Calculation of soil moisture regimes from the climatic record

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FOREWORD

Early versions of this document were written before 1980 when products of the computer model described herein were being used in support of soil classification throughout the United States and in other countries. The process of review, approval, and publication was interrupted several times by retirements or transfers of the authors and other key people.

Now, the model has been used widely and is known in a general way by many people. Further, the original computer model is no longer operational and products in the original output format are no longer available. Accordingly, I have removed several sections of the early versions that are no longer pertinent. I have retained and revised sections that describe and explain how the computer model worked.

Ellis G. Knox
February 1996

CALCULATION OF SOIL MOISTURE REGIMES FROM THE CLIMATIC RECORD

By Franklin Newhall and C. Reese Berdanier [1/]

INTRODUCTION

Soil moisture regimes (Soil Survey Staff, 1992) reflect seasonal patterns of variation in the moisture condition of the soil. They are used in Soil Taxonomy to differentiate many classes in the suborder, great group, and subgroup categories.

A model of moisture accretion and depletion, commonly known as the Newhall model, was developed to apply weather data to decisions about soil moisture regime in the application of Soil Taxonomy (Soil Survey Staff, 1975, page 53). It can be run for any weather station having adequate records of monthly precipitation and temperature. The model does not attempt a sophisticated simulation of water movement in and out of the soil. It is conceptually simple but tedious and suitable for computer use.

The model was used by the Soil Survey Staff in the Soil Conservation Service to predict the number of days in a year that parts of the soil moisture control section are moist or dry for thousands of locations in the United States and many locations in other countries.

The original model, written by Newhall in COBOL, is no longer available. It was revised and rewritten by van Wambeke (1981, 1982, 1985, 1986) with an output format in FORTRAN. A version in BASIC (FLEXNSM Program) was available in 1992 from Dr. A. van Wambeke, Department of Soil, Crop, and Atmospheric Sciences, Cornell University, Ithaca, New York.

This report documents the assumptions, logic, and procedure of the original model.

ASSUMPTIONS AND DEFINITIONS FOR THE SOIL MOISTURE MODEL

As in other soil moisture models, the soil is regarded as a reservoir with fixed capacity. In the model, water is added by precipitation, the amount exceeding the retention capacity of the soil is lost by deep leaching or runoff, and stored soil water is removed by evapotranspiration. This model uses Thornthwaite's procedure (1948) to estimate evapotranspiration (PE) from abundant data on temperature and day length. It differs from most previous models because of certain assumptions about the relationship of infiltration and rainfall intensity and about the amount of energy required to remove moisture from various layers of the soil.

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The soil moisture profile

The soil moisture profile extends from the surface to that depth above which the water retention difference (WRD) is 200 mm. WRD (Burt, 1995) is the difference between the amount of moisture held in the soil horizon at a tension of 33 kPa (1/3 bar) and the amount held at 1500 kPa (15 bars). It can be expressed on a volumetric or a thickness basis. It is assumed that below this profile there is no active exchange of moisture with the atmosphere. The actual thickness of the soil moisture profile depends on the WRD of individual soil horizons. It ranges from less than 80 centimeters to more than 240 centimeters.

The soil moisture control section

The soil moisture control section (MCS) is defined in Soil Taxonomy (Soil Survey Staff, 1975, p. 53). Its upper boundary is the depth to which a dry soil (at a tension of more than 1500 kPa but not air dry) is moistened by 25 mm of water moving downward from the surface in 24 hours. The lower boundary is the depth to which the dry soil is moistened by 75 mm of water moving downward from the surface in 48 hours. These depths may be measured in the field but the necessary observations seldom are made. The boundaries may be approximated by calculating the depths of cumulative WRD of 25 and 75 mm. Thus, the moisture control section is the layer having 50 mm of WRD that lies below a surface layer having 25 mm of WRD. The thickness of the MCS depends on soil texture, bulk density, amount and size of rock fragments, and other soil properties that affect WRD. The soil moisture profile considered in this model has a third layer, below the MCS, that has 125 mm of WRD.

