

ASSESSING THE EFFECT OF SOIL USE CHANGES ON SOIL MOISTURE REGIMES IN MOUNTAIN REGIONS (CATALAN PRE-PYRENEES NE SPAIN)

By

J.C. Loiza Usuga*, E. Jarauta-Bragulat**, J. Porta Casanellas***, R.M. Poch Claret***

Abstract

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Soil moisture regimes under different land uses were observed and modeled in a representative forest basin in the Catalanian Pre-Pyrenees, more specifically in the Ribera Salada catchment (222.5 km²). The vegetation cover in the catchment consists of pasture, tillage and forest. A number of representative plots for each of these land cover types were intensely monitored during the study period. The annual precipitation fluctuates between 516 and 753 mm, while the soil moisture content oscillates between 14 and 26% in the middle and low lying areas of the basin, and between 21 and 48% in shady zones near the river bed, and in the higher parts of the basin. Soil moisture and rainfall are controlled firstly by altitude, with the existence of two climatic types in the basin (sub-Mediterranean and sub-alpine), and further, by land use. Two models were applied to the estimated water moisture regimes: the Jarauta Simulation Newhall model (JSM) and the Newhall simulation model (NSM) were found to be able to predict the soil moisture regimes in the basin in the different combinations of local abiotic and biotic factors. The JSM results are more precise than the results obtained using another frequently used method, more specifically the Newhall Simulation Model (NSM), which has been developed to simulate soil moisture regimes. NSM was found to overestimate wet soil moisture regimes. The results show the importance of the moisture control section size and Available Water Capacity (AWC) of the profile, in the moisture section control state and variability. The mountain soils are dominated by ustic and occasionally xeric regimes. Land use changes leading to an increase in forest areas would imply

* Laboratory of Hydrology and Soil Conservation, Forestry and Technology Center of Catalonia, Solsona, Spain. Correo electrónico: jc.loaiza@ctfc.es

** Department of Applied Mathematics III, Politechnical University of Catalonia. Barcelona, Spain: Correo electrónico: jarauta@etsecepb.upc.es

*** Department of Environment and Soil Sciences, University of Lleida, Lleida, Spain: Correo electrónico: jporta@macs.udl.cat , rosa.poch@macs.udl.cat

drier soil conditions and therefore drier soil water regimes. These effects are most evident in degraded shallow and stony soils with low AWC.

Key words: soil moisture regimes, hydrologic simulation, mountain ecosystems, land use.

Resumen

Los regímenes de humedad del suelo bajo diferentes usos del suelo fueron observados y modelados en una cuenca forestal modelo en el Prepirineo meridional Catalán, específicamente en la cuenca de la Ribera Salada (222.5 km²). La vegetación presente en la cuenca consiste en pasturas, cultivos y bosques. Un número representativo de parcelas experimentales por cada uso del suelo fueron monitoreados de forma intensiva durante el periodo estudiado. La precipitación anual fluctúa entre 516 y 753 mm, mientras el contenido de humedad del suelo oscila entre 14 y 26% en la parte baja y media de la Cuenca y entre 21 y 48% para zonas de umbría cerca de las riberas, y en las partes altas de la cuenca. La humedad del suelo y las lluvias están controladas en primer lugar por la altitud, con la existencia de dos pisos climáticos en la cuenca (sub-Mediterráneo y sub-alpino), y además por los usos del suelo. Dos modelos fueron implementados para estimar los regímenes de humedad del suelo: El Modelo de Simulación Jarauta (JSM) y el Modelo de Simulación Newhall (NSM) encontrando que pueden predecir los regímenes de humedad del suelo en la cuenca para diferentes combinaciones de factores bióticos y abióticos a escala local. Los resultados usando JSM son más precisos que los obtenidos mediante el modelo más usado, concretamente NSM, el cual ha sido específicamente desarrollado para la simulación de los regímenes de humedad del suelo. El NSM tiende a sobre estimar los regímenes de humedad del suelo, tendiendo hacia regímenes húmedos. Los resultados muestran la importancia de la profundidad de la sección control del suelo y la capacidad de retención de humedad del suelo, en el estado y variabilidad de la sección control de humedad del suelo. Los suelos en zonas de montaña mediterránea están dominados por regímenes ústicos y excepcionalmente xericos. Los cambios en los usos del suelo están direccionados hacia un incremento de las áreas forestales lo cual implica una disminución en la humedad del suelo. Estos efectos son más evidentes en suelos superficiales degradados y pedregosos con baja retención de humedad.

