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Introduction

Irrigation is practised primarily to correct a defect in the distribution and amount of the natural rainfall of the climate of an area. It is common knowledge that the annual precipitation at Ottawa, 35 inches, is greater than the summertime evaporation of 19 inches. Unfortunately a large part of this precipitation occurs during the cooler months of the year when the evaporation rate is low. During the summertime, when evaporation rate is high, rainfall is often, but not always, inadequate for maximum crop production. This unfortunate distribution of precipitation is more or less general throughout the so-called humid climatic zone of Eastern Canada.

Since the need for irrigation depends upon climate it is only natural that the answer to many problems in connection with irrigation planning should be found through a study of climatic data. By the appropriate analysis of past records of temperature and rainfall, it is possible to answer such questions as the following:

1. How much reserve water is required to irrigate a given area?
2. How large a system is needed to irrigate a given field during the driest periods?
3. At what period throughout the summer is the water needed?

Besides using climatic data for planning an irrigation system, the use of daily weather data is helpful in determining when and how much water to apply throughout the season. When water is limited it is important that none be wasted and that it be applied at the right time before crops have begun to suffer. Even where water is abundant it is important to apply the correct amount. Too much water may leach plant foods from the root zone as well as produce a waterlogged condition, unfavorable for crop growth since it reduces soil aeration.

Water Holding Capacity of Soils

The maximum amount of water which a soil will hold without being waterlogged is termed field capacity. This is the water held in the small spaces between soil particles after excess water has drained from the larger pore spaces.

The minimum amount of soil moisture which is available to crops is known as the permanent wilting percentage. Should soil moisture fall below this amount the crop will sustain permanent injury from which it cannot recover.

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The amount of water contained by the soil between the field capacity percentage and the permanent wilting percentage is known as available water. The percentage water contained by various soils at field capacity and at the permanent wilting percentage is shown in Table 1. The actual available water in inches which is held in a 1-foot layer of various soil types is also shown. It will be noted that sandy soils with large pores hold less moisture than the finer clays having smaller pore spaces. This is because water readily drains out of the larger pores in the coarser soils, percolates downwards, and is lost to the roots of the crop.

Table 1 Average Field Capacity, Wilting Point, and Water Storage Capacity of Soils*

Soil Type	Field Capacity	Wilting Point	Normal Water Storage Capacity of 1 foot of soil
	Per cent	Per cent	inches
Sandy loam	10	3.5	1.0
Loam and Silt loam	18	7.0	1.5
Clay loam and silty clay loam	26	10.5	1.8
Clay	35	17.0	2.2

*Soil Research Laboratory, Swift Current:
"Soil moisture, wind erosion and fertility of some Canadian Prairie Soils"
Canada Department of Agriculture Pub. 819; 1949 with modifications.

Since different crops root to different depths, it is obvious that the total amount of soil moisture available to a crop depends both on the rooting depth and the soil type. It is the usual practice to put on irrigation when half of the soil moisture available to the crop has been used up. This is a good practical rule-of-thumb although there is evidence that maximum crop growth is achieved when the soil moisture is kept as near field capacity as possible.

The Concept of Soil Moisture Budget

The use of weather data in connection with irrigation requires acceptance of certain fundamental concepts in connection with the gain and loss of moisture by soil. Starting with a field under subhumid conditions in which the only source of water is that applied from above in the form of either rain or irrigation and the only loss is through evaporation from soil and transpiration from the crop, it is a simple matter to calculate day to day changes in the soil moisture content. In terms of the deficit of soil moisture below field capacity, the deficit at the end of to-day equals yesterday's deficit plus to-day's evaporation and transpiration minus to-day's rainfall and irrigation. In other words evaporation from soil and transpiration from plants use up water and so increase the soil moisture deficit.

Rainfall and irrigation add water and thus decrease the deficit, that is to say return the state of the soil moisture towards field capacity. The soil acts simply as a reservoir for the moisture.

