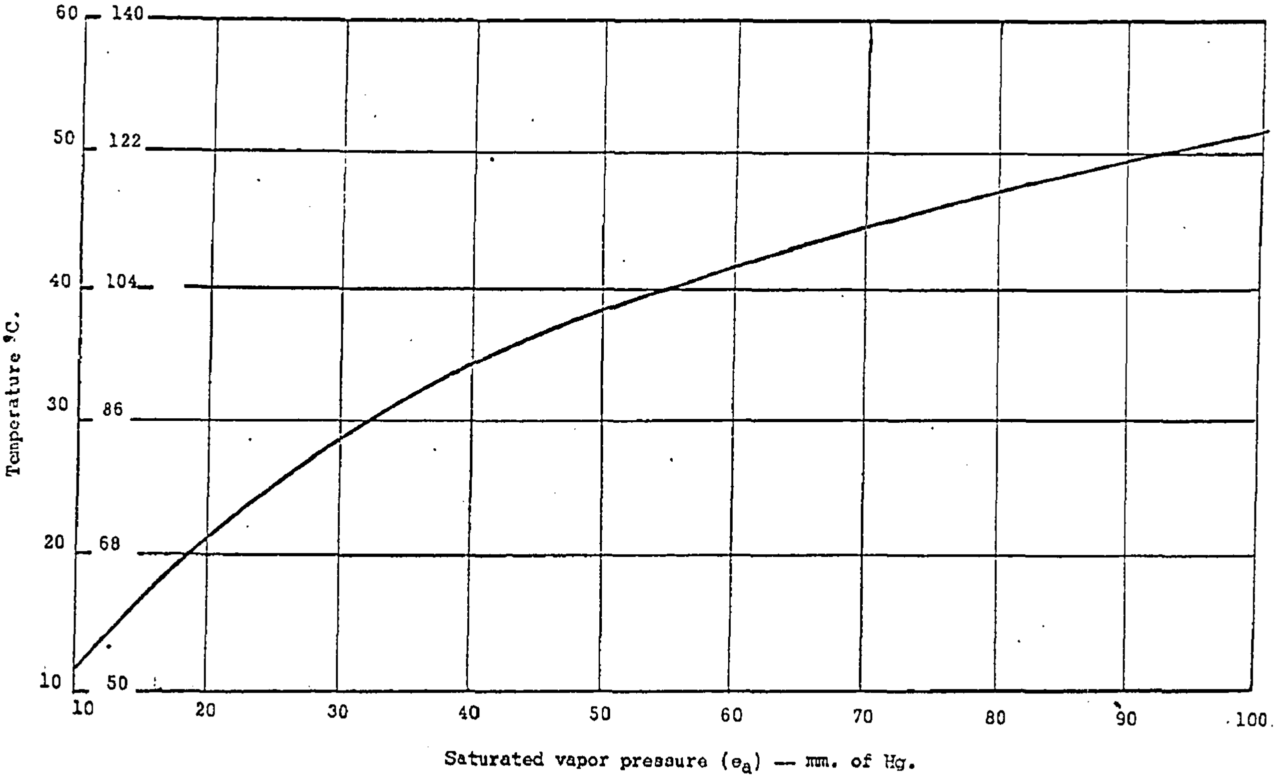


Figure 4 Temperature vs. $\Delta\left(\frac{\text{d Saturation Vapor Pressure, m.m. Hg}}{\text{d Temperature, °F.}}\right)$ for use with Penman's method for calculating evapo-transpiration.

