FREQUENCY OF OCCURRENCE OF EVAPORATION EXTREMES AS APPLIED TO THE DESIGN OF IRRIGATION SYSTEMS

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Currently, the practice followed in the design of irrigation systems is to calculate the irrigation interval based on an empirically-derived peak consumptive use rate applied to the amount of available water which can be stored in the crop root zone. In these calculations, it is assumed that the peak use rate will occur continuously until the available soil moisture supply has been completely depleted. By employing this procedure, no consideration is given to the fact that use of a given peak consumptive rate over different periods of time incorporates a different probability of occurrence or level of risk to the design of different systems. That is, a peak consumptive use rate of 0.30 in/day for a period of 10 days will not occur with the same frequency of occurrence as the same use rate over a period of 20 days. Because of these differences, it would seem logical to attempt to standardize irrigation system design based on some acceptable level of risk (recurrence interval) as is followed in the design of other engineering facilities. The final test of the rationality of this approach for irrigation system design will depend, to a large extent, on whether the inclusion of a probability level will result in a significant reduction in the costs to the system over the cost of a system designed by conventional procedures.

FREQUENCY DISTRIBUTION OF EVAPOTRANSPIRATION EXTREMES FOR SASKATOON

One of the most commonly used frequency distributions which has been applied successfully to describe populations of climatic data is the Extreme-Value Distribution proposed by Gumbel (1). The theory of extremes states that if x_1, x_2, x_3..................xn are independent extreme values observed in "n" samples of equal size, N, and if x is an unlimited, exponentially distributed variable, then as n and N approach infinity, the cumulative probability, p, that any extreme will be less than x is given by the formula,

$$p = e^{-e^{-y}}$$

where e = base of naperian logarithms, and

y = reduced variate which characterizes the distribution of x values.

Jensen and King (2) in Washington State found the distribution could be applied to describe the population of annual pan evaporation extremes of different consecutive day periods. A similar study to the aforementioned was conducted by Nicholaichuk (4) on 26 years of data recorded at Saskatoon (1937-1962) to test the applicability of the distribution for describing evapotranspiration extremes under Prairie conditions. In this study, daily potential evapotranspiration amounts were calculated from meteorological data recorded during the months of May through October by Penman's equation:

$$E_T = \frac{\triangle H + \delta Ea}{\triangle + \delta} \quad \text{.................} \quad 1$$

where E_T = potential evapotranspiration,

$\triangle$ = slope of the saturated vapor pressure curve at air temperature,

H = daily heat budget at the earth's surface,

δ = Constant for conversion of units, and

Ea = evaporation from water surface when at air temperature.

In these determinations, a reflection coefficient of 0.25 was assumed for the surface.

Using the daily potential evapotranspiration amounts thus obtained, the annual extreme values for 1-30 consecutive day periods were tabulated and plotted on "Gumbel" paper using a plotting position as defined by the formula,

$$F = \frac{m}{n + 1} \quad \text{.............................} \quad 2$$

where F = frequency of occurrence of an extreme equal to or greater than the extreme in question,

m = rank of the extreme in the array when arranged in decreasing order of magnitude, and

n = number of years of record.

A regression line was fitted to the data of each consecutive day period.

A sample plot using the extremes for the 5-consecutive day period is shown in figure 1. It can be observed

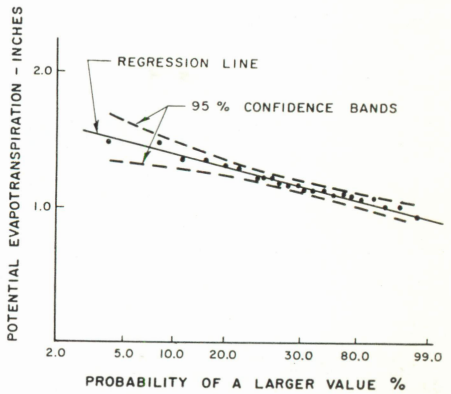

Figure 1. Frequency distribution for 5 consecutive day annual potential evapotranspiration extremes at Saskatoon.

in the figure that there is some tendency for the points to cycle about the fitted straight line. This property is to be expected inasmuch as the calculated potential evapotranspiration amounts are highly dependent on temperature readings and temperature extremes tend to show the same sinusoidal variation on an extreme value plot. In general, the amplitude of the cycles on all plottings were small; hence, it was concluded the extreme-value distibution could be used to describe the population.