Palabras clave: regímenes de humedad del suelo, modelos de simulación hidrológica, ecosistemas de montaña, usos del suelo.

1. Introduction

The regulation of water resources is an urgent priority in the management of ecosystems, particularly in Mediterranean environments. Mediterranean climates are characterized by intra-annual rainfall variability, with conditions of water deficit in Summer and a very strong impact of human activity (Rius, *et al.*, 2001; Ceballos & Martínez, 2002; Gallart, *et al.*, 2005). During the last five decades, land use in the Pyrenees has known a strong change, with a replacement of pastures and tillage by forests (Ubalde, *et al.*, 1999). This dynamic change is typical for all Spanish mountainous areas (Lasanta, 1988; Pounds, 1987; Cantera, 1997; Ubalde, *et al.*, 1999).

Several studies from different climate regions have shown that land use change induces a change in the soil hydrological properties affecting the hydrological regime (Giertz, *et al.*, 2005; Bormann & Klaassen, 2008) and it is well known his strong impact on the hydrologic dynamics

of Mediterranean basins (Ubalde, *et al.*, 1999; Gallart, *et al.*, 2005; Orozco, *et al.*, 2006). However, the consequences of land use changes on the future water resources availability in these areas are at present poorly understood. Up till now, a number of studies have focused on a description of the dynamics of the water behaviour in the catchments (Diekkruger, *et al.*, 1995; Batalla & Sala, 1996; Sala & Farguell, 2002; Llorens, *et al.*, 2003; Verdú *et al.*, 2000; Gallart, *et al.*, 1994, 2005; Orozco, *et al.*, 2006; Latron & Gallart, 2007; Loaiza & Poch, 2009) and soil moisture behaviour of such catchments (Crow & Wood, 2002; Giertz, *et al.*, 2005; Gallart, *et al.*, 2005; Bormann & Klaassen, 2008; Loaiza & Poch, 2009).

The physical and biological processes in Mediterranean environments are highly dependent on the spatial variability of soil water availability (García-Pausas, *et al.*, 2004). The intra-annual variability of temperature and soil moisture in these environments, together with rainfall distribution, conditions how the ecosystems functions (Casals, *et al.*,

2000). At the same time, land-use changes imply strong consequences for plant species composition (**De Bello, et al.**, 2005) and this might have direct consequences on water resources. These changes affect in a direct way the soil moisture behaviour, vegetal species distribution and hydrologic dynamic of the basins. Further, in Mediterranean ecosystems, water is considered to be key factor limiting plants grow, survival and competition (**Sebastia**, 2007). Changes in soil moisture behaviour affect the distribution of dominant grass species limited biomass production, growth, reproduction and resource allocation of the plants (**Kariklanderud**, 2005).

Soil moisture regime is an important property of the soil that provides relevant information about the availability of soil water for plants and the use and management of the soil (**SSS**, 1975, 2006; **FAO**, 2006). The concepts of normal year, soil moisture control section and classes of soil moisture regimes have been introduced (**SSS** 1975). From an operational point of view a number of methods have been devised to estimate the soil moisture regime out of meteorological records, but all these methods suffer from some shortcomings (**Jarauta et al.**, 1993; **FAO**, 2006). A comprehensive comparison of the ability of agroecosystems models to predict soil water status has been performed and published by **Diekkrüger et al.** (1995). Several researchers have used environmental information in soil moisture regime estimation: **Waltman et al.** (1997, 2002) in USA; **Trnka et al.** (2002); **Kapler et al.** (2006) in Czech Republic; **Costantini et al.** (2002) in Italy; **Tavernier & Van Wambeke** (1976a, 1976b) in Spain and Morocco; **Van Wambeke** (1976, 1981, 1982, 1985, 2000) in Syria, Lebanon, South America, Africa, Asia and North America. The obtained predictions by soil moisture regime simulation models provide a historical context of drought events (**Waltman et al.**, 2002). With these models it is possible to determine the probabilities of occurrence of a particular group of soil climate conditions in simulated sceneries (**Trnka et al.**, 2002) and economic relations of resources for specific regions (**Waltman et al.**, 1997, 2002). In Italy, **Costantini et al.** (2002) used the soil moisture simulation model to predict soil moisture regimes and soil moisture and correlated it with potential soil erosion.