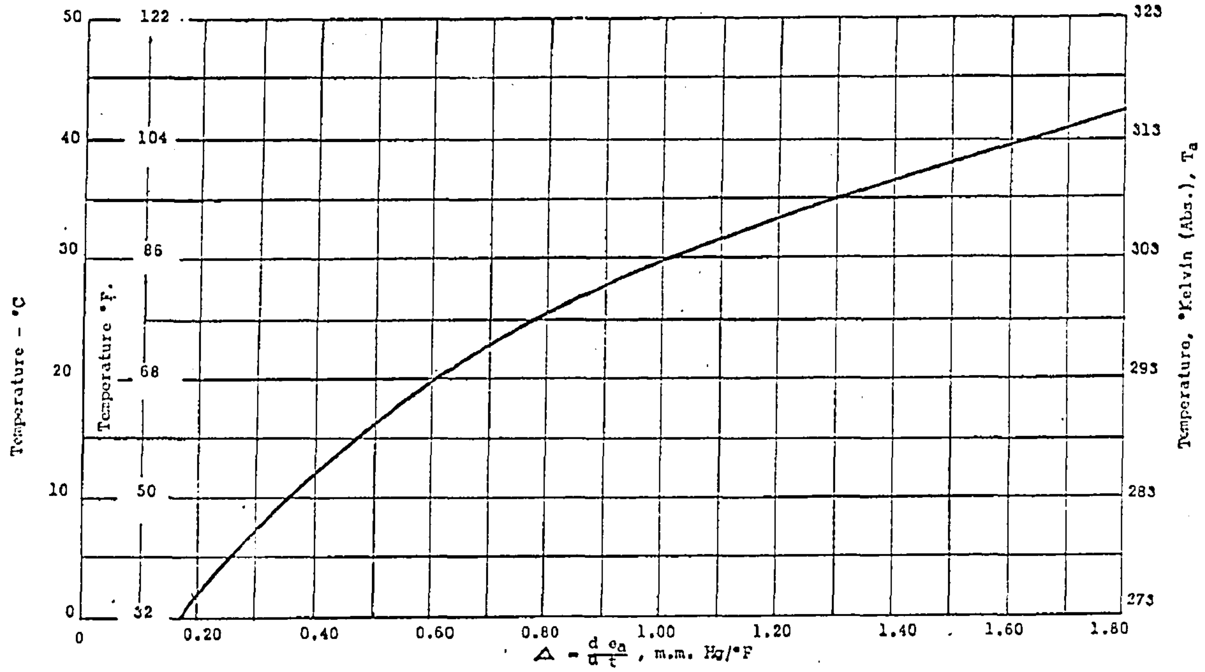


Table 11 Calculation sheet for Penman method of computing evapo-transpiration

Location: Thames River, Ontario. Latitude 43°N. Crop: Alfalfa

A. DATA:	A	M	J	J	A	S	O
1. Air Temp.-°F.	43.5	53.4	63.3	67.9	67.5	60.9	49.7
2. Relative Humidity - %(Est.)[17]	74	73	75	73	75	78	81
3. Sunshine n/N - %(Est.)(10)(13)	41	48	56	61	56	49	42
4. Windspeed, μ_2 - Mi/day at 2 m.(Est.)[17]	133	110	97	84	81	96	100
5. Radiation rate, R_A - mm. H_2O/day (see Appendix II, Table 13)	13.5	15.7	16.7	16.2	14.5	11.7	8.6
6. Reflection coefficient - %(Est.)	25	25	25	25	25	25	25
B. SOLVING EXPRESSION: $R_A(1 - r)(0.18 + 0.55\ n/N)$							
7. $(1 - r)$	0.75	0.75	0.75	0.75	0.75	0.75	0.75
8. $(0.18 + 0.55\ n/N)$	0.41	0.44	0.49	0.52	0.49	0.45	0.41
9. Item 5 x item 7 x item 8	4.15	5.18	6.14	6.32	5.33	3.95	2.64
C. SOLVING EXPRESSION: $T_a^4(0.56 - 0.092\sqrt{e_d})(0.10 + 0.90\ n/N)$							
10. Vapour pressure							
(a) Saturated, e_a (See Appendix II, Fig.3)	-	11.0	16.0	18.5	18.0	14.5	8.0
(b) Actual $e_d = (R.H. \times e_a)$	-	8.0	12.0	13.5	13.5	11.3	6.5
(c) $\sqrt{e_d}$	-	2.8	3.5	3.7	3.7	3.4	2.5
11. σT_a^4 (See Appendix II, Table 9)	12.30	13.28	14.31	14.86	14.80	14.00	12.90
12. $(0.56 - 0.092\sqrt{e_d})$	0.56	0.30	0.24	0.22	0.22	0.25	0.33
13. $(0.10 + 0.90\ n/N)$	0.47	0.53	0.60	0.65	0.60	0.54	0.48
14. Item 11 x item 12 x item 13	3.24	2.11	2.06	2.12	1.95	1.89	2.04
D. SOLVING FOR H							
15. Item 9 minus item 14	0.91	3.07	4.08	4.20	3.38	2.06	0.60

