Formula for calculating from weather data the residual soil moisture during soil drying[*]

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COMPENDIO

Se consideró la base experimental para el modelo del agotamiento de la humedad del suelo, el cual tiene una etapa de E constante de evapotranspiración combinada con una de E/PET en disminución y además durante la segunda etapa hay la presuposición de que la razón de la evapotranspiración a la evapotranspiración potencial disminuye linealmente con la humedad extraíble decreciente del suelo. Una fórmula para la humedad residual del suelo basada en dicha presuposición se derivó y concuerda bien con los valores en las tablas de Thornthwaite y Mather. Se demostró su uso especialmente en condiciones tropicales. La fórmula tiene la ventaja de ser flexible ya que se puede aplicar a suelos con cualquier valor de agua extraíble total, se puede evaluar rápidamente con una calculadora electrónica de escritorio con una función de potencia, y se puede usar fácilmente en programas para computadoras — El autor.

Introduction

THE estimation of soil moisture content from certain climatic and soil data is becoming increasingly important for evaluating soil water resources for forest and crop zoning (5, 11, 55, 58, 73), determining crop irrigation needs for a given soil type in an area (36, 54, 62), estimating the drainage load of an area (35, 63), run-off water yields (30) and determining the trafficability of the soil at any given time of the year (63). Naturally a direct determination of soil moisture is the best method of obtaining this information. The dynamic nature of soil moisture requires daily, weekly or monthly averages for useful interpretation which at the same time makes it difficult to obtain extensive information of this type.

Information on the probability of occurrence of certain values of soil moisture is necessary to evaluate soil water resources in a meaningful and practical manner, such as the risk of water deficit (11, 63), the probability of irrigation needs (5, 12, 15) or the chances of excess water during a given time of the year (4). From a statistical viewpoint this means having soil moisture information for approximately 20 years. However, very little direct soil moisture information exists, and when it does it is confined to the soil of a given weather station. With this background the value of estimating soil moisture content from climatic and easily obtainable soil data (the moisture holding capacity of the root zone) is appreciated.

Since the soil dries between rains or irrigation applications, a method of evaluating evapotranspiration for drying soil is important. Thornthwaite and Mather's method (62, 63) for predicting residual soil moisture from the atmospheric water balance (potential evapotranspiration - precipitation) has obtained reasonable agreement with field data. Methods using their assumptions in computer programs have also been quite successful (41, 72). The method requires the use of the authors' tables (64) which are available for certain total soil moisture holding capacities between 25 and 400 mm, since no formula was shown and presumably the tables were estimated by computer approximation. However, in reality, the effective root zone of a soil can have any value of total moisture holding capacity and a method adapted to any value will be of much practical use. For example, there are soils derived from volcanic ash (Hydric Dystrandepts) which have total moisture holding capacities up to 700 mm for 1.0 meter depth of soil (23). Thus, deriving a formula for residual soil moisture from Thornthwaite and Mather's assumption (63) that relates evapotranspiration rate to total

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[*] Received for publication September 11, 1975

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soil moisture content will solve the problem. The objective of this paper is to derive such a formula and show its use, especially in tropical areas.

Water balance

Thornthwaite (60, 63) introduced the water balance method for calculating soil moisture using a bookkeeping method which may be summarized in the following manner:

$$W_2 = W_1 + R - E \qquad [1]$$

W_1 = Initial soil water content (expressed as height)

W_2 = Final soil water content

R = Infiltrated rain

E = Evapotranspiration

The soil has a moisture storage limit (field capacity) and when W_2 exceeds this value a condition of surplus exists and drainage begins. When E is greater than R (negative atmospheric water balance) stored soil moisture is utilized by the crop thereby creating a soil deficit. New rainfall or irrigation initiates the recharging of the soil moisture.