Part of this soil moisture budget equation can be readily evaluated. Rainfall is easily measured and the amount of irrigation water applied to a crop can be determined. The other part, evaporation and transpiration, is more difficult to determine. There have been several systems developed for estimating this by calculation or indirect measurement. Thornthwaite (1) has developed the concept of potential evapotranspiration, which in effect postulates: the combined total daily rate of evaporation and transpiration from a given land area is independent of the crop and is determined solely by certain meteorological factors, provided that the crop is growing, completely covers the ground from aerial view, and has an adequate moisture supply.

The argument for this is: The conversion of water to water vapor requires about 590 calories of heat per gram of water, regardless of whether the water comes from the soil, plant cell, or possibly from droplets on the plant. Under field conditions the heat available for converting water to water vapor is that from direct solar and sky radiation and that conveyed to the crop from the surrounding air by turbulent flow. Since the amount of heat from these two sources is limited, there is a well-defined maximum rate of conversion of water to vapor which can take place under a given set of meteorological conditions. Hence the term ''potential''. ''Evapotranspiration'' expresses the combined processes of direct evaporation from soil plus transpiration from the crop.

There are three points to note in connection with this concept:

1. *Daily rate of use of water*: All crops do not use the same total amount of water. A short-season crop such as peas will use less total water than a long-season crop such as sugar beets, although the average daily rate of use will be nearly the same for the two crops.
2. *Adequate soil moisture*: It is not easy to define just what is meant by adequate moisture. Irrigation experts agree that the soil moisture content adequate for crop growth should not fall below 50 per cent of the total soil water available to the crop. There is evidence to indicate that optimum soil moisture is at or slightly above field capacity. It is reasonable to assume that vertical root distribution and porosity within the root zone both govern the actual amount of water available to a crop. Adequate moisture for a shallow-rooted crop on a sandy soil may be much different from that for a deep-rooted crop on a clay loam soil. It follows that the amount of moisture available to a shallow-rooted crop on a sandy soil will not last as many days as will the larger amount of water available to a deep-rooted crop on a clay soil. This is one of the main reasons for sandy soils being more droughty than clay soils.
3. *Crop completely covers the ground*: Since the combined processes of evaporation from the soil and transpiration from the crop affect soil water content, four conditions of plant cover and soil surface are considered:

(a) Soil surface wet; complete crop cover.

In this case the crop will intercept nearly all the heat from the sun and the wind and a maximum amount of this heat will be used in the transpiration process. Evaporation from the soil will be only a small fraction of the potential evapotranspiration.

(b) Soil surface wet; incomplete crop cover.

Here the crop will only intercept a fraction of the heat from the sun and wind. The remainder will be absorbed by the soil and used for evaporating surface soil water. The ratio of transpiration to total evapotranspiration will depend upon the fraction of the heat intercepted by the crop. As long as the soil surface is wet, the total of the evaporation and transpiration will equal the potential evapotranspiration.

(c) Soil surface dry; complete crop cover.

This case will not be much different from (a) above. Since the crop cover intercepts most of the heat, very little reaches the soil surface. Transpiration, which is the main process here, accounts for most of the potential evapotranspiration.

(d) Soil surface dry; incomplete plant cover.

Under these conditions the heat not intercepted by the crop falls on dry soil and since there is no moisture for evaporation the temperature of the soil rises. Transpiration from the crop will be proportional to the heat intercepted by leaves of the crop and will be less than the potential evapotranspiration.

Estimating Potential Evapotranspiration

Several methods have been suggested for estimating potential evapotranspiration. Probably the best known and simplest method is that of Thornthwaite (1), based on mean air temperature and daylength. This system is relatively simple and uses readily available information that has been recorded over the years by many climatological observing stations. One weakness of Thornthwaite's formula is that it does not take into account such important factors in the evapotranspiration process as sunshine, wind and vapor pressure.

Penman (2) at Rothamstead has developed a more complex equation which considers all these meteorological factors. Although this equation gives good estimates of potential evapotranspiration it is very cumbersome to use.

Several attempts have been made to obtain measurements of potential evapotranspiration, both direct and indirect. The direct method consists of enclosing a mass of soil in a tank to which water is added daily. Various means may be provided for measuring the water consumed daily by a crop growing in such a tank. This method has proved satisfactory for checking theories and formulae relative to potential evapotranspiration, but is too bulky and cumbersome for wide-scale use.

