The Newhall Simulation Model for estimating soil moisture & temperature regimes

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1 Introduction

This paper describes the rationale of two software programs that use the Newhall model for the determination of soil moisture regimes: one is written in BASIC, the other one is written in and compiled in FORTRAN 77.

This text is an excerpt of a mimeographed article by Frank Newhall [2], which explained the rationale of his soil moisture regime model that he developed in the Soil Conservation Service of USDA as a climatologist working with Guy D. Smith. The sections which follow are only a part of Newhall's paper and are limited to the description of the mechanisms that his model uses to follow soil moisture changes and identify soil moisture regimes on the basis of monthly rainfall and temperature data.

The BASIC software works with monthly input data of only one year (either one indiviual year, monthly averages of a number of years, or normal years), longitude and latitude information, and computes potential evapotranspiration according to Thornthwaite [4]. It calculates the criteria that Soil Taxonomy [3] uses to define soil moisture and soil temperature regimes and classifies the regimes according to these criteria. The original Newhall model that he wrote in COBOL used inputs of several years, calculated the criteria of each year, and computed the frequency of occurrence of each of them durimg the years that data were available. It identified the soil regimes on the basis of these frequencies. The BASIC software discussed in this paper therefore differs in its approach from the original Newhall model by using average years. Newhall actually was opposed to the use of average input data. The BASIC model however strictly follows the mechanisms that Newhall used for moisture changes in the soil profile, as well as the Soil Taxonomy definitions of the moisture and temperature regimes.

Other additions were introduced in the BASIC model. The subdivisions of the soil moisture regimes were set up by A. Van Wambeke in 1976 in a research perspective and not modified since. They do not correspond to certain subdivisions that Soil Taxonomy uses in some taxa. The BASIC model also allows changes in the water holding capacity of the soil moisture profile that can be increased to 400 mm water. Finally, a year in the BASIC software is only 360 days long and all months last 30 days.

The FORTRAN model follows Newhall's rationale entirely and works with input data of several years that are processed separately. It allows changes in the water holding capacity of the moisture profile, and changes in the factors that relate air temperatures with soil temperatures.

2 Preliminary Assumptions of the Newhall Model

2.1 The Soil Moisture Profile

The soil moisture profile considered by the model extends from the surface down to the depth of an available water holding capacity (AWC) of 200 mm (≈8"). The soil depth needed to achieve this AWC depends on the pore geometry of the soil, and ranges from 80 cm in a well-structured clay to 200 cm in a light sandy loam; in a wide range of medium-textured soils, the depth required is 100 to 135 cm[1].

The profile is divided into 8 layers each of which retains 25 mm of available water; the second and the third layer form the **moisture control section** (MCS). This is defined by Soil Taxonomy as the layer having an upper boundary at the depth to which a dry (tension of more than 1500 kPA) but not air dry soil will be moistened by 25 mm

Moisture Control Section

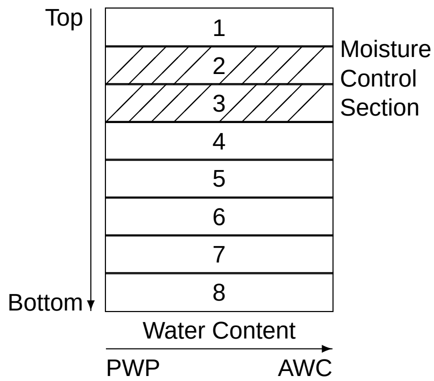
[1] [1], Table 2.3/7

of water moving downward from the surface within 24 hours. The lower boundary is the depth to which a dry soil will be moistened by 75 mm of water moving downward from the surface within 48 hours.

Figure 1 represents Newhall's soil moisture profile. The vertical axis indicates the depth of the eight layers, and the horizontal axis scales the amounts of available water present in each of them. The tension at which water is held in the profile decreases from left (**permanent wilting point**, PWP) to right (**field capacity**, FC). Each layer is divided into eight slots to form an eight by eight square matrix of 64 slots, which is designated as the *soil moisture diagram* as shown in Table 1. Each slot can be filled with a value corresponding to an amount of water which can vary between 0 and 1/64th part of the total available water holding capacity, or 3.125 mm in the case of water holding capacity of 200 mm.

Soil Moisture Diagram

Figure 1: Newhall's Soil Moisture Profile



2.2 Water Uptake and Water Removal

The model simulates the **downward movement of moisture** into the soil as the progression of a wetting front; it is further referred to as *accretion*. The distance that the wetting front moves downward depends on the amount of water needed to bring all the soil above it to field capacity.

When the wetting front reaches the bottom of the profile and the complete soil moisture profile is at field capacity, the **excess water** is lost either by *percolation* or by *runoff*.