The soil moisture diagram

The conceptual diagram used in the computer model divides the soil moisture profile into 200 depth increments. Each increment has 1 mm of WRD. Each increment is divided into 200 segments; each segment represents 0.005 mm of WRD. The moisture tension of an increment ranges from 33 kPa, when all of the segments are filled, to 1500 kPa or dryer, when all of the segments are empty. The 199 parallel diagonals through this 200-by-200 grid are called slants. Depth increments, segments, and slants are the units manipulated by the computer. These concepts are illustrated for a 16-by-16 grid in Figure 1.

Accretion of moisture in the soil

Water from precipitation is added by depth increments. The model assumes that water from precipitation enters the soil from the top, filling all segments of each increment of soil before entering the next lower increment (Figure 2B). If the wetting front, the deepest increment filled by accretion, reaches the bottom of the soil moisture profile, excess moisture is assumed to be lost through deep percolation or by surface runoff.

The model divides total monthly precipitation (MP) into two parts. One half of MP is considered to be heavy precipitation (HP) that moves into any available water retention capacity. The other half of MP is considered to be light precipitation (LP) that is directly available for loss by evapotranspiration at the full rate of PE for the month. The difference between LP and PE is called net moisture activity (NMA). Only LP in excess of PE (positive NMA) is added into soil storage, up to the capacity for retention. By convention, the lowest increment to which moisture is added is made to be full at the end of the event.

Depletion of soil moisture

Water depleted by evapotranspiration is removed from the soil moisture profile by slants (Figure 2C, D). The model assumes that moisture is removed most readily from the depth increments most nearly filled and those nearest the top of the soil moisture diagram. That is, the energy required to remove water from the soil (expressed in units of PE) depends on moisture tension as well as depth in the profile. Accordingly, the model assumes that the requirement for removal of moisture is equal for the segments of one slant.

If all segments in the diagram are filled, depletion begins with slant 1 (Figure 1) and proceeds sequentially to the last slant. In early stages of depletion, one unit of PE removes one unit of moisture. As the soil profile becomes partially depleted of moisture, more units of PE are required to remove each unit of moisture as illustrated for the simplified diagram of Figure 1. In the computer model, using a 200-by-200 grid diagram with 399 slants, one unit of PE removes one unit of water in slants 1 to 60, the PE units required increase logarithmically from one to five from slants 69 to 320, and five units are required in slants 320 to 399.

PE is assumed to be uniformly distributed over the month. Only PE in excess of LP (negative NMA) is available to deplete water from the soil moisture profile.

OPERATIONS OF THE MODEL

Calculation of moisture states

The soil moisture regime is determined by moisture conditions in the MCS over a time period of one or more years. Moisture conditions of the MCS, in turn, are determined from the moisture states for the whole soil moisture profile. The computer model calculates three moisture states per month (two at mid month and one at the end of the month) from MP and normal monthly PE for each month of the selected climatic record.

Step 1. First half of month. This gives the moisture state at the middle of the month, just before step 2.

1.1. Compute light precipitation (LP).

LP = MP/2

1.2. Compute net moisture activity (NMA).

NMA = LP - PE

1.3. Add or remove water from the soil moisture profile.

If NMA > 0, apply NMA/2 to fill available segments by depth increments, starting at the top of the soil moisture diagram.

If NMA < 0, apply NMA/2 to exhaust filled segments by slants, starting with the lowest slant number.

Step 2. Mid month. This gives the moisture state in the middle of the month, just after accretion of HP.

2.1. Compute heavy precipitation (HP).

HP = MP/2

2.2 Apply HP to fill available segments by depth increments, starting at the top of the soil moisture diagram.

Step 3. Second half of the month. This gives the moisture state at the end of the month.

3.1. Compute LP. (Same as 1.1)

3.2 Compute NMA. (Same as 1.2)

3.3. Add or remove water from the soil moisture profile. (Same as 1.3.)

Moisture conditions of the moisture control section

For each moisture state generated, the MCS is classified dry in all parts (D), dry in some parts and moist in some (B), or moist in all parts (M). In terms of the soil moisture diagram (Figure 2), a part of the MCS is dry when all segments of at least one depth increment are empty. A part of the MCS is moist when one or more segments of at least one depth increment are filled.

Duration of moisture conditions

Periods between steps 3 and 1 (first half of the month) and between steps 2 and 3 (second half of the month) can be 14, 15, or 15.5 days. The interval between steps 1 and 2 is zero. If consecutive diagrams have the same moisture condition, the MCS is considered to have the same condition for all days in the period. When conditions change during a half-month period, the durations of the initial and subsequent conditions are computed through consideration of the NMA required to move from the initial moisture state to the state at the change to the next condition.