The regression lines representing the potential evapotranspiration extremes for different consecutive day periods are plotted in figure 2. Superimposed on the figure are lines joining points of equal average daily potential evapotranspiration amounts representing 0. 20, 0. 25, 0. 30, and 0. 35 inches per day. Several pertinent points concerning the occurrence of different extreme evapotranspiration amounts are evident in the diagram.

(a) The slopes of the lines tend to increase with the longer consecutive-day periods. This trend is to be expected since the absolute difference in magnitude in potential evapotranspiration extremes, measured within a given period of record, would increase as the length of the consecutive-day period considered.

(b) The probability (frequency) of occurrence of a given average daily potential evapotranspiration extreme decreases as the consecutive-day period increases. For example, an average daily extreme of 0. 25 inches per day or greater has a probability of occurrence of 50 percent, (recurrence interval = 2 years) over a 2-day period and 2 percent (50 year) for a 30-day period.

(c) Within a given range of consecutive-day periods representing a practical range in irrigation intervals, the range in probability values encompassed by a given average daily potential evapotranspiration extreme increases as the size of the daily extreme increases.

RELATIONSHIP BETWEEN POTENTIAL EVAPOTRANSPIRATION AND CONSUMPTIVE USE

In order to use figure 2 in the design of irrigation systems, it is necessary that a relationship between the potential evapotranspiration amounts

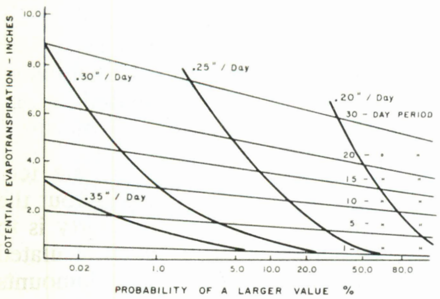

Figure 2. Frequency distribution of potential evapotranspiration amounts for Saskatoon.

and actual consumptive use values of a given crop be established. Nicholaichuk (4) compared the two values for a heavy stand of alfalfa at Saskatoon under conditions where the moisture level of the soil was maintained above that which the soil would retain at seven atmospheres pressure. In this study, the consumptive use values of the crop were determined from direct readings of soil moisture made with a neutron gauge. The findings of his study, shown in figure 3, indicate that consumptive use, CU, can be related to potential evapotranspiration, E_T, as

$$CU = 0.95\ E_T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

These results provide evidence that when water is non limiting, meteorological factors predominate in determining the consumptive use rate for the alfalfa crop. Also, there is evidence that the Penman equations used to calculate the potential evapotranspiration amounts provide reasonable estimates of consumptive use of comparative accuracy for all time intervals considered; 2, 6 and 14 days.

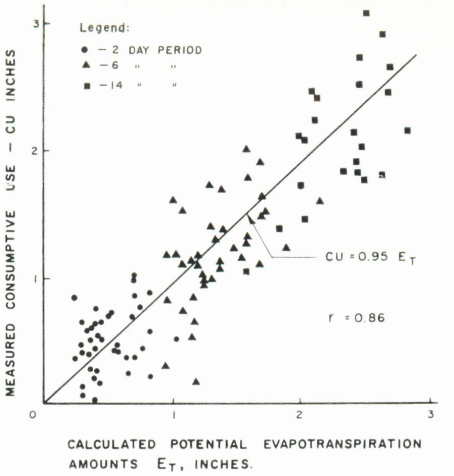

Figure 3. Measured consumptive use of irrigated Alfalfa vs. calculated potential evapotranspiration amounts for various consecutive day periods.