TABLE 11 (continued)

	A	M	J	J	A	S	O	
E. SOLVING FOR								
$E_a = 0.35\,(e_a - e_d)\,(1 + 0.0098\,\mu_2)$								
16. $0.35\,(e_a - e_d)$	-	1.05	1.40	1.75	1.58	1.12	0.05	
17. $(1 + 0.0098\,\mu_2)$	2.30	2.08	1.95	1.82	1.79	1.94	1.98	
18. Item 16 x item 17	-	2.18	2.73	3.19	2.83	2.17	0.10	
F. SOLVING FOR $E_T = \dfrac{\Delta H + 0.27\,E_a}{\Delta + 0.27}$								
19. Δ (see Appendix II, Fig. 4)	0.24	0.39	0.53	0.59	0.58	0.30	0.35	
20. ΔH	0.22	1.20	2.16	2.48	1.96	0.62	0.21	
21. $0.27\,E_a$	-	0.59	0.74	0.86	0.76	0.59	0.03	
22. $\Delta + 0.27$	0.51	0.66	0.80	0.86	0.85	0.57	0.62	
23. E_T = (mm. of water per day)	0.43	2.71	3.63	3.88	3.20	2.12	0.39	Annual Total
(in. of water per day)	0.017	0.107	0.143	0.153	0.126	0.083	0.015	
(in. of water per month)	0.51	3.31	4.29	4.74	3.91	2.50	0.48	19.74

TABLE 12

Calculations (Jensen and Haise Method)

Month	R_{so}	S a/	R_s	$\left(\frac{E_t}{R_s}\right)$	T (°F.)	E_t (in.)
J	5.0	.23	2.45	–	19.7	–
F	6.9	.31	3.73	–	22.4	–
M	10.9	.34	6.10	.036	29.0	0.22
A	12.9	.41	7.74	.239	43.5	1.85
M	15.2	.48	9.73	.378	53.4	3.68
J	15.6	.56	10.76	.516	63.3	5.55
J	15.5	.61	11.16	.581	67.9	6.48
A	14.3	.56	9.87	.575	67.5	5.68
S	12.0	.49	7.80	.483	60.9	3.77
O	9.4	.42	5.73	.326	49.7	1.87
N	7.1	.27	3.62	.151	37.2	0.55
D	5.7	.20	2.68	–	25.0	–

a/ calculated from reference (10) and (13) for Woodstock, Ontario.

TABLE 13

Total solar and sky radiation for cloudless skies (calculated from Budyko, 1956, Table 1) expressed in inches evaporation equivalent (1 gram water = 590 calories).

Latitude ° N	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60	1.1	2.6	6.4	10.3	13.9	14.9	14.4	10.9	7.0	4.1	1.7	0.8
55	2.0	3.7	7.7	11.1	14.3	15.1	14.7	11.8	8.2	5.1	2.7	1.5
50	3.1	5.0	9.0	11.9	14.7	15.3	15.0	12.5	9.5	6.4	3.9	2.5
45	4.4	6.3	10.3	12.7	15.1	15.5	15.3	13.4	10.7	7.7	5.1	3.8
40	5.8	7.7	11.3	13.3	15.3	15.7	15.5	14.1	11.7	8.9	6.5	5.1
35	7.2	9.1	12.3	14.0	15.3	15.7	15.5	14.5	12.5	10.1	7.9	6.4
30	8.5	10.1	13.0	14.4	15.3	15.7	15.5	14.8	13.2	11.0	9.1	7.6
25	9.5	11.0	13.5	14.5	15.3	15.6	15.4	14.9	13.7	11.7	10.0	8.7
20	10.3	11.7	13.9	14.5	15.1	15.3	15.1	14.8	14.0	12.3	10.9	9.7
15	11.1	12.2	14.0	14.4	14.7	14.8	14.7	14.5	14.1	12.8	11.5	10.5
10	11.6	12.7	14.0	14.2	14.1	14.1	14.1	14.1	14.1	13.1	12.0	11.1
5	12.0	13.0	13.9	13.9	13.6	13.2	13.4	13.7	13.9	13.3	12.4	11.5
0	12.3	13.2	13.6	13.5	12.8	12.0	12.5	13.1	13.6	13.3	12.7	12.0