One of the devised methods is the Newhall simulation model (**Van Wambeke**, 2000) that has been studied and evaluated by **Jarauta** (1989), **Jarauta et al.** (1993) and **Porta et al.** (2003). This model proposed to take into account complete meteorological information, daily and monthly rainfall, effective precipitation, vegetation and soil data. They propose a Jarauta Simulation Model (JSM) that tries to correct some shortcomings of the Newhall Simulation Model (NSM) found by **Tavernier & Van Wambeke** (1976a,

1976b), **Ibáñez & Gascó** (1983), **Lázaro et al.** (1978), **Elías & Ibáñez** (1983) in the estimation of soil moisture regimes in xeric-aridic transitional regions in Spain.

The estimation of soil moisture regimes has to deal with the probability of several conditions of the soil moisture status in an average year, and therefore has to be based on long observation period. The calculation of a soil moisture regime to one single year is not correct in the sense that it does not characterize an average year related to a vegetation type or to a land use potential. Nevertheless, their determination for a short series of years, and the comparison of estimated and measured regimes, gives a first approximation to its probability of occurrence and shows the applicability of the models. The aim of this research is to relate the soil moisture content and soil moisture regimes in Mediterranean soils with different uses by estimating soil moisture regimes. The particular aims of the paper are: (i) to study the soil moisture behaviour under actual conditions, considering different land use, and (ii) to implement a hydrologic model to estimate the different moisture regimes in the basin and to compare the results to the results obtained using JSM and NSM.

2. Site description

The experimental area, the Ribera Salada basin, is located in the Pre-Pyrenean mountainous area of Northeastern Spain. The basin covers an area of 222.5 km². Figure 1 shows the location of the study area and the observation sites. The climate is mainly Mediterranean and varies to sub-alpine in the highest parts of the basin, with a mean annual precipitation ranging from 624 mm in the low lying areas to 874 mm in the highest areas. The mean temperature during the Summer is 20°C during and 5.1°C during the Winter. The relief is tabular with slopes often higher than 20% with an altitude ranging from 420 to 2385 m. The substrate consists of massive conglomerates and calcareous sandstones merging to calcareous siltstones. Soils are shallow, calcareous and stony. Most soils are classified as Lithic and Typic Ustorthents (**SSS**, 1993, 2006). A description of the complete soil survey can be found in **Orozco et al.** (2006). The predominant land use is forestry, from brook forest to subalpine and sub-Mediterranean vegetation. The agricultural zone is mainly planted with potatoes, alfalfa, and cereal with a low level of nitrogen fertilization. There are also high mountain grasslands with a low technologic level and low trampling.

3. Data acquisition

The observational data were acquired from 1998 through 2005; eight experimental plots of 5 x 5 m² were