For example, when NMA is negative and the condition of the MCS changes from M to B or D during a half-month period, the duration (in days) of each condition is computed as follows (for one-half month = 15 days):

I = Initial soil moisture state
F = Final soil moisture state
PE available = -NMA/2
PE I to B = PE required to change from I to soil moisture state that initiates B
PE B to D = PE required to change from soil moisture state that initiates B to soil moisture state that initiates D

When I = M and F = B:

$$\text{Duration of M} = 15 \times \frac{\text{PE I to B}}{\text{PE available}}$$

Duration of B = 15 - duration of M

When I = M and F = D:

$$\text{Duration of M} = 15 \times \frac{\text{PE I to B}}{\text{PE available}}$$

$$\text{Duration of B} = 15 \times \frac{\text{PE B to D}}{\text{PE available}}$$

Duration of D in days = 15 - (duration of M + duration of B)

Dates of change in moisture condition, derived from durations of D, B, and M during each half month, are converted to day numbers of the year. (Day numbers run from 001 to 365 for January 1 to December 31. February 29 is excluded.) For example, Table 1 lists day numbers of all changes in moisture condition for a 10-year period of record at Rosemont, Nebraska. Such information yields the number of days that the MCS exhibits specific moisture conditions as shown in Tables 2 and 3.

Table 2 relates to the ustic soil moisture regime. It shows the number of days that the MCS was dry in some or all parts (moisture conditions B or D) when the soil temperature was 5 °C or higher. The table shows a 70% probability (7 years out of 10) of meeting the ustic requirement of 90 or more days.

Table 3 shows the greatest number of consecutive days when the MCS was dry in all parts during the 120 days following the summer solstice. The requirement of 45 days or more for the xeric soil moisture regime was met in only 4 out of 10 years.

COMPARISONS WITH OBSERVED DATA

Data from direct observations of the soil moisture status or content of well characterized soils were available for few locations. Most commonly, water contents as a weight percent of oven-dry soil in several consecutive layers downward from the surface were measured at intervals during the year. From these data and water retention at 1500 kPa, it was possible by interpolation to count the number of days that the soil in given layers exceeded 1500 kPa tension. Then, using WRD values for the same layers, computer model results, expressed as in table 1, were obtained for the identical time period and the resulting numbers of days were compared.

Figure 3 shows the calculated and observed values of the number of days when the selected soil layer was dry in all parts during the period when the estimated soil temperature was 5 ^{O}C or higher. Data in the figure are for the layer that most closely approximates the MCS. The data reflect 128 station-years of observations at seven stations, mostly in the Great Plains between 1905 and 1930. Despite scatter, the correlation coefficient between calculated and observed values is 0.81.

This test was made for moisture condition D (dry in all parts) because it seemed plausible to attribute very low moisture content to all parts of the MCS. The two other moisture conditions cannot be tested in the same way because the distribution of moisture in parts of the observed layer cannot be assumed, and it is not possible to infer whether some parts are dry or not.

A different test used data taken at Rosemont, Nebraska. Moisture content was calculated for layers of a six-layer profile using an early version of the soil moisture diagram with 40 rather than 200 increments. The calculation was for the beginning, middle, and end of each month during which the soil moisture observations were made. The model explained about 40 percent of the variation of moisture in the surface layer, 60 percent in the second layer, and 50 percent in the third layer.

SUMMARY

The computer model described in this publication can be used to estimate aridic (torric), xeric, ustic, and udic soil moisture regimes as defined in Soil Taxonomy (Soil Survey Staff, 1992). Factors used in the model are precipitation and evapotranspiration. Results of the model should be applied judiciously because the calculated moisture regimes are estimates derived from climatic data, not soil data. However, the estimates are useful guides for the tentative classification of soils.

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Table 1. Day numbers when changes occurred in the calculated condition of MCS, Rosemont, Nebraska 1948-1957.

