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A PROGRAM FOR SOIL MOISTURE REGIME ESTIMATION WITH STOCHASTIC PRECIPITATION AND TEMPERATURE SIMULATION MODELS. APPLICATION TO NORTH-EAST OF SPAIN

E. Jarauta-Bragulat
Dept. of Applied Mathematics III
Section of Civil Engineering Statistics
ETSECCPB, Politechnical University of Catalonia, Gran Capità s/n, Edif. C2
08034 Barcelona
SPAIN

M.À. Colomer-Cugat and D. Vila-Navarra
Dept. of Mathematics, ETSEA
University of Lleida
Av. A. Rovira Roure, 177
25006 Lleida
SPAIN

ABSTRACT

Soil moisture regime is an essential property of soils for its classification according to "Soil Taxonomy System"; it is important also for irrigation planning, crop ordering and hydrologic resources evaluation of a zone. Soil moisture regime of a region can be only determined by direct field measures of soil temperature at 50 cm depth and the soil water content during a continuous series of years in some selected points of the region. If information needed for soil moisture regime determination is not available, it must be estimated with a simulation model; this is based on a model of soil temperature and soil water balance in the soil moisture control section, using climatic data information. If climatic data are not available, a model for generating series of temperature and precipitation values is needed. We present in this paper an integrated model for soil moisture regime estimation which consists of: (1) an stochastic model for precipitation and temperature series generation from data of neighbouring points; (2) a model for soil water balance, soil temperature and soil moisture regime simulation. An application to soil moisture regime estimation in the north-east of Spain is also included.

1. SOIL MOISTURE REGIME AND ITS DETERMINATION.

Soil moisture regime is a property of natural soils (soils with no irrigation water), which is essential to classify them according to "Soil Taxonomy System" (see [6]); it is also important for soil genetics study, irrigation planning, crop ordering and hydrologic resources evaluation of a zone. Soil moisture regime is referred to the evolution of water available for plants (soil water whose matric potential ψ_m is greater than -1500 kPa) in a part of the soil profile named *soil moisture control section (SMCS)* along the year and along a series of years. The *SMCS* is defined as the part of soil profile with upper limit of 25 mm of available water capacity and lower limit with 75 mm of available water capacity. The soil moisture regime is defined from the following variables: the soil moisture contents (θ), the *SMCS* state (M = moist, D = dry, B = both), the soil temperature at 50 cm depth (T_s), the mean annual soil temperature at 50 cm depth (T_{ma}), the mean soil temperature at 50 cm depth in summer (T_{su}) and the mean soil temperature at 50 cm depth in winter (T_{wi}).

In a non-tropical region ($T_{ma} < 22°$C and $T_{su} - T_{wi} \geq 5°$C) soil moisture regime is determined by appling the following criteria about the *SMCS* state:

(A) it is dry in all parts more than half the time (cumulative) with $T_s > 5°$C;

(B) it is moist in some or all parts along 90 consecutive days or more when $T_s > 8°$C;

(C) it is dry in some or all parts along 90 cumulative days or more;

(D) it is dry in all parts along 45 consecutive days or more in the four months following the summer solstice (june, 21th);

(E) it is moist in all parts along 45 consecutive days or more in the four months following the winter solstice (december, 21th),

as is established in "Soil Taxonomy" (see [6]). Five classes of soil moisture regimes can be obtained: *AQUIC, ARIDIC (TORRIC), UDIC, USTIC, XERIC* ; for a complete description and analysis, see [3], [4] and [6]. By definition, soil moisture regime can be only determined by direct field measures of T_s and θ in the *SMCS* during a continuous series of years, in a set of selected testing points in the zone. For complete soil moisture regime determination, the following information is needed on each testing point: the soil moisture characteristic curve $\psi_m(\theta)$; the soil moisture control section limits; the soil temperature at 50 cm depth T_s along the year; the intervals in which $T_s > 5°\mathrm{C}$ and with $T_s > 8°\mathrm{C}$; the soil moisture contents periodically (usually 7 or 14 days) determined along the year and the soil moisture control section state in each sample day.

From this information, determination of soil moisture regime is done as follows: determine the *SMCS* state in all days of the year (computed by linear interpolation with the soil moisture control section state in each sample day); do the same along a series of years; compute the relative frequences of occurrence of each "Soil Taxonomy" criterion and finally, you establish the class of soil moisture regime on each sample point. If no field data are available but climatic data (dayly or monthly precipitation and dayly or monthly mean air temperature) are available, soil moisture regime must be estimated with a simulation model as is described in section 3. If no climatic information is available, a model for its estimation is needed; we present one in the next section.