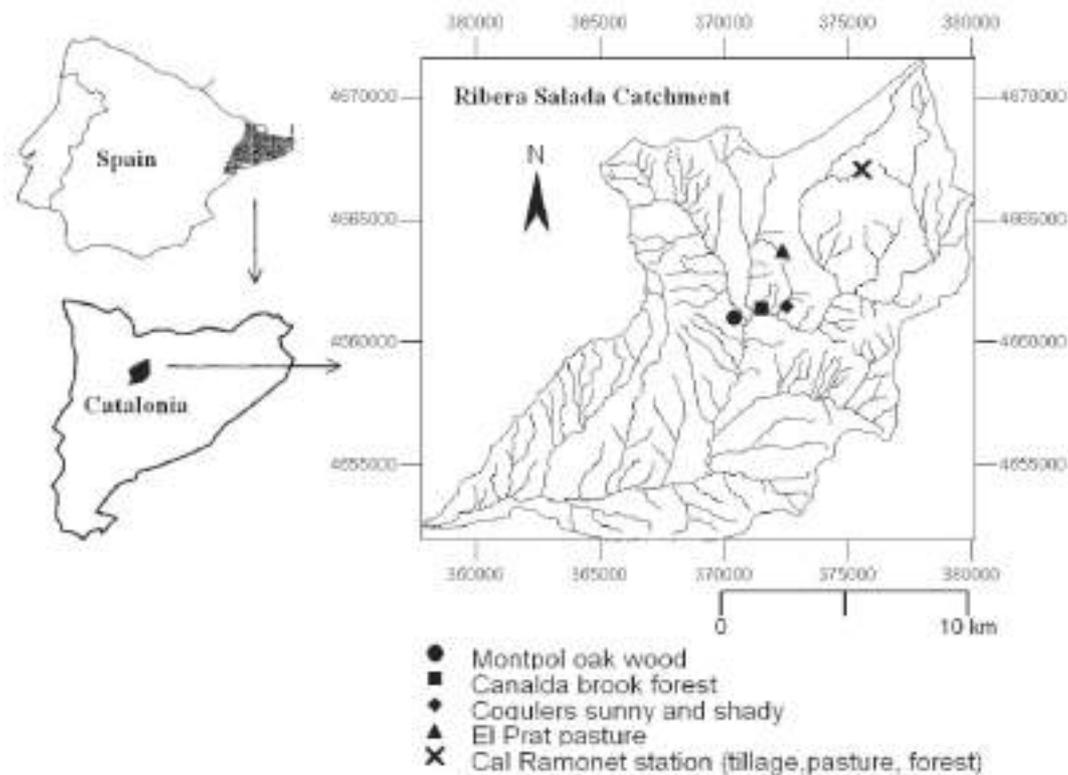


Figure 1. The study area.

selected based on representative soil types and land uses of the catchment. Table 1 lists the names of these stations, together with their land use and soil type. The location of these stations is shown in Figure 1. A number of these stations have longer observation periods than others, but from 2003 through 2005 all stations were operational. The meteorological information was obtained from the Xarxa Agrometeorològica de Catalunya (XAC) meteorological station. This station is named Lladurs and is placed at the same location as the Montpol station. Air temperature and relative humidity were measured using a Vaisala HMP45 sensor (Vaisala, Helsinki, Finland). Soil temperature was measured at a depth of 5 and 50 cm using a 107-L sensor (Campbell Scientific, Leicestershire, UK). Wind speed was measured using a Young 05103 sensor (RM Young, Traverse, Michigan, USA). Rainfall was measured using an ARG 100 rain gauge (Campbell Scientific, Leicestershire, UK). All these measurements were taken with an interval of one second and stored with an interval of one minute. All instruments were controlled by a CR10X data logger (Campbell Scientific, Leicestershire, UK). Furthermore, data from the Cal Ramonet rainfall station of the Forestry and Technology Centre of Catalonia were available. These observations were obtained using a RGB1 rain -gauge

(Campbell Scientific, Leicestershire, UK). Rainfall information was measured with a five minute interval and stored using a CR10X data logger (Campbell Scientific, Leicestershire, UK). With each land use area, three sites were selected to measure the hydraulic conductivity (K_s) measured by the disk infiltrometer (Perroux & White, 1988); particle distribution using hydrometer methodology (Bouyoucos, 1962), as well as porosity, stone content and the soil moisture content at field capacity and the wilting point (SSS, 1992). A soil control section was established according to the soil taxonomy criteria. Table 2 shows the results of these in situ measurements.