Year	Moisture Conditions and Day Numbers								
1948	M 043	B 192	M 196	B 215	D 223	B 349			
1949	M 062	B 226							
1950	D 177	M 196	B 225	D 240	B 256				
1951	M 045								
1952	B 252								
1953	M 045	B 196	D 217						
1954	M 135	B 179	D 184	B 227	D 254				
1955	B 015	D 125	B 135	D 161	B 166	D 193	B 196	D 213	B 258
1956	D 130	B 166	D 188	B 227	D 239				
1957	B 065	M 074	B 220	M 227	B 262				

Table 2. Number of days when calculated condition of MCS was D or B from day 100 to day 326, the average period when soil temperature equals or exceeds 5 ^{o}C., Rosemont, Nebraska 1948-1957.

Year	Duration of Conditions D and B (day numbers and consecutive days)		Number of Days of D or B
1948	196 - 192 = 4,	326 - 215 = 111	115
1949	326 - 226 = 100		100
1950	196 - 100 = 96,	326 - 225 = 101	197
1951	none		0
1952	326 - 252 = 74		74
1953	326 - 196 = 130		130
1954	135 - 100 = 35,	326 - 179 = 147	182
1955	326 - 100 = 226		226
1956	326 - 100 = 226		226
1957	227 - 220 = 7,	326 - 262 = 64	71

Table 3. Greatest number of consecutive days of calculated condition D in MCS from day 172 to day 292, the 120-day period that begins with the summer solstice, Rosemont, Nebraska, 1948-1957

Year	Duration of Condition D (day numbers and consecutive days)		Greatest Number of Consecutive days
1948	292 - 223 = 69		69
1949	none		0
1950	177 - 172 = 5,	256 - 240 = 16	16
1951	none		0
1952	none		0
1953	292 - 217 = 75		75
1954	227 - 184 = 43,	292 - 254 = 38	43
1955	196 - 193 = 3,	258 - 213 = 45	45
1956	227 - 188 = 39,	292 - 239 = 53	53
1957	none		0