2. MODEL FOR PRECIPITATION AND TEMPERATURE SERIES SIMULATION.

Some models for independent generation of series of precipitation and temperature values have been developed; nevertheless, we have been analyzing the correlation between both variables and we have found a significative coefficient of correlation. Taking into account this correlation, we have formulated a precipitation-temperature composed model with air temperature values conditioned to rainfall occurrence. This model consists of a five-valued random variable $(X_n(t), Y_n(t), Z_n(t), R_n(t), T_n(t))$, whose definition and calculus are as follows.

▪ **Variable** $X_n(t)$. It is defined as a discret random variable which expresses if there is or not rainfall occurrence in the n-day of the t-month along the year. It is modelized by a first order Markov chain with two states: $X_n(t) = \{E_0, E_1\}$, where $E_0 = \{\text{precipitation } = 0\}$ and $E_1 = \{\text{precipitation } > 0\}$. Initial and transition probabilities are given by:

$$P\Big[X_1(t) = E_i\Big] = p_i^X(t), \qquad P\Big[X_n(t) = E_j \Big| X_{n-1}(t) = E_i\Big] = p_{ij}^X(t),$$
$$(0 \le i, j \le 1,\ 2 \le n \le 31,\ 1 \le t \le 12).$$

▪ **Variable** $Y_n(t)$. It is defined as a discret random variable that expresses the interval in which the precipitation value belongs in the n-day of the t-month along the year. It is modelized by a multinomial distribution with six possible states; if we denote the following precipitation values (mm): $\omega_0 = 0,\ \omega_1 = 1,\ \omega_2 = 4,\ \omega_3 = 8,\ \omega_4 = 15,$ and then we consider the following six intervals for precipitation values, P: $E_0 = \{P = 0\}$; $E_i = \{\omega_{i-1} < P \leq \omega_i\}$ $(i = 1,2,3,4)$; $E_5 = \{P > 15\}$, then the multinomial distribution is defined by the following probabilities:

$$P\Big[Y_n(t) = E_i \Big| X_n(t) = E_j\Big] = \begin{cases} 1, & \text{if } j = 0, i = 0 \\ 0, & \text{if } j = 0, i > 0 \\ 0, & \text{if } j = 1, i = 0 \\ p_i^Y(t), & \text{if } j = 1, 1 \leq i \leq 5, \end{cases}$$

$$(1 \leq n \leq 31,\ 1 \leq t \leq 12,\ \sum_1^5 p_i^Y(t) = 1).$$

▪ **Variable** $Z_n(t)$. It is defined as a discret random variable that represents the interval in which the temperature is in the n-day of the t-month along the year. It is modelized by a first order Markov chain with four possible states defined as follows: for each month of the year we take into consideration three temperature limits: $\omega_0(t), \omega_1(t), \omega_2(t)$, $(1 \leq t \leq 12)$, and then we consider four intervals for temperature values in each month: $E_0 = \{T < \omega_0(t)\}$, $E_1 = \{\omega_0(t) \leq T < \omega_1(t)\}$, $E_2 = \{\omega_1(t) \leq T < \omega_2(t)\}$, $E_3 = \{T \geq \omega_2(t)\}$. Thus we have the following initial and transition probabilities:

$$P\Big[Z_1(t) = E_i \Big| X_1(t) = E_k\Big] = p_{ki}^Z(t),$$
$$P\Big[Z_n(t) = E_j \Big| Z_{n-1}(t) = E_i, X_n(t) = E_k\Big] = p_{kij}^Z(t),$$
$$(0 \leq i,j \leq 3,\ \ 0 \leq k \leq 1,\ \ 2 \leq n \leq 31,\ 1 \leq t \leq 12).$$