Soil moisture was continuously measured using ECH2O (Decagon Devices Inc., Pullman, Washington, USA) sensors at 30 cm depth, with four sensors per site from 1998 through 2005. Measurements were taken and stored with an interval of one hour, using an Em5 data logger (Decagon Devices Inc., Pullman, Washington, USA). In order to ensure a good contact, the soil was previously sieved and placed around the sensor at field, avoiding the direct contact with stones. The sensors were calibrated for each site in the period 2003-2004. The calibration was performed following the guidelines of the manufacturer.

Table 1. Land use and soil type of the study plots. The fractional coverage of the land and soil types in the catchment are indicated between brackets (units are percentages).

Station	Land use	Soil Type [SSS 2006]
Montpol oak wood Canalda brook forest	<i>Quercus Ilex</i> [18] <i>Buxus Sempervirens</i> ¹ <i>Pinus Sylvestris</i> ¹ <i>Quercus Ilex</i> ¹ [12]	Typic Calciustepts [4] Typic Ustifluvents [1]
Cogulers shady	<i>Pinus Sylvestris</i> [25]	Typic Ustorthortents[25]
Cogulers sunny	<i>Pinus Sylvestris</i> [25]	Typic Calciustepts [4]
El Prat pasture	Pasture [8]	Typic Haploustepts [12]
Cal Ramonet Tillage	<i>Solanum Tuberosum</i> ² <i>Triticum Sativum Vulgare</i> ² <i>Medicago Sativa</i> ² <i>Onobrychis Viciifolia</i> ² [15]	Typic Calciudolls[7]
Cal Ramonet pasture	Mountain Pasture [6]	Typic Calciudolls[7]
Cal Ramonet pine forest	<i>Pinus uncinata</i> [18]	Miscellaneous Rock [1]

¹ Forest compound "forest near river".

² In culture rotation.

Volumetric soil moisture values were determined using in-situ obtained soil samples. These results were compared to the volumetric soil moisture values registered by the sensors. Linear calibration equations for the different soil types were obtained, with r^2 values ranging from 0.74 to 0.92. A more detailed description of these measurements can be found in **Loaiza & Pauwels** (2008).

4. Jarauta simulation model

This soil moisture model used in this study, the JSM makes it possible to daily or hourly rainfall data in the prediction of soil moisture regime with limited data availability. The JSM considers, the rainfall infiltration efficiency into the soil using, and takes into account soil boundary characteristics that affect infiltration and evapotranspiration. Infiltration capacity is modelled using the hydraulic conductivity (Ks) in combination with daily climatological data. To calculate the amount of water extraction from the soil profile through evapotranspiration, the model uses an adaptation of the Blaney- Criddle formula, realized by **Doorenbos and Pruitt** (1977). The maximum field capacity is 200 mm and the minimum value is 50mm. These values depend on the soil boundary and or soil water retention. The soil temperature's average is obtained by means of an equation that correlates the averages of the air temperature and the soil temperature.

The temperature values are homogeneous, just like the increase of temperature in winter and summer. The average of temperature differences (air-soil) is obtained and these data make it possible to know the soil temperature's average at 50cm depth. The outputs (soil moisture and soil temperature) work with different water soil capacities and a wide array of crops. For an overview of the field experiments and test sites to which the model has already successfully been applied, we refer to **Jarauta**, 1989; **Jarauta et al.**, 1993 and **Porta et al.**, 2003.

5. Newhall simulation model

The NSM is the traditional model used by the Natural Resources Conservation Service of the United States Department of Agriculture to estimate soil moisture regimes according to soil taxonomy (SSS, 2006; **Waltman et al.**, 1997). The soil moisture regimes has been studied and modeled at a large number of locations, more specifically in Europe (**Tavernier & Van Wambeke**, 1976a; **Robson & Thomasson**, 1977; **Item**, 1978; **Elias & Ibañez**, 1983; **Wösten et al.**, 1985; **Cescatti**, 1992; **Jarauta et al.**, 1993; **Kapler et al.**, 2006) Asia (**Van Wambeke**, 1976, 1985; **Stuart et al.**, 1985), Africa (**Tavernier & Van Wambeke**, 1976b; **Watson**, 1981; **Van Wambeke**, 1982) and America (**Newhall**; 1976; **Van Wambeke**, 1981; **Davidoff & Selim.**, 1988; **Jeutong et al.**, 2000; **Waltman et al.**, 2002). **Van Wambeke** (2000)