Several instruments for indirectly determining evapotranspiration have been used. Commonly used are: the 4-foot diameter open water tank, the Piché atmometer, the Livingston porous spherical bulb atmometer, the Wright and the Summerland evaporation pans and the black Bellani plate atmometer.

Actually these instruments measure only the drying ability of the air, not potential evapotranspiration. Tests conducted at the Central Experimental Farm indicate that the black Bellani plate atmometer is a superior instrument for measuring the drying ability of the air or, preferably, "latent evaporation"(3) (4).

The black Bellani plate atmometer is an inexpensive, flat, black, porous plate which is easily kept wet. The water evaporated from the black surface can be conveniently measured over periods as short as a few minutes or as long as several days. With the black plate fully exposed to sunshine and the free flow of the air, variations of latent evaporation agree very closely with variations of potential evapotranspiration as calculated by Penman's equation. In other words, the black Bellani plate atmometer appears to integrate the influence of the four meteorological factors: sunshine, wind, temperature and water vapor pressure, in much the same manner as does a crop.

Latent evaporation is not directly equivalent to potential evapotranspiration but can be converted by multiplying by a simple conversion factor. Measurements of latent evaporation are made in terms of the volume of water (expressed in cubic centimeters) evaporated from a standard black surface area. The conversion factor to change latent evaporation to potential evapotranspiration is about 0.0034 inches per cubic centimeter. This value is an average of several comparisons with free water evaporation, actual evapotranspiration measurements and data based on irrigation experience. It may have to be adjusted slightly as more comparative data are obtained.

Climatic Data and Irrigation Planning

A simple and powerful tool for determining irrigation requirements by using past climatological data is afforded by acceptance of the concept of potential evapotranspiration, and its application for the calculation of soil moisture deficit (5). Since there are long-term records of daily temperature and precipitation at numerous stations, climatological studies of the soil moisture budget are based on these factors only.

The soil moisture budget at Ottawa was studied using daily temperature and precipitation data for the past 66 years. It has been calculated for five different soil water storage capacities using machine tabulation analysis.

A summary of the data from this analysis is shown in Tables 2 to 7. Here are shown the supplemental water requirements for various months and the whole season assuming various storage capacities for various risks. The risk is shown as percentages and can be interpreted as the number of years in 100 that at most a certain amount of supplemental water will be required. For example, if the soil moisture storage capacity is 1 inch, Table 2 shows that the annual supplemental water requirement will exceed 10.8 inches only once in 10 years or 10 per cent of the time. In other words the risk of the supplemental water requirements exceeding 10.8 inches is only 10 chances in 100. In designing an irrigation system some farmers may be willing to take a greater risk and purchase less equipment. Furthermore, it may not be economical to obtain a sufficiently large irrigation system so that only a small risk of not having enough equipment need be taken.

Few crops need irrigation throughout the whole summer from April to October. When estimating equipment requirements for irrigating short-season crops it will be advantageous to use tables 3 to 7 which show the monthly supplemental water requirements for various soil moisture storage capacities and various risks.

During the peak of the dry weather, which normally occurs in July, a certain risk has to be assumed in not being able to irrigate all the land frequently enough. Table 9 can be used for determining this risk. It shows the risk taken by assuming that the daily supplemental water will not exceed a certain value. If, for example, certain equipment will irrigate the equivalent of .20 inch per day (e.g. 1 inch on 20 acres in 5 days at rate of 4 acre-inches per day) then the risk of not completing irrigation on the last field before the first needs more water is 17 1/2 per cent in July. Obviously more equipment and more water would be required to reduce this risk.