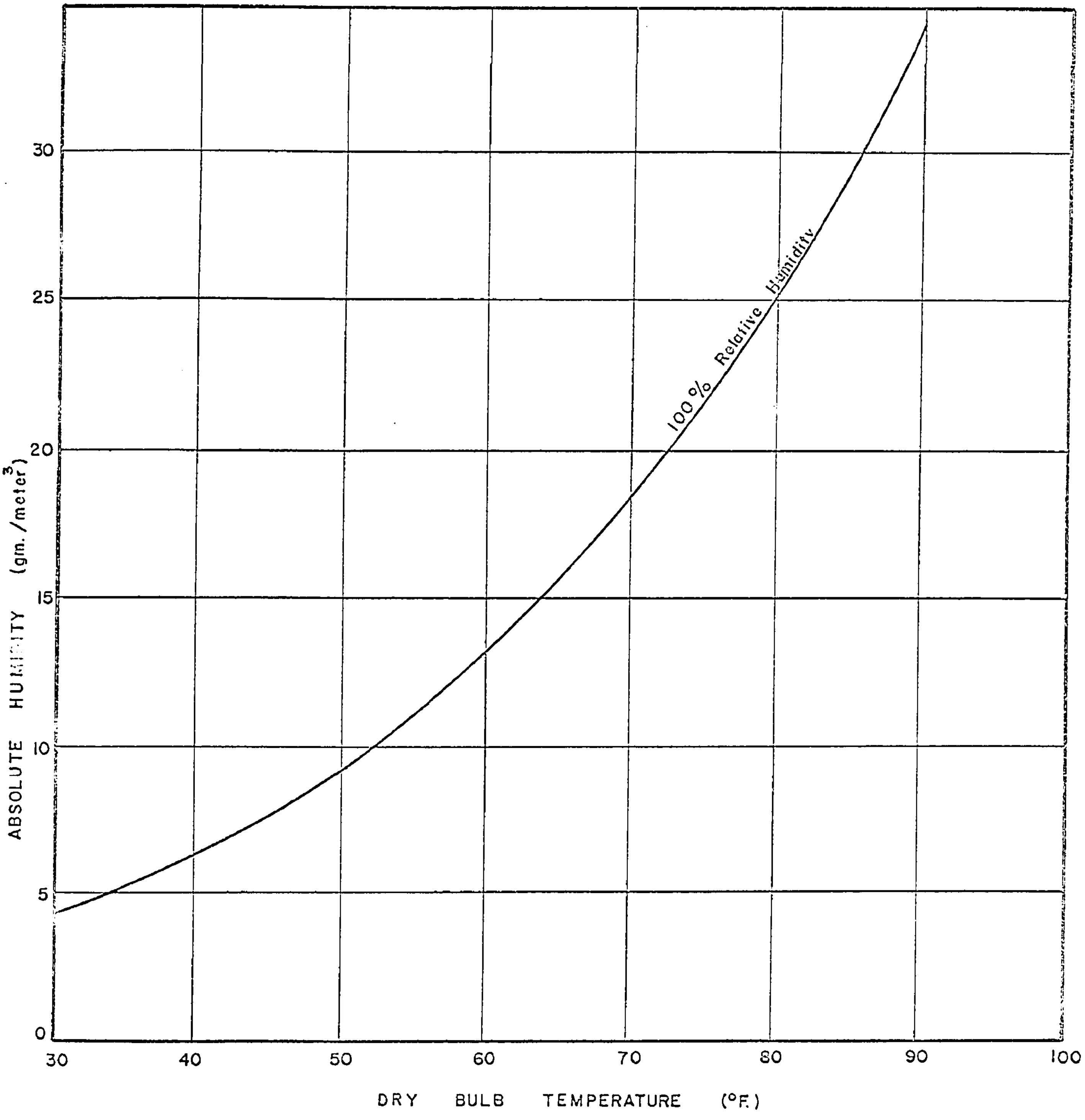
TABLE 14

Calculations (Hamon Method)