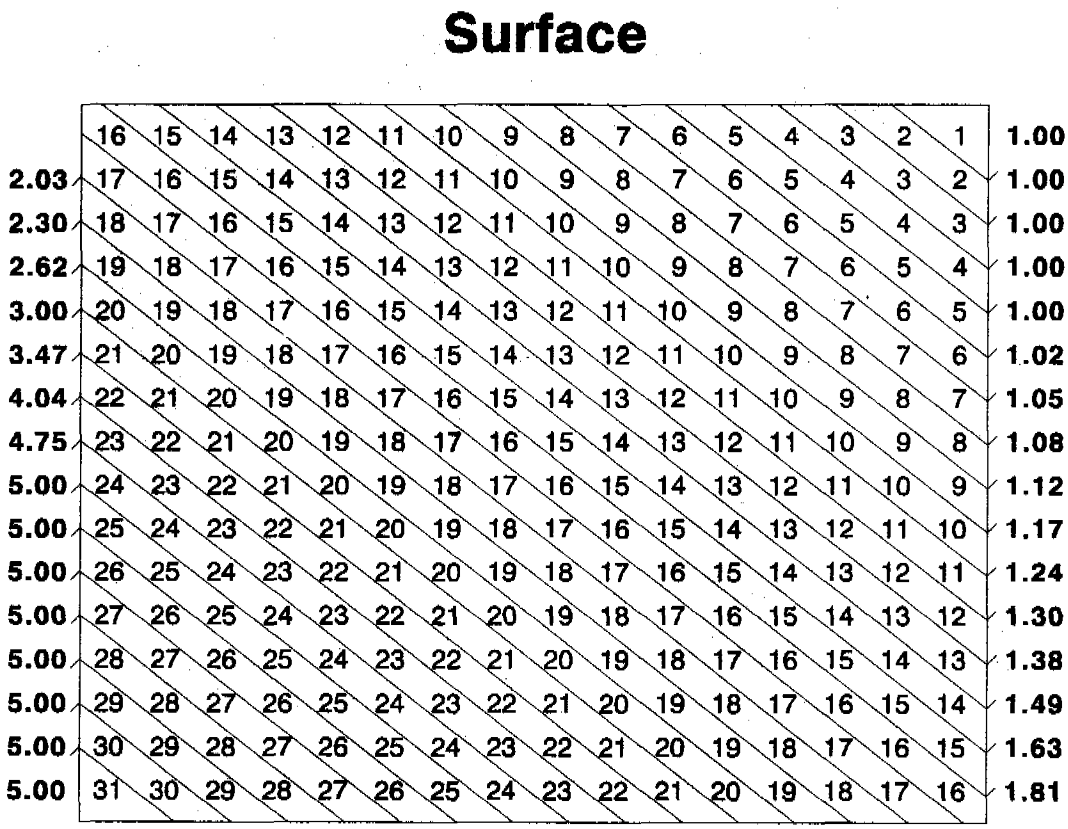

Figure 1. Simplified soil moisture diagram with 16 depth increments, 16 segments in each increment, and 31 slants identified by number. Bold numbers to the right and the left indicate the number of PE units to remove a unit of moisture.

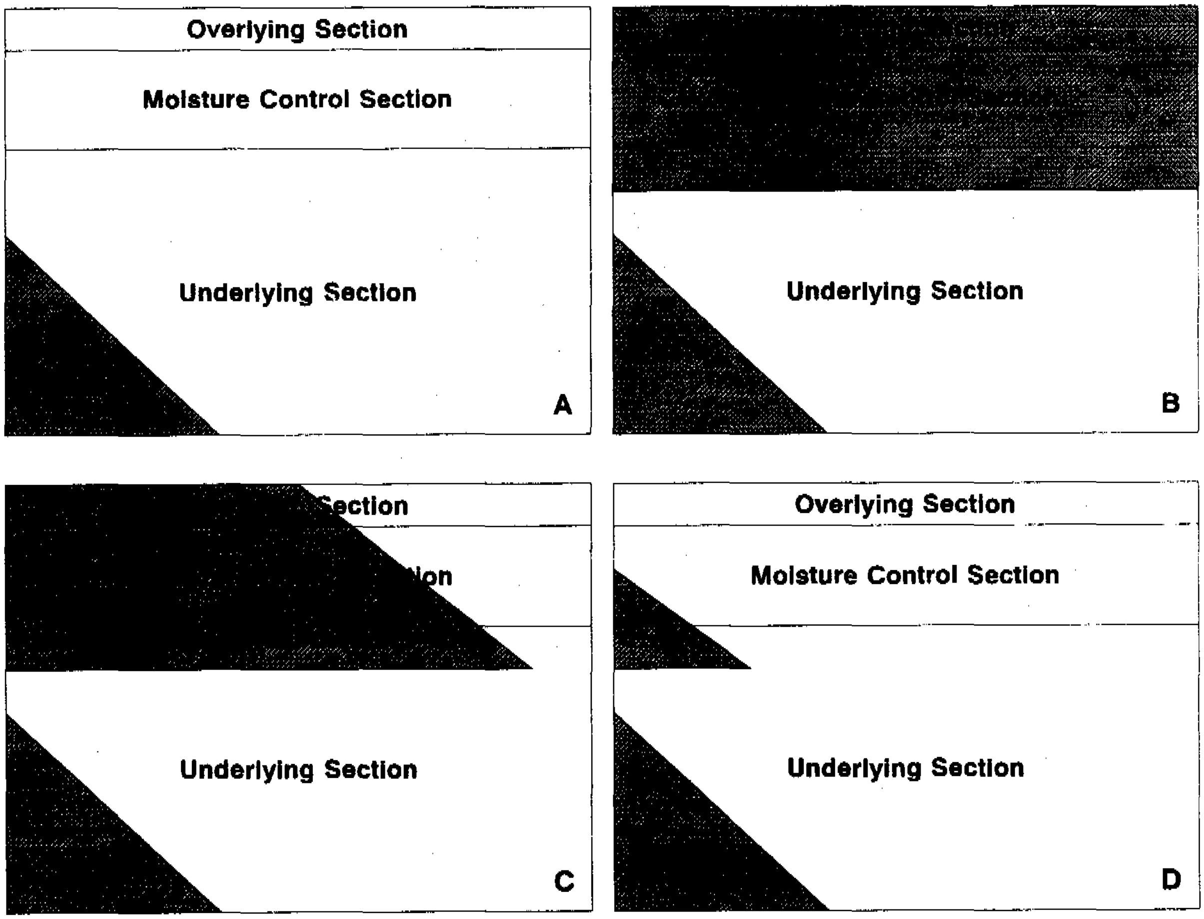

Figure 2. Simplified soil moisture diagrams showing the three sections of the soil moisture profile. The diagrams illustrate four moisture states and three moisture conditions of the moisture control section (MCS).