PROBABILITY OF OCCURRENCE OF PEAK CONSUMPTIVE USE EXTREMES AS A FACTOR IN IRRIGATION DESIGN

On the basis of the preceding discussions, it is obvious that when a single value for the peak consumptive use rate is used in a given area to determine the irrigation interval then conceivably each irrigation system could be designed at a different level of risk depending on the type of crop and soil. Table 1, was developed from equation 3 and figure 2, to show the range in probability of occurrences of different peak consumptive use rates for varying water holding capacities normally used for design purposes. It is evident from the data presented in table 1 that when low consumptive use rates are used in the design of irrigation systems for soils having low moisture holding capacities, the systems may not have sufficient capacities to meet the crop requirements for as many as six out of every ten years. On the other hand, systems designed for soils of high moisture holding capacity, using high peak consumptive use rates would result in a design that would fail to meet crop requirements only once in five thousand years. Obviously, these extremes in design would have serious economic consequences. Under design will of course, mean that crop production is seriously curtailed. At the same time, the added cost to system components required to meet crop requirements which can not be expected to occur within the lifetime of the system are unreasonable.

It would appear then, that in the design of irrigation systems, one should be prepared to accept some measure of under design, which means that water applications would fail to meet crop requirements on some occasions. Just how frequently one could justify economically a water deficiency, in terms of a saving on investment is difficult to assess at this time because there is not sufficient data available for the region on the relative production of crops when subjected to different levels of water deficiency. In forage crop production where at least two crops per year are produced, a water deficiency expected to occur once in ten years would affect only one crop in 20 and if it resulted in a yield reduction of 50 percent (assumption) would mean an average drop in production of only 2.5 percent. This decrease in production might easily be justified by the reduction in cost of the system, especially sprinklers. On the other hand, for production of grains, vegetables, etc. at one crop per year, a water deficiency expected to occur once in ten years and resulting in a 50 percent yield reduction for that year involves an average loss of five percent which may be more difficult to justify.

TABLE I. PROBABILITY (%) OF THE PEAK CONSUMPTIVE USE RATE EQUALLING OR EXCEEDING A GIVEN VALUE FOR A PERIOD OF TIME REQUIRED TO EXHAUST THE WATERHOLDING CAPACITY

Consumptive Use Rate inches/day	Soil Moisture Holding Capacity of Root Zone — inches			
	2	3	4	5
0. 30	1. 5	0. 5	0. 05	0. 02
0. 25	9. 5	5. 5	3. 8	3
0. 20	57	43	33	20

In addition to the fact that the probability of occurrence of peak rates may be used to indicate reasonable irrigation intervals, and thus reduce the design requirements of irrigation systems, consideration should be given to the fact that crops use water at rates less than the potential rates as the soil moisture levels drop below field capacity. A number of soil moisture budget systems have been proposed, which would allow the extension of the irrigation interval beyond that indicated by the use of potential rates. As an example, the modulated water budget system proposed by Kerr (3), when unaffected by precipitation between irrigations, has the effect of reducing the average use rate to 0. 75 of the potential use rate or to 0. 71 of the potential evapotranspiration rates determined by Nicholaichuk (4). Thus any root zone soil moisture holding capacity, can be divided by the factor 0. 71 to give the potential evapotranspiration equivalent, which is, the depth of water evaporated and transpired on the basis of Penman calculation during the time in which the crop would extract the root zone soil moisture. This equivalent value can then be used in figure 2 to determine the irrigation interval for any desired probability. Table 2 indicates the values of the potential evapotranspiration equivalents, normal design irrigation intervals based on peak consumptive use rates of 0. 25 inches per day and irrigation intervals based on a 10 by the use of potential rates. As an percent probability that a given potential evapotranspiration extreme will be equalled or exceeded for typical root zone soil moisture holding capacities at Saskatoon. It will be noticed that the change in irrigation interval is due primarily to the modification introduced by the soil moisture budget. This is to be expected since the normal irrigation interval is based on a consumptive use rate of 0. 25 inches per day which is very near to the value for the 10% probability level (see table 1).