▪ **Variable** $R_n(t)$. It is defined as a continuous random variable that represents the precipitation value in the n-day of the t-month along the year. It is defined as follows: if $a \in \mathbb{R}$ is any real number, the distribution function of $R_n(t)$ is given by:

$$P\Big[R_n(t) \leq a \ \Big|\ Y_n(t) = E_0\Big] = \begin{cases} 0, \text{ if } a < 0 \\ 1, \text{ if } a \geq 0 \end{cases}$$

$$P\Big[R_n(t) \leq a \ \Big|\ Y_n(t) \in E_i\Big] = \begin{cases} 0, & \text{if } a \leq \omega_{i-1} \\ \dfrac{\Gamma(a) - \Gamma(\omega_{i-1})}{\Gamma(\omega_i) - \Gamma(\omega_{i-1})}, & \text{if } a \in E_i,\ 1 \leq i \leq 4; \\ 1, & \text{if } a > \omega_i; \end{cases}$$

$$P\Big[R_n(t) \leq a \ \Big|\ Y_n(t) = E_5\Big] = \begin{cases} 0, & \text{if } a \leq \omega_4 \\ \dfrac{\Gamma(a) - \Gamma(\omega_4)}{1 - \Gamma(\omega_4)}, & \text{if } a \in E_5 =]\omega_4, +\infty[. \end{cases}$$

$(1 \leq n \leq 31,\ 1 \leq t \leq 12;\ \ \Gamma(*)$ is the gamma distribution function$)$.

▪ **Variable** $T_n(t)$. It is defined as a continuous random variable that represents the temperature value in the n-day of the t-month along the year. It is defined as follows: if $b \in \mathbb{R}$ is any real number, the distribution function of $T_n(t)$ is given by:

$$P\Big[T_n(t) \le b \ \Big|\ Z_n(t) = E_0\Big] = \begin{cases} \dfrac{N(b)}{N(\omega_0) - N(\beta)}, & \text{if } b \le \omega_0 \\ 1, & \text{if } b > \omega_0 \end{cases}$$

$$P\Big[T_n(t) \le b \ \Big|\ Z_n(t) = E_i\Big] = \begin{cases} 0, & \text{if } b \le \omega_{i-1} \\ \dfrac{N(b) - N(\omega_{i-1})}{N(\omega_i) - N(\omega_{i-1})}, & \text{if } b \in E_i, 1 \le i \le 2, \\ 1, & \text{if } b > \omega_i \end{cases}$$

$$P\Big[T_n(t) \le b \ \Big|\ Z_n(t) = E_3\Big] = \begin{cases} 0, & \text{if } b \le \omega_2 \\ \dfrac{N(b) - N(\omega_2)}{1 - N(\omega_2)}, & \text{if } b > \omega_2 \end{cases}$$

$(1 \le n \le 31,\ 1 \le t \le 12;\ \ N(*)$ is the normal distribution function).

For details and a complete description of this model see [1] and [2]. For a series of precipitation and temperature simulation, 43 independent parameters are needed for each month of the year; parameter estimation is done from the climatic series of the 10 nearest observatories to point P. Two coefficients are defined: one for the distance $(C_D(i))$ and another for the altitude $(C_A(i))$; finally we compute a global influence coefficient from these two coefficients. Obviously, far observatories have very little influence on the value of coefficients.

3. MODEL FOR SOIL MOISTURE REGIME ESTIMATION.

A first simple model for soil moisture regime estimation from climatic data (monthly precipitation and mean monthly air temperature) was formulated by F.Newhall in 1976; for a complete description of this model, see [3] and [5]. Some problems with this model were pointed out by Jarauta (see [3] and [4]) and so a new model has been developed to solve them. Schematically, the elements and variables of this new model are as follows:

- **Soil profile.** It is modelized by a real valued matrix $S_r = (s^i_j) \in \mathbb{R}(r, 8)$, where $r = 2, 3, \cdots, 8$, depending of the soil profile kind; each element takes values in the interval $0 \le s^i_j \le 3.125$ mm of water, $1 \le i \le r, 1 \le j \le 8$. Each row of the matrix represents a soil horizon with 25 mm of available water capacity; thus, the *SMCS* is represented by rows s^2 and s^3 of matrix S_r. The total capacity of S_8 is 200 mm of water; this has been considered enough for representing the root zone in the major part of crops. When soil matrix is full, excedent water is to be considered lost by surface runoff or deep percolation.

- **Infiltration process.** The infiltration water is the precipitation water with a runoff coefficient; the infiltration of water into soil is simulated by a sequence of filling, following the columns of S_r matrix in each row (horizon). Precipitation can be obtained from climatic data (monthly or dayly) or by the model for generating series described in the section before.