Thornthwaite (60) originally assumed that all soils had an available water holding capacity (field capacity-wilting point) of 100 mm and that the evapotranspiration rate of a crop was the same from field capacity to wilting point and became zero at wilting point. The latter idea is similar to that of Veihmeyer and Hendrickson (68) with results obtained from fruit trees in California with deep rooting and in areas of apparently low evaporative demand. Richards and Wadleigh (49) discussed Veihmeyer and Hendrickson's experiments and pointed out the difference between equal availability as measured by constant evapotranspiration rates between field capacity and wilting point and equal availability as defined as constant yields between these two moisture points. Veihmeyer and Hendrickson obtained constant evapotranspiration rates, but in many of their experiments fruit yield was reduced by soil water deficits, and this result agrees with those of other researchers, who have demonstrated that soil water deficits affect the yield and growth of a variety of crops and trees.

Halstead (61) by using an energy balance method, showed that at 10 cm depth, 100 per cent of net radiation was used in evaporation when the soil was at field capacity and 0 per cent when the soil was at 1 per cent soil moisture, which was considered to be the wilting point. Similar data was presented by Thornthwaite and Mather (62), and Ritchie, Burnett and Henderson (50) obtained similar results with cotton and grain sorghum; however the 100 per cent rate started to decrease at a threshold soil moisture level.

Subsequently Thornthwaite and Mather (62, 63) have considered the total soil moisture content at field capacity as a starting point in soil depletion studies, and used the principle that when the soil is at field capacity potential evapotranspiration occurs, and as the soil dries the rate of evapotranspiration is proportional to the total amount of water remaining in the soil.

Instead of a standard value of available water holding capacity used in the earlier method of 100 mm, a new standard value of total water holding capacity of 300 mm was used to prepare a soil moisture depletion table (63). Realizing the limitation of one standard value of total moisture holding capacity to be applied to all soils, Thornthwaite and Mather (64) prepared tables for soils with certain total moisture holding capacities ranging from 25 to 400 mm.

Potential evapotranspiration

Thornthwaite (60) developed the concept of potential evapotranspiration (PET) to avoid the problem of the variability of evapotranspiration (E) observed with different soil moisture contents. It represents the maximum value of evapotranspiration rate of a crop cover when soil water is not limiting, that is, at field capacity. The potential evapotranspiration rate thus becomes a function of the evaporating power of the prevailing climate and is independent of soil-plant factors. Penman (45) made a similar definition of potential evapotranspiration considering the case of the soil surface being completely covered by the crop. It should be pointed out that the soil with non-limiting water conditions should also have non-saline conditions. During conditions of potential evapotranspiration, a model has been developed which considers plant cover as a passive evaporation surface or a wet wick (67). Many crops with well developed canopies that cover the soil have similar potential evapotranspiration rates. This phenomenon can be explained by an energy balance analysis. Plant cover reflects a certain percentage (albedo) of incoming solar and sky radiation. The unreflected radiation (net radiation) energy is utilized in evapotranspiration and the heating of the crop, the air and the soil. Under potential evapotranspiration conditions almost all the net radiation energy is used in evapotranspiration (61, 62, 63). A low Bowen ratio* (0,1) reported by Gates and Hanks (27) for well watered crops and data from Ritchie, Burnet and Henderson (50) also support this idea. Thus, if different crops have similar values of albedo they should have similar potential evapotranspiration rates, since most of the absorbed radiant energy is used in evapotranspiration.

Thornthwaite (61) found that most of the common vegetables have albedos similar to grass, that is approximately 26 per cent; Davies and Buttimor (13) obtained similar results. They found a value of 25 per cent for grass, corn, tomatoes, wheat, peppers, tomatoes, tobacco and cucumbers. Data from Angstrom (12) show variations from 14 per cent for a pine forest to 26 per cent for grass. Moist sand had 9 per cent. Gates and Hanks (27) review data ranging from 14 per cent - 29 per cent for crops and observe that the natural variation in plant color appears to have relatively little influence on

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* The ratio between sensible heat and latent heat (used in evaporation).

reflection. Ramdas (48) on the other hand obtained data showing that color effects in soil are great. Baumgartner (6) estimated the albedos of forests to be about 8 per cent - 10 per cent, Stanhill (56) estimates a value of 15 per cent - 20 per cent for a pine forest and Pereira and McCulloch (46) estimated a value of 12 per cent for a bamboo forest, 18 per cent for broad-leafed tropical rain forests and 21 per cent for short green grass, all well watered. These data indicate that the albedo range for forest trees seems to be somewhat lower but with many values similar to agricultural crops.