TABLE II. PROPOSED IRRIGATION INTERVALS FOR SASKATOON

Root Zone Soil Moisture Holding Capacity (MHC)	Potential Evapotranspiration Equivalent	Normal Irrigation Interval MHC/0.25 in/day	Irrigation Interval Based on a 10% Probability that a Given Potential Evapotranspiration Extreme will be Equalled or Exceeded.
inches	inches	days	days
2	2.8	8	12
3	4.2	12	18
4	5.6	16	25
5	7.0	20	32

EFFECT OF EXTENDED IRRIGATION INTERVALS ON COSTS OF A SPRINKLER SYSTEM

The effect of extended irrigation intervals on the cost of sprinkler systems would have to compensate for the loss of productivity due to water deficiency if the preceding changes in design criteria are to be economically beneficial. If one assumes that forage will produce 4 tons per acre from two cuttings annually and that the extended irrigation interval will result, on the average, in a 2.5 percent drop in yield, then the annual loss due to the use of the smaller system would be 0. 10 tons per acre with a monetary value estimated at 2. 50 dollars assuming the cost of forage at 25 dollars per ton. Similarly the annual loss in grain production, say five percent of an 80 bushel oat crop, might have a value of about 3. 50 dollars per acre. The annual per acre reduction in cost of a sprinkler irrigation system, due to the extended irrigation interval may be attributed primarily to lower investment and depreciation costs. The use of a normal capital recovery factor, based on six percent interest, of about 0. 120, applied to the reduction in cost of the system would represent a reasonable assessment of the economic advantage from extending the irrigation interval. Thus a reduction of 21 dollars per acre or 29 dollars per acre in capital investment for forage and grain respectively would represent approximately the break even point.

Calculation of costs of a sprinkler system to cover an area of 40 acres, using different root zone moisture holding capacities and irrigation intervals, indicate capital cost savings of the magnitude shown in table 3. These savings are essentially the same, regardless of the moisture holding capacity, due mainly to the fact that in each case the extended irrigation interval allowed a one inch reduction in main line size, a decrease in the number of laterals from three to two and a reduction in size of pump and power unit of approximately 30 percent. The one exception is of course, the case where the normal design is based on a peak consumptive use rate of .30 inches per day and this has been included only to indicate the extreme condition caused by a poor choice of the peak use rate for normal design.

TABLE III. COST SAVINGS IN SPRINKLER IRRIGATION DESIGN WITH EXTENDED IRRIGATION INTERVALS

Root Zone Soil Moisture Holding Capacity-Inches	Irrigation Intervals Normal	Irrigation Intervals Extended	Reduction in Capital Cost 40 acre system	Reduction in Capital Cost Per acre
	Peak Use = 0. 25 in/day			
2	8	12	$1150.00	$29.00
3	12	18	1080.00	27.00
4	16	25	1150.00	29.00
5	20	32	1040.00	26.00
	Peak Use = 0. 30 in/day			
4	13	25	1390.00	35.00

The cost savings shown in table 3 indicate the possibilities of justifying economically the use of irrigation intervals extended considerably beyond those normally used for the design of irrigation systems. The preceding analysis is based on considerations applicable to the Saskatoon area and are presented solely as a means of pointing out the possibilities of a more realistic approach to the design of sprinkler irrigation systems. There is not sufficient information available at the present time to indicate clearly the level of probability of consumptive use which would represent the most economical system design. Nevertheless it is clearly evident that significant reductions in capital cost can be achieved through the use of evaporation frequency data.

SUMMARY

The annual potential evapotranspiration extremes for different consecutive-day periods, calculated from 26 years of meteorological data recorded at Saskatoon by the Penman's heat budget method, were found to follow an "Extreme-Value" distribution. These values, when modulated to account for such factors as soil moisture stress, soil type and type of crop can be used to estimate peak consumptive requirements in irrigation design.

It is shown that a given average daily consumptive use rate does not occur with the same probability of occurrence for different periods of time. Consequently, when a single value is used to determine irrigation intervals

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for system design under different soils and crops; each individual irrigation system will be designed with capacities to meet the requirements of meteorological events having different probabilities of occurrence. It is suggested that a more rational approach to design may be accomplished by using a peak consumptive use value of a given probability. Several examples are presented showing the reduction in capital costs of a sprinkler irrigation system when using the proposed design criteria in place of the conventional procedures.

LITERATURE CITED

1. Gumbel, E. J. Statistical Theory of Extreme Values and some Practical Applications. National Bureau of Standards. Applied Mathematics. Series 33, Washington. 1954.
2. Jensen, M. C. and King, L. Design Capacity for Irrigation Systems. Agr. Engr. 43:522-525, 1962.
3. Kerr, H. A. The Development of an Irrigation Budget. Unpublished M.Sc. Thesis. University of Saskatchewan Library, Saskatoon, 1963.
4. Nicholaichuk, W. Frequency of Occurrence of Evaporation Amounts. Unpublished M.Sc. Thesis. University of Saskatchewan Library, Saskatoon, 1964.