Table 2 Annual Supplemental Irrigation Requirement
(at Ottawa for various percentage risks assuming various soil moisture Storage capacities within root zone of crop)

Risk	Storage Capacity				
%	1″	2″	4″	6″	10″
			(Inches Supplemental Water)		
75	6.4	3.7	.7	–	–
50	7.9	5.8	3.1	.9	–
25	9.4	7.9	5.5	3.3	–
20	9.8	8.4	6.1	3.9	–
15	10.3	9.0	6.8	4.6	.7
10	10.8	9.7	7.7	5.4	1.5
5	11.6	10.8	9.0	6.7	2.7
1	13.2	12.9	11.4	9.1	5.1

Table 3 Monthly Supplemental Irrigation Requirements
(at Ottawa for various percentage risks assuming soil moisture storage capacity of one inch within root zone of crop)

Risk	May	June	July	Aug.	Sept.	Oct.
%			(Inches supplemental water)			
75	–	1.1	1.7	1.1	.3	–
50	.3	1.7	2.5	1.9	.8	–
25	1.2	2.3	3.4	2.8	1.3	.2
20	1.4	2.4	3.6	2.9	1.5	.3
15	1.6	2.6	3.8	3.2	1.6	.4
10	1.9	2.8	4.1	3.5	1.8	.5
5	2.3	3.2	4.6	3.9	2.1	.7
1	3.2	3.8	5.5	4.8	2.7	1.1

Table 4 Monthly Supplemental Irrigation Requirements
(at Ottawa for various percentage risks assuming soil moisture storage capacity of *two* inches within root zone of crop)

Risk	May	June	July	Aug.	Sept.	Oct.
%	(Inches of supplemental water)					
75	—	—	.8	.7	—	—
50	—	.6	1.7	1.6	.5	—
25	—	1.3	2.6	2.5	1.1	—
20	.1	1.5	2.8	2.7	1.3	.1
15	.4	1.7	3.1	3.0	1.4	.2
10	.7	2.0	3.4	3.3	1.7	.4
5	1.1	2.3	3.9	3.8	2.0	.6
1	2.0	3.0	4.8	4.7	2.6	1.1

Table 5 Monthly Supplemental Irrigation Requirements
(at Ottawa for various percentage risks assuming soil moisture storage capacity of *four* inches within root zone of crop)

Risk	May	June	July	Aug.	Sept.	Oct.
%	(Inches of supplemental water)					
75	—	—	.3	.3	—	—
50	—	—	.9	1.2	.2	—
25	—	.1	2.0	2.1	.9	—
20	—	.3	2.3	2.4	1.1	—
15	—	.5	2.6	2.5	1.3	.2
10	—	.8	3.0	3.0	1.6	.3
5	—	1.3	3.5	3.5	1.9	.6
1	—	2.2	4.6	4.4	2.6	1.0

Table 6 Monthly Supplemental Irrigation Requirements
(at Ottawa for various percentage risks assuming soil moisture storage capacity of *six* inches within root zone of crop)

Risk	May	June	July	Aug.	Sept.	Oct.
%	(Inches supplemental water)					
75	—	—	—	—	—	—
50	—	—	—	.7	—	—
25	—	—	.4	1.7	.8	—
20	—	—	.7	1.9	1.0	—
15	—	—	1.2	2.2	1.2	—
10	—	—	1.5	2.5	1.5	.2
5	—	—	2.1	3.0	1.9	.5
1	—	—	3.3	4.0	2.6	1.0

Table 7 Monthly Supplemental Irrigation Requirements
(at Ottawa for various percentage risks assuming soil moisture storage capacity of *ten* inches within root zone of crop)

Risk	May	June	July	Aug.	Sept.	Oct.
%			(Inches supplemental water)			
75	–	–	–	–	–	–
50	–	–	–	–	–	–
25	–	–	–	–	–	–
20	–	–	–	–	–	–
15	–	–	–	–	–	–
10	–	–	–	–	–	–
5	–	–	–	–	.8	–
1	–	–	–	1.5	2.5	.5

Table 8 Risk of July Daily Crop Water Requirements at Ottawa Exceeding a Specified Amount

Least Daily Water Requirement (inches)	Risk per cent (days in 100)
.10	99
.13	90
.15	75
.17	50
.19	25
.21	10
.24	1

Determining Actual Irrigation Requirements

Keeping a daily soil moisture budget is a quick and convenient means of determining the time of needed irrigation. When planning such a scheme it is necessary to predetermine the amount of stored soil moisture which is available to the crop. This amount depends upon the rooting depth of the crop and the water-holding capacity of the soil within the main root zone.