The similarity of albedos between crops explains the conclusion of Angus (3) who observed that under similar climatic conditions different crops with well developed canopies showed similar evapotranspiration. The height of crops hardly influences their evapotranpiration capacity; it is the area of soil shaded which is important (7, 69). This is explained by data that show that most of the radiant energy is absorbed in the upper layer of the plant and thus the greater part of transpiration occurs there (38). In view of these results the earlier concept of transpiration ratio, which links total plant water consumption to dry matter production is not considered valid. DeWit (16) in a review of worldwide data has pointed out that many crops between latitudes 55 N and 55 S have sufficient solar radiation to satisfy their photosynthetic saturation point, and under this condition of excess radiation, there is no relationship between carbon assimilation and water use. This is especially so for crops between latitudes 40 N and 40 S. Taylor (59) arrived at a similar conclusion.

There are several methods of estimating PET: the heat balance and vapor movement methods using several measurements of climatic data, correlation with climatic data, and correlation with the evaporation from a free water surface. The relationship PET/Evaporation from a free water surface, has been called f by Penman (45). Good correlation has been experimentally obtained between PET and pan evaporation (8, 47) and as a result the relationship PET/Pan Evaporation, is considered a good estimate of f. The U.S. Weather Bureau class A pan has been widely used for this purpose. The evaporation pan method is more fully discussed here because there is a growing quantity of experimental data of f values for different crops. In areas where pan evaporation data do not exist, weather data can be used in its estimation.

Data of García and López (24), Legarda and Forsythe (37) and Hasan and Jones (32) suggest that for a given locale inside the tropical belt between 15°N and 15°S variations in relative humidity have a primary role in evaporation changes and formulas that use this factor have considerable success. On the other hand formulas that depend only on temperature and daylength such as that of Thornthwaite have little success in his belt due to the relatively small seasonal change during the year.

Once pan evaporation is measured or estimated for an area, the product of this value and f for a particular crop will give the potential evapotranspiration of this crop. The majority of crops studied have values which vary from 0.8 to 1.1 for maximum canopy development (10, 18). The relatively small variation on a worldwide basis can be explained by the previously discussed similarity of albedo between agricultural crops. Douglass (17) concluded that when there are non-limiting soil water conditions, a dense grass cover and a complete forest cover have the same potential evapotranspiration. A bare soil at field capacity is in its first stage of evaporation, the constant rate stage, because evaporation depends only on climatic conditions (42). Actually, the evaporation rate will be constant only if the daily climatic conditions are constant, so we can adjust the constant rate concept for the more realistic daily climatic variations, and call it the constant f stage. In Hawaii, Campbell, Chang and Cox (9) found f to be 0.4 for bare soil, whereas Hargreaves (31) found a value of 0.42. The data of Campbell, Chang and Cox (9) show how the value of f for sugar cane increases to a maximum as the canopy develops. In a similar way the data of Hargreaves show the increase of f for cotton as it develops. The following are some values of f for fully developed canopies: beans 1.0, corn 0.85 (34), beans 1.07 - 1.19, corn 0.98 - 1.39, flood rice 1.04 - 1.14, peanuts 1.02 - 1.23, bananas 0.89 - 0.92, *Canavalia ensiformis* 1.10, *Crotalaria usaramoensis* 1.16 (18).

There are some notable exceptions to the general range of f values. Ekern (21) found that 12 month-old pineapple, *Ananas comosus* (L.) Merr., with a well developed canopy has an f value of 0.2, because its stomata are closed during the day and gaseous interchange occurs with soil air through channels in the roots and stems. This mechanism possibly exists in *Opuntia* and other succulent plants (cacti). Ferri (22) mentions species found in the "caatingas" of Brazil that only open their stomata in the early mornings even during the rainy season. For orange trees Hilgeman and Rodney (33) obtained f values of 0.45 to 0.58 and Van Bavel, Newman and Hilgeman (66) suggested that orange trees have high stomatal resistance even when the plant is well supplied with water. Van Bavel (67) suggested that some forest trees behave likewise. Many xerophytes may have similar mechanisms.