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to permit coils to be cooled to room temperature by refrigerant before blowers start.

Gas Analysis

It is accepted practice to analyze storage atmospheres daily and regulate scrubbing time or venting if necessary. Faithful attention to this routine task is essential and much time is saved by providing for gas analysis at a central point such as office or engine room (figure 5). Polyethylene tubing, ¼ inch, makes satisfactory gas sampling lines which can be connected to a manifold fitted with stopcocks and equipped with a small diaphragm pump to draw the sample. Oxygen and CO_2 can be analyzed simultaneously by using simple orsat type equipment for CO_2 and a Beckman D_2 instrument for O_2. The convenience and economy of time inherent in this arrangement justifies the cost where six or more analyses are made daily.

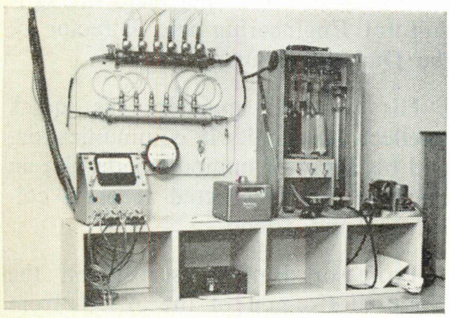

Figure 5. A convenient arrangement of gas sampling and analysis equipment in the office of the CA storage. In addition to gas analyses, temperature readings in one or more locations and static pressure can be determined in any of the rooms from this central point.

Thermometers

An accurately calibrated recording thermometer to measure return air temperature is an invaluable means of assessing plant operation as well as providing a permanent record. For additional verification, an indicating thermometer should be located in the storage so as to be visible from one of the glass inspection ports.

While not essential, remote temperature indicating equipment may be used to advantage particularly in a large storage, in monitoring air and fruit temperatures in various parts of the room. Thermister type equipment with narrow range and matched, calibrated probes is inexpensive and has proven highly satisfactory in practice. The instrument with multi-point switch can be located centrally with gas analysis equipment for convenient determination of temperature at the time gas analysis is made.

Static Pressure Gage

One more instrument which provides useful information to the CA operator is a static pressure gage which indicates + or — static pressure in fractions of an inch to ± one inch to two inches of water pressure. Various commercial instruments are available but a simply made "U" tube manometer suffices. The pressure gage connected one to a room or one common instrument connected to the gas manifold helps the operator to account for changes in oxygen levels in the storages and permits assessment and adjustment of pressure fluctuations due to refrigeration cycling and defrosting.

REFERENCES

1. Eaves, C. A. 1959. A Dry Scrubber for CA Apple Storages. Transaction Am. Soc. Agr. Eng. 2(1), 127-128.
2. Johansson, J. 1963. Use of Molecular Sieve as a CO_2 Adsorbent in Experimental Controlled Atmosphere chambers. Proc. Am. Soc. Hort. Sci. 83, 172-174.
3. Mann, G. 1958. The Use of Ethanolamine in Scrubbers for Fruit Stores. Mod. Refrig. 61 (727): 990,992-994.
4. Mann, G. 1960. Construction of Cold Stores for Fresh Fruit and Vegetables. 2. Building and Engineering Requirements. Ditton Lab. Memoir 10, 5-20.
5. Sainsbury, G. F. Heat Leakage Through Floors, Walls and Ceilings of Apple Storages. U.S. Dept. Agr. Market Res. Rep. 315.
6. Smock, R. M. 1958. Controlled Atmosphere Storage of Apples. Cornell Univ. Exp. Sta. Bul. 759.
7. Smock, R. M. 1959. Water Removal of Carbon Dioxide from Controlled Atmosphere Storages. Proc. N.Y. State Hort. Soc.
8. Smock, R. M. Private Communication.
9. Wells, A. 1962. Effects of Storage Temperature and Humidity on Loss of Weight by Fruit. U.S. Dept. Agr. Market. Res. Rep. 539.