An experiment was conducted at Ottawa during the summer of 1955 to compare the timing of irrigation as indicated by the electrical resistance block method and by the meteorological budget method using evaporation measurements. The black Bellani plate was used for determining potential evapotranspiration. The assumed soil moisture storage capacity for both methods was 3 inches. Each time the storage dropped to half of this value, to 1 1/2 inches, 1 inch of irrigation water was applied. A ½-inch buffer was allowed in case rain occurred immediately following irrigation. Otherwise the soil might become saturated, a condition deleterious to growth.

Throughout the summer 15 inches of irrigation water were added to the soil using the electrical resistance moisture block method and 14 inches to the soil using the meteorological budget method. Considering that 11 inches of rain also fell on both plots, the difference in water received by the two methods was only about 4 per cent. The labor involved in keeping the meteorological budget was about 1/10 of that required for measuring moisture by the electrical resistance block method.

A sample soil moisture budget calculation is shown in Table 9. In this table "Deficit" is considered as the deficiency in stored soil moisture. In other words it is the amount of irrigation water required to bring the soil moisture to field capacity.

In calculating the budget it must be remembered that potential evapotranspiration is water used by the crop and tends to increase the deficit. Therefore P. E. values must be added to the deficit. On the other hand rain and irrigation replenish the soil moisture and decrease the deficit. If rain and irrigation exceed the deficit, there will be a surplus and this amount is entered in the surplus column. This either runs off or percolates to below the root zone and is lost to the crop.

By August 1st the soil moisture deficit had dropped to 2.17 inches. Irrigation was overdue. One inch was applied on the 2nd. The high rate of water use on the 2nd and 3rd, 0.25 and 0.23 inches respectively, increased the deficit to 1.65 inches by the end of the 3rd. Another inch of irrigation was applied on the 4th and together with 0.37 inches of rain this reduced the deficit to 0.45 inches. Sufficient rain fell thereafter to keep the deficit below 0.80 inches for several days. On the 13th, 0.89 inches of rain fell when the soil deficit was only 0.51 inches. Consequently there was a surplus which would either run off or percolate through to the subsoil and be lost to the crop roots. Following this heavy rain, the soil deficit increased as rains became lighter and less frequent. By the 26th it was obvious the deficit was going to be 1.50 inches so an inch of irrigation water was applied.

Conclusion

A little experience with this budget system will indicate its value in planning irrigation schedules. The average daily use of water by crops is about 0.15 to 0.20 inches. Furthermore, experience and the careful consideration of the daily weather forecast will help in estimating the amount of water the crops can be expected to use. For example, hot sunny weather with low humidity and some wind will be accompanied by high water use, probably 0.25 to 0.35 inches per day. On cloudy, humid, and cool days less will be used, probably 0.05 to 0.10 inches per day.

The meteorological budget method provides a systematic means for applying weather data and weather forecasts to the irrigation scheduling problem.

Table 9 Soil Moisture Budget

Ottawa August, 1955

Date	Latent Evaporation	Potential Evapotranspiration = L.E. X 0.0034	Rain	Irrigation	Soil Moisture Deficit	Soil Moisture Surplus
	c.c.	ins.	ins.	ins.	ins.	ins.
1					2.17	
2	74	.25		1.00	1.42	
3	67	.23			1.65	
4	50	.17	.37	1.00	.45	
5	40	.14	.08		.51	
6	53	.18	.40		.29	
7	43	.15			.44	
8	41	.14			.58	
9	64	.22			.80	
10	24	.08	.65		.23	
11	27	.09			.32	
12	57	.19			.51	
13	12	.04	.89		.00	.34
14	47	.16	.02		.14	
15	47	.16	.11		.19	
16	13	.04			.23	
17	28	.10			.33	
18	36	.12			.45	
19	58	.20			.65	
20	46	.16	.37		.44	
21	70	.24			.68	
22	49	.17			.85	
23	39	.13			.98	
24	48	.16			1.14	
25	44	.15			1.29	
26	46	.16			1.45	
27	56	.19	.02	1.00	.62	
28	46	.16			.78	
29	54	.18			.96	
30	26	.09	.37		.68	
31	60	.20			.88	

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