Atmospheric water balance

In order to establish the evaporating power of a particular climate without reference to soil moisture conditions, the PET must be used in relation to precipitation (P). The expression (P-PET) called here the atmospheric water balance serves this purpose and was used by Thornthwaite and Mather (62, 63). When the atmospheric water balance is negative then the soil will begin to dry out, and the more negative it is the greater will be the climatic capacity for drying the soil.

Models of moisture depletion

Studies on soil drying have isolated the constant rate stage which depends only on the evaporative demand of the climate and the falling rate stage which follows and depends strongly on soil factors including soil moisture (42, 45). As explained earlier for climates of variable evaporative demands, these stages may be considered as those of constant *f* and falling *f*. The constant *f* stage continues to a certain threshold soil moisture value and then the "falling *f*" stage begins, which shall be referred to here as the decreasing E/PET stage, since *f* refers only to potential evapotranspiration conditions. For a given soil the value of the threshold soil moisture depends on the evaporation rate. Activation energy studies of Wiegand and Taylor (71) suggest that the constant *f* stage is mainly evaporation with some unsaturated flow, while the end of the decreasing E/PET stage is mainly water vapor diffusion in the soil. Two similar drying stages have been observed in the drying of leaves (65) and as a result it is difficult to say whether the soil or plant leaves dominate in the much observed evaporation behavior with constant *f* and decreasing E/PET stages. Similar drying curves have also been observed with shelled corn (29).

A common model for evapotranspiration is to consider the driving force of the water as the potential drop between the soil water in the root zone and the water vapor at the leaf border. Resistance to water flow is offered by the soil in the root zone, the stem, branches and leaves. Apparently greatest resistance is met in the soil of the root zone and the leaves (26, 38).

Figure 1 can be used to describe two extremes of experimentally observed moisture depletion curves. Curve 1-4-5 shows the experience of Veihmeyer and Hendrickson (68) with fruit trees where *f* remains constant until the soil dries to the lower limit of extractable water. On the other hand curve 1-5 approximates data obtained by Deanmead and Shaw (14) for corn with soil equivalent to 10 cm root depth and PET of 6.4 mm/day (52) and data of Thornthwaite (61) for a 10 cm soil depth. An intermediate curve such as 1-2-5 was obtained by Deanmead and Shaw (14) for corn at an equivalent 10 cm root depth but for lower rates of PET of 4.1 - 5.6 mm/day. Studies suggest that if PET is 1.3 - 2 mm/day or less a curve tending to the 1-4-5 type is obtained irrespective of soil depth (40, 43). The average of the experimental and semi-empirical values of PET not affected by soil depth or moisture is 2.2 mm/day, and this is used in the present model (25, 28, 40, 43, 53, 70).

The term extractable water is defined by Ritchie (52) as the quantity of soil water in the entire profile in excess of the minimum quantity observed in the soil when plant evapotranspiration practically stops because of dry soil. The term is useful because the 15 bar moisture value may or may not be this lower limit. Data of Deanmead and Shaw (14) suggest that for values of PET greater than 5.6 mm/day, this may be so but for lower values of PET the soil tends to dry beyond the 15 bar percentage. In Thornthwaite's data (61) the sandy soil dried to 1 per cent (wet weight basis), and Thornthwaite and Mather (63) used 0 per cent as the lower limit. The lower limit of extractable water will have to be defined for each case treated.

Tanner (57) has reviewed models of E/PET versus extractable water which considers each of the different cases shown in Fig. 1 as valid in addition to some curvilinear paths. Zahner (72) has a model which combines curves 1-4-5 and 1-5 according to soil texture. A moisture minimum measured in the field was used as the lower limit of extractable water. The residual soil moisture was calculated by an IBM 7090 computer and fair agreement with field data was obtained. McCown (41) used a model similar to curve 1-2-5 where zone 2 beings at 50 per cent extractable water. Residual water was determined by computer simulation. Good agreement with field data was obtained. Ritchie and Jordan (51) have proposed an exponential function for E/PET versus extractable water for the decreasing E/PET zone. However, information on the time necessary to arrive at the lower limit of extractable water is needed, thus limiting the predictive nature of the equation. Eagleman (19) has suggested a cubic model which takes into account the influence of different values of PET and soil depth on the type of depletion curve. The 15 bar moisture is used as the lower limit of extractable water. Its complexity requires that residual soil moisture be calculated by a computer. Satisfactory agreement was obtained with field data. Linacre (39) has suggested a simpler form of Eagleman's equation (20).