A. Water has been depleted by slants to below the MCS.
The moisture condition is D.

B. Water has filled increments from the top to below the MCS.
The moisture condition is M.

C. Water has been depleted by slants but all parts of the MCS are still moist.
The moisture condition is M.

D. Further water depletion by slants has made part of the MCS dry.
The moisture condition is B.

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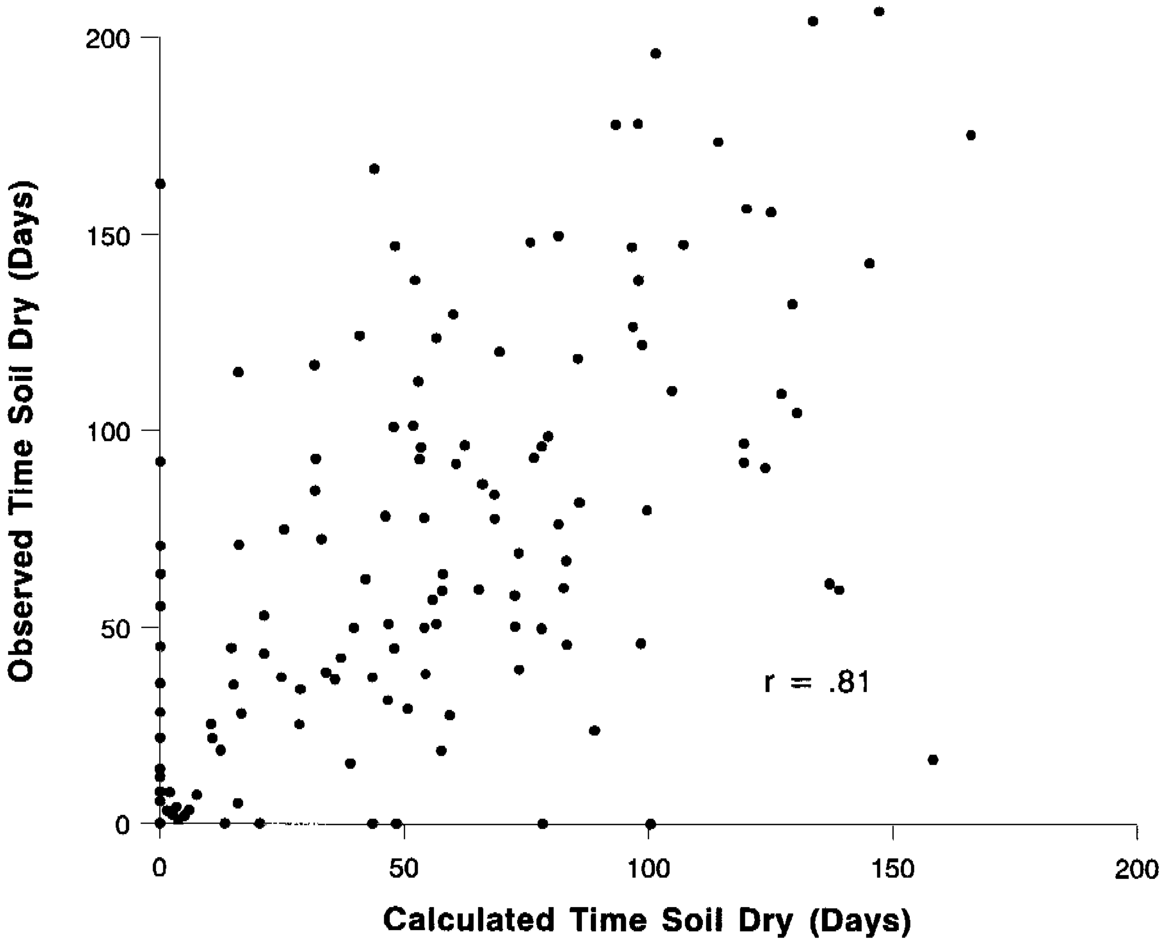

Figure 3. Number of days that soil layer is dry in all parts during period when soil temperature is estimated to be 5 °C or higher.