The rate of **removal of water out of the soil**, or *depletion*, depends on the energy available for moisture extraction, expressed in terms of *potential evapotranspiration* (PE) which acts on the soil and the plants growing in the soil. The energy required to remove moisture from the soil depends on the amount of water (AW) present and the forces exerted by the soil to retain it. Water is removed more readily when the soil water is at low tensions than when the water content in the profile is at a minimum.

Less energy is used by the model to remove water from the upper layers of a soil than from the lower layers. The time needed to extract water from the soil depends on the depth at which it is located; this is in line with the fact that roots are more abundant near the surface than in deeper layers.

Depletion continues until the soil is at wilting point, e.g. when the soil moisture tension is 1500 kPA. The amount of water held in the soil is assumed not to be reduced below the amount held at 1500 kPA.

2.3 Distribution of Climatic Factors in the month

Precipitation

The monthly precipitation (MP) is distributed in each month according to the following sequence:

1. One half of the monthly precipitation (HP for *heavy precipitation*) falls during one storm in the middle of the month; this moisture enters the soil immediately without losses, except when the available water capacity of the soil moisture profiles is exceeded.

2. One half of the monthly precipitation (LP for *light precipitation*) occurs in several light falls, and is partly lost by evapotranspiration before it enters the soil; it can only infiltrate into the soil when LP exceeds the potential evapotranspiration.

Potential Evapotranspiration

The potential evapotranspiration (PE) is assumed to be uniformly distributed during each month. Not all its energy is used to extract water from the soil. A part is used to dissipate as much light precipitation as possible before it reaches the soil. If there is surplus energy, it is used for water extraction from the profile. PE is calculated according to Thornthwaite.

3 The Time-Step Progression of the Model

Each month, all of which are assumed to have 30 days, is divided into three parts. The first is a 15-day period of light precipitation (LP), the second is the heavy rainfall (HP) which occurs at midnight between the 15th and 16th of the month, and the third corresponds to another fortnight of light precipitation.

For each of these events water is either added to the soil or extracted from it. At the completion of each step, the **moisture condition** of the soil is determined, and if it changed, the model computes the number of days that each condition prevailed in the moisture control section.

The **starting** soil moisture condition of the profile is determined by running the simulation program for a number of consecutive iterations using each time the same yearly input until the moisture content of December 30th does not differ by more than one hundredth of the content found at the same date in the immediately preceding iteration. The program then starts the diagnostic processing of monthly data with an initial amount of water in each slot equal to the one found on December 30th.

When all months are processed the soil moisture conditions for each day are combined in the **moisture condition calendar** which forms the data base for the determination of the soil moisture regime criteria according to the definitions of Soil Taxonomy.

3.1 Processing sequence during one month

Each **half-month interval** is processed using the following inputs: monthly precipitation (MP) and monthly potential evapotranspiration (PE). The steps are as follows:

1. compute light precipitation, where $LP = MP/2$
2. compute the net potential evapotranspiration (NPE), where $NPE = (LP - PE)/2$

If $NPE > 0$, accretion will take place during this period; otherwise, water will be extracted from the profile.

All heavy precipitations in the middle of each month are processed by computing the heavy precipitations $HP = MP/2$ and entering this amount in the profile as accretion.

3.2 Changes in Water Content during each Period

Accretion

To simulate the additions of moisture to the profile, water is entered in the soil in,each non-full slot following a specific order shown in the soil moisture diagram of Table 1.

Table 1: Slot Sequence during Accretion

O1	02	03	04	05	06	07	08
09	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

The sequence starts with the left slot in the top row. Water is added to each successive slot in a row until the row is filled, or until the water supply is exhausted. When a row is completely full the program proceeds with the immediately underlying row, starting again on the left side of the moisture diagram. The accretion procedures in this way simulate the downward movement of a wetting front.

Depletion

The sequence for the extraction of water from the profile starts with the top right-hand slot and scans the slots in successive right-downward diagonals, as shown in Table 2

During the sequence each slot is examined, and if water is present, it is removed from it. The depletion stops when the potential evapotranspiration, or the energy it represents for the period being processed, is exhausted.

The rate of depletion is inversely proportional to the tension under which the water is held. It also varies with the depth of the layer. Both factors are taken into account in the calculations by means of the **depletion requirement diagram** which indicates the

Table 2: Slot Sequence during Depletion

29	22	16	11	07	04	02	01
37	30	23	17	12	08	05	03
44	38	31	24	18	13	09	06
50	45	39	32	25	19	14	10
55	51	46	40	33	26	20	15
59	56	52	47	41	34	27	21
64	63	61	58	54	49	43	36

value by which a unit of energy (expressed as evapotranspiration) has to be multiplied to extract one unit of water from the soil. This matrix of values is given in Table 3.