Formula for residual soil moisture

The experimental data discussed suggest that the types of depletion curves shown in Figure 1 are reasonable working approximations. A guide is needed to choose the value of the fraction of extractable water, C, that initiates the decreasing E/PET phase. The experimental evidence suggests that the value of C depends on the soil depth used by the plant and the value of PET. It is convenient to consider C_d which depends on soil depth and C_e which depends on evapotranspiration rate. Then

$$C = C_d \, C_e \qquad [2]$$

with the restrictions of $0 < C_d < 1$ and $0 < C_e < 1$. Figure 2 shows the value of C_d versus soil depth for values of PET between 6 - 6.4 mm/day, which values will make C_d approximate unity when depth approximates 0. On the other hand Figure 3 shows the value of C_e versus PET, when the soil is shallow, that is, less

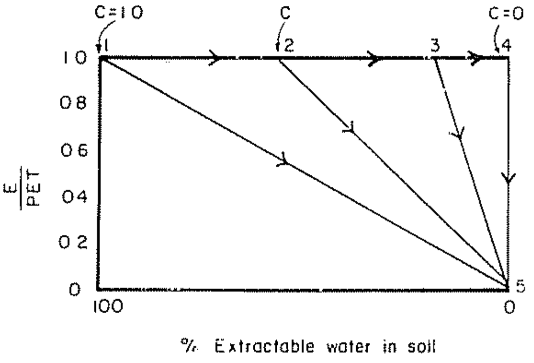

Fig. 1.—*Model for moisture depletion.*

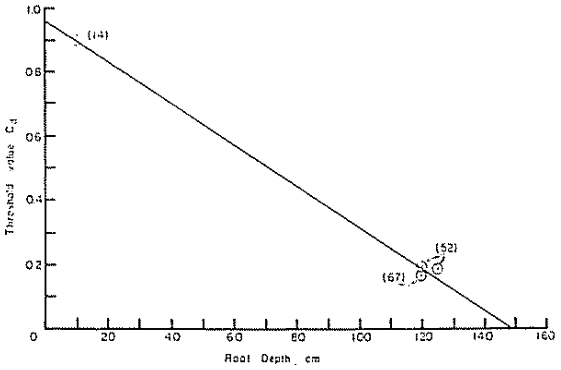

Fig. 2.—*Threshold value* (C_d) *of extractable water as influenced by rooting depth. For potential evapotranspiration greater than 6 mm/day*

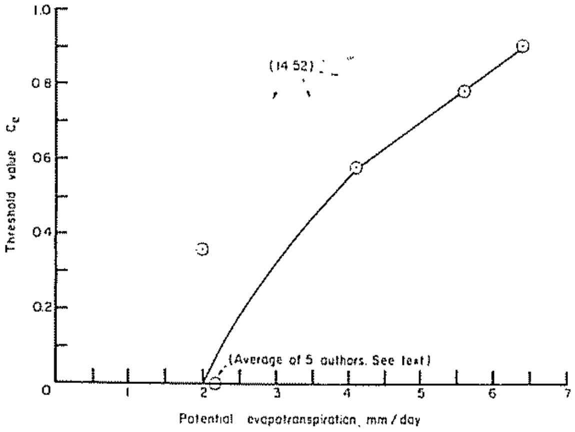

Fig. 3.—*Threshold value* (C_e) *of extractable water as influenced by potential evapotranspiration when soil is less than 10 cm deep.*

than 10 cm depth. A knowledge of the soil depth occupied by the majority of plant roots and the PET, together with the use of equation [2] will give the desired value of C.