- **Evapotranspiration process.** The amount of evapotranspiration water is computed by Blaney-Cridle method adapted by Jarauta following Doorenbos and Pruitt and formulated (see [3]) as a finite-difference equation which computes actual evapotranspiration in the t-day of the month as a function of soil water content in the $(t-1)$-day and potential evapotranspiration of crop. Thus, evapotranspiration water in the t-day is computed as:

$$E(t) = \lambda e^{-\lambda} W(t-1),\ \lambda = \frac{E_c}{(1-q)W(S_r)},\ E_c = k_c \cdot E_o,$$

being: $W(t-1)$ the soil water content in the $(t-1)$-day, E_c the potential evapotranspiration of the crop, E_o the potential evapotranspiration of the reference crop, k_c the crop coeficient, q the available water fraction, and $W(S_r)$ is the available water capacity of soil matrix. Evapotranspiration process of water is simulated by an output sequence, following the inverse diagonals of S_r matrix, for taking into account the redistribution process.

- **SMCS state.** From dayly water balance in soil, a *SMCS* dayly state matrix Θ_j is computed for each year of the series $(1 \leq j \leq n)$.

- **Soil temperature.** It is computed by linear interpolation from mean weekly air temperature. Thus, a soil temperature matrix T_j is computed for each year of the series $(1 \leq j \leq n)$.

- **Soil moisture regime.** Intervals with $T_s > 5°C$ and $T_s > 8°C$ are computed from matrix T_j in each year, and annual soil moisture regime R_j is computed $(1 \leq j \leq n)$. Finally, the class of soil moisture is obtained by applying Soil Taxonomy criteria (with some modifications, as is exposed in [3]).

4. COMPUTER IMPLEMENTATION.

To do all computations prescribed in the model, a pack of computer programs has been prepared. It is writen in FORTRAN language (VMS version) using the IMSL routines. The pack consists on:

- **Principal.for** Is the main program and it controlles all the process; as input it has: point coordinates (X, Y, Z), number of years to process, kind of soil profile and crops in the zone. After this, ten nearest observatories are selected, all containing computed parameters for coeficients.

- **Lectura.for** Subroutine for initial probabilities of Markov chains, transition matrices parameters and mean and variance of each state.

- **Markovt1.for** Subroutine for temperature states generation from initial values vector and transition matrix.

- **Markovl1.for** The same as before for precipitation.

- **Normalt.for** Subroutine for dayly temperature values estimation from the corresponding state of the day using normal distribution.

- **Lognormal.for** The same as befor for precipitation, using lognormal and gamma distributions.

- **Blaneycr.for** Subroutine for evapotranspiration computations using Blaney-Cridle method.

- **Balanc.for** Subroutine for soil water balance simulation and soil moisture control section state computation.

- **Regims.for** Subroutine for soil moisture regime determination from all computations done before. Computation is done for each year of the series and finally for the complete series of years.

- **Resultat.for** Subroutine for model output generation. For each year it consist in an ASCII file of 365 rows and 5 columns (mean temperature, precipitation, evapotranspiration, water contents in soil profile and soil water in the soil moisture control section. In screen, output is different, presenting monthly results, total annual precipitation, total annual evapotranspiration and estimated soil moisture regime class.

5. MODEL APPLICATIONS AND CONCLUSIONS.

A first application of the model has been done in a semi-arid zone of Catalonia (north-east of Spain) in which we have some testing points with a series of six years of field data; *Xeric* and *Aridic* moisture regimes were obtained, with very good agreement between field data and model estimation results. A second application has been done with climatic data of several observatories of Catalonia, now without field data; *Xeric*, *Aridic*, *Udic* and *Ustic* moisture regimes were obtained; these results seem to be quite good with field observation and crops in each area and some testing points will be taken in the future for better testing of the model. For details see [7].

Conclusions

(1) The proposed integrated model seems to be a very good approach for soil moisture regime estimation according the Soil Taxonomy System.

(2) Soil Taxonomy classification needs to be adapted to other climates, because they are refered only to the USA climate characteristics.

(3) The soil moisture regime classes estimated for soils in Catalonia are *Udic* in the north zone, *Xeric* and *Aridic* in the central area and *Xeric* and *Ustic* in the coastal zone. No error evaluation of the model is possible on the estimation of soil moisture regime in Catalonia, because no field data exists in this region.

6. REFERENCES

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