Table 3: Depletion Requirements

1.65	1.40	1.23	1.13	1.05	1.00	1.00	1.00
2.07	1.69	1.46	1.26	1.15	1.07	1.02	1.00
2.68	2.14	1.74	1.46	1.28	1.17	1.09	1.00
3.58	2.80	2.22	1.78	1.49	1.31	1.19	1.11
4.98	3.80	2.93	2.30	1.84	1.53	1.34	1.21
5.00	5.00	4.03	3.07	2.38	1.89	1.57	1.37
5.00	5.00	5.00	4.31	3.22	2.47	1.95	1.61
5.00	5.00	5.00	5.00	4.62	3.39	2.57	2.01

The processing continues until the entire evapotranspiration potential has been used, or until all slots have been set to zero. In the latter case any remaining depletion amount is not carried forward but is discarded.

3.2.1 Definitions of Soil Moisture Conditions

Soil Taxonomy recognizes three **soil moisture conditions**. They are diagnostic for determining the moisture regime of a pedon, and are evaluated in the moisture control section.

1. The moisture control section is *dry in all parts*. It is also called *completely dry*. The Newhall model accepts this condition when the leftmost slots numbered 09, 17, and 25 in Table 1 are all empty. (soil completely dry)

2. The moisture control section is *moist in all parts*, or *completely moist*. The Newhall model defines this condition when none of the leftmost slots numbered 09, 17, 25 in Table 1 is empty. (soil completely moist)

3. The moisture control section is *dry in some parts* or *moist in some parts*. It is also called *partly dry* or *partly moist*. The Newhall model considers this condition only when the moisture control section does not fulfill the requirements for (a) nor (b), e.g. when it is neither completely dry nor completely moist. (soil partly moist, partly dry)

The Newhall model includes slot 25 which is located outside the moisture control section (MCS) to determine the soil moisture condition. In an accretion step this slot signals that the MCS is completely full. In a depletion sequence it increases the amount of water which has to be extracted from the soil before a change to the completely dry condition is recorded. The inclusion of slot 25, and the diagonal extraction pattern, compensate in part for the fact that the model ignores all upward movements of water in the soil which in reality participates in the moisture supply to the MCS.

3.3 Moisture conditions in each two-week period

If the moisture condition changes during a period of light precipitation, the relative durations of each moisture condition is computed using the following equations:

$$DX = 15 \cdot RPEX/NPE$$

where DX is the duration in days of condition X, and $RPEX$ is either the amount of potential evapotranspiration needed to change this condition into the next one during a depletion phase (for example from completely moist to partly moist) or rainfall during an accretion phase. NPE is the potential evapotranspiration (or rain) which was available during the half-month being processed.

The duration of the moisture condition which ends a half month is calculated by difference, or

$$DE = 15 - DX - DX2$$

where DE is the duration of the soil moisture condition which ends the half month, and where DX and $DX2$ are the durations of the preceding conditions.

3.4 Changes in Soil Temperature

The definitions of both soil moisture and temperature regimes require the calculation of the periods when soil temperature is above or below certain critical values, e.g. 6^{o}C or 8^{o}C, as given in the definitions.

The beginning and ending dates of the period when the soil temperature is above or below a given critical value are approximated from the sequence of mean monthly temperatures.

The onset of a period when the soil temperature *rises above* a critical level is obtained by linear interpolation between the 15th day of each month; 21 days are then added to this date to compensate for the time lag between air and soil temperature at 50cm.

The onset of a period when the soil temperature *falls below* a critical level is obtained by linear interpolation between the 15th day of each month; 10 days are then added to this date to compensate for the time lag between air and soil temperature at 50cm; this lag is about half of the lag when the soil is warming up. This is because the soil is usually wetter when warming up than when cooling down, and so has a higher thermal capacity.

4 Determination of Moisture and Temperature Regimes

The model in the BASIC software processes the monthly data of one year and computes a calendar in which the moisture condition of each day is recorded. For the calculations of lengths of periods of soil conditions that extend across calendar years, the model attaches an identical second year to the input.

The two-year calendars are then scanned and the number of consecutive or cumulative days during which given soil climatic conditions prevail are calculated. These are included in the output, and listed in the tables.

A References

References

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[3] Soil Survey Staff, 1998. *Keys to Soil Taxonomy*, 8^{th} edition. US Government Printing Office: Washington, DC.

[4] Thornthwaite, C.W., 1948. *An approach towards a rational classification of climate*. Geographical Review **38**: 55.