The value of residual moisture may be calculated in two steps. For the constant *f* phase the residual moisture can be calculated from a modified form of equation [1].

$$W_2 = W_1 + \text{atmospheric water balance} \qquad [3]$$

For the decreasing E/PET phase, the considerably successful linear function will be used, i.e. E/PET is directly proportional to the per cent of extractable water in the profile. Let W be the water in the soil profile expressed as height and K be the total capacity of the profile to retain extractable water. Let A be the magnitude of the daily negative atmospheric water balance and t be time in days. For soil drying we may write:

$$\frac{dW}{dt} = -\frac{W}{K} \times A \qquad [4]$$

$$dt = -\frac{dW}{W} \times \frac{K}{A} \qquad [5]$$

Integrating we get:

$$t\Big]_{t_1}^{t_2} = \ln W \times \frac{K}{A}\Big]_{W_1}^{W_2} \qquad [6]$$

$$\therefore t_2 - t_1 = -2.3\frac{K}{A}(\log W_2 - \log W_1) \qquad [7]$$

If $t_1 = 0$ and $W_1 = K$, then

$$\log\frac{W_2}{K} = -\frac{t_2 A}{2.3K} \qquad [8]$$

$$\therefore \frac{W_2}{K} = 10^{\frac{-t_2 A}{2.3K}}$$

$$W_2 = K \times 10^{-\frac{t_2 A}{2.3K}} \qquad [9]$$

Equation [9] is the residual moisture when the soil begins to dry at full capacity. The expression t_2A is the total atmospheric water balance for the time lapse t_2 days. If the soil begins to dry out at W_1 then a more general form of equation [9] will be:

$$W_2 = W_1 \times 10^{\frac{-t_2A}{2.3K}} \qquad [10]$$

Comparison between equation [9] and Thornthwaite and Mather's tables

Thornthwaite and Mather (64) consider extractable water as total soil moisture. Their value of "PE" is equivalent to t_2A in equation [9]. Table 1 shows excellent agreement between the residual moisture calculated by the formula and values from Thornthwaite and Mather's tables for K = 300 mm. Similar agreement was obtained for other values of K. This case is one in which the falling E/PET phase begins at field capacity when C = 1.

Table 1.—Comparison between residual soil moisture values calculated by formula with those in Thornthwaite and Mather's tables K = 300 mm

t_2A mm	$\frac{-t_2A}{2.3K}$	Residual moisture from formula $K \times 10^{\frac{-t_2A}{2.3K}}$ in mm	Residual moisture from tables of Thornthwaite and Mather, in mm
1	—0.001449	299.0	299
5	—0.007246	295.0	295
10	—0.01449	290.1	290
20	—0.02899	280.6	280
150	—0.2174	181.8	181
200	—0.2899	153.9	153
250	—0.3623	130.3	130
300	—0.4348	110.2	109
350	—0.5072	93.31	92
400	—0.5797	78.96	78

Discussion

The equation developed can be applied in any model which uses the assumption that E/PET falls linearly with a decrease in soil moisture. It is adaptable to any definition of extractable water, once the values used for its upper and lower limits are known. When the curve is of the 1-2-5 type of Figure 1, the upper limit of the extractable water is C. A greater quantity of more precise evapotranspiration data in relation to root depth will help to improve the guide for choosing C in the model of Figure 1. The lower limit may vary between the 15 bar percentage and oven-dry soil (0 per cent). The formula permits the rapid calculation of residual moisture with any desk electronic calculator with a power function; in addition, it facilitates easier programming in computers. A soil of any value of extractable water can be handled by the formula, thus providing more flexibility than Thornthwaite and Mather's tables.

Summary

The article discussed the experimental basis of a soil moisture depletion model which combines a constant *f* stage of evapotranspiration with a decreasing E/PET stage, in addition to the use during the latter stage of the assumption that the ratio of evapotranspiration to potential evapotranspiration, decreases linearly with decreasing extractable soil moisture. A formula for residual moisture based on the assumption has been derived and it agrees well with the values in the tables of Thornthwaite and Mather. Its use has been demonstrated, especially under tropical conditions. The formula has the advantage of flexibility as it can be applied to soils of any value of total extractable water, can be quickly computed with a desk electronic calculador with a power function, and can be easily used in computer programs.

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