Month	D	No. of days in month.	T (^{o}F.)	P_t (gm./meter^3)	P.E. (in.)
J	0.82	31	19.7	—	—
F	0.82	28	22.4	—	—
M	1.02	31	29.0	—	—
A	1.12	30	43.5	.074	1.53
M	1.26	31	53.4	.105	2.85
J	1.27	30	63.3	.149	3.96
J	1.29	31	67.9	.174	4.94
A	1.20	31	67.5	.172	4.23
S	1.04	30	60.9	.137	2.44
O	0.95	31	49.7	.094	1.45
N	0.81	30	37.2	.057	0.61
D	0.78	31	25.0	—	—

TOTAL = 22.01 inches.

Fig. 5 Absolute Humidity vs. Dry Bulb Temperature.



NOTATION

A	cross-sectional area
C	empirical coefficient = 0.55 (Hamon method)
D	possible hours of sunshine (Hamon method)
d	monthly day-time coefficient (Hargreaves method)
e	monthly evaporation (Hargreaves method)
(e)	uncorrected potential evapo-transpiration (Thornthwaite method)
E_a	evaporation (Penman method)
E_t	evapo-transpiration or consumptive use
e_a	saturation vapour pressure at mean air temperature
e_d	saturation vapour pressure at mean dew point
F	effective heat in thousands of day degrees (Lowry-Johnson method)
F	sum of monthly consumptive use factors = $\sum \frac{t \times p}{100}$ (Blaney-Criddle method)
H	daily heat budget at surface (Penman method)
h	mean monthly relative humidity at noon (Hargreaves method)

i	heat index
K	empirical seasonal consumptive use coefficient (Blaney-Criddle and Hargreaves method)
k	monthly crop coefficient (Hargreaves method)
L	water losses
N	maximum possible duration of bright sunshine
n	actual duration of bright sunshine
P	total precipitation for the month
P.E.	average potential evapo-transpiration (Hamon method)
P_t	saturated water vapour·weight density
p	monthly percentage of day-time hours of the year (Blaney-Criddle method)
Q	$= V A$ = streamflow
R_A	mean monthly extra terrestrial radiation (Penman method)
R_s	solar radiation under existing conditions (Jensen and Haise method)
R_{so}	solar radiation on cloudless days (Jensen and Haise method)
r	reflection coefficient of surface

S	fraction of possible sunshine for time period
ΔS	change in storage
T, t	mean monthly air temperature
T_w	$= \frac{\Sigma (T \times P)}{\Sigma P}$ = mean annual weighted temperature
T_a	absolute temperature
U	potential evapo-transpiration or consumptive use
μ_1	mean wind speed at any height
μ_2	mean wind speed at 2 meters
V	velocity
σ	Boltzman constant = 2.01×10^{-9} mm./day

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VITA AUCTORIS

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1944	In September, 1944, he entered S.S. No. 13, Public School in the Township of East Gwillumbury, York County, Ontario.
1951	In September, 1951, he enrolled at Newmarket District High School, Newmarket, Ontario, where he obtained his secondary education.
1957	In September, 1957, he enrolled at Queen's University, Kingston, Ontario, where he attended a course in Civil Engineering for one year.
1958	In September, 1958, he enrolled at Ontario Agriculture College, Guelph, Ontario, where he attended a course in Agricultural Engineering for three years.
1961	In September, 1961, he entered Essex College of Assumption University of Windsor in the Applied Science course.
1964	In May, 1964, he graduated from University of Windsor, with a B.A.Sc. in Civil Engineering and in September, he entered the course leading to M.A.Sc. in Civil Engineering at University of Windsor.