modified the original model (Newhall, 1976) and introduced new subdivisions of soil moisture regimes and variable soil moisture storage. The model was originally developed to simulate soil moisture changes and to identify soil moisture regimes based on monthly rainfall and temperature data. NSM monthly input data is restricted to a period of one year. Winter and Summer soil temperature averages are evaluated by means of the monthly air temperature averages, using Soil Taxonomy criteria. NSM also assumes that all precipitation events are effective unless soil moisture is saturated. With respect to the soil moisture profile, the model assumes a profile from the surface downwards to the depth of an available water holding capacity (AWC) of 200 mm. 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 at which the water is removed out of the soil depends on the energy available for moisture extraction, expressed in terms of potential evapotranspiration. NSM uses longitude and latitude information to obtain potential evapotranspiration following the Thornthwaite equation (Thornthwaite & Mather, 1957). A full description is provided by Van Wambeke (2000).

6. Results and discussion

6.1. Precipitation and soil water content measurements

The average precipitation over the study period is 621 mm. An ustic regime has been obtained for all years and sites, except for Canalda brook forest and Cal Ramonet forest, when the precipitation over the study area was 507 mm, and a xeric regime was obtained. The highest saturated hydraulic conductivity (K_s) is observed for grassland soils and crop land soils followed by forest, Table 2. According to Loaiza & Poch, 2009, the infiltration capacity of the soil

in Ribera Salada catchment is affected to land cover type and explained the low runoff values. This xeric regime was obtained in superficial or stony soils under forests and in bank zones, where soil moisture is controlled by means of water table level fluctuations. In all other conditions an ustic regime was still obtained, except for the Cogulers shady site, where ecologic conditions favor soil water retention. The observed soil moisture retention percentage is low in all plots, except in old agricultural terraces (more specifically the Cal Ramonet site) and Cogulers shady, Table 3. In this site the moisture retention percentage is slightly higher, which leads to a lower number of consecutive dry days. This phenomenon favors the presence of ustic moisture regimes in the basin. The presence of xeric regimes (which are typical Mediterranean regimes) is conditioned by the distribution and volume of the precipitation and the depth of the soil control section.

Figure 2 shows the evolution of the monthly averaged soil moisture content and precipitation in the study sites, for the three years in which data were available for all sites. The precipitation is highest in the first place during the Fall, and in the second place during Springtime. During Winter and Summer low precipitation rates are observed. The soil moisture is depleted during the Summer and replenished during the Fall. During the Winter the soil moisture content decreases again, but to a lesser extent than during the Summer, which can be explained by the effect of evapotranspiration. Overall, the duration of the dry season determines the soil moisture regime. In general, ustic soil moisture regimes prevail, except for the Cogulers shady site. However, when the precipitation in the Fall initiates later than usual, xeric regimes are obtained in shallow soils and riparian zones. Here it can be seen that during the drought periods in Summer and Winter the soil moisture values decrease to the wilting point and below. The duration of the drought periods depends on the temporal distribution of the precipitation. During the periods

Table 2. In-situ measured soil physical parameters

Station	Ub [cm]	Lb [cm]	SHC [mm/h]	FC [%]	WP [%]	SC [%]	Porosity [%]	BD [gr/cm ³]	Texture Class
Montpol oak wood	5	62	6.75	27.15	11.63	40	49.60	1.53	Sandy loam
Canalda brook forest	4	64	7.75	29.50	13.20	36	51.98	1.4	Loam
Cogulers shady	4	64	4.88	25.03	13.16	45	55.16	1.55	Loam
Cogulers sunny	5	40	8.92	21.48	16.35	38	49.60	1.35	Sandy loam
El Prat pasture	5	40	10.93	38.05	15.04	28	46.03	1.50	Loam-loamy sand
Cal Ramonet	5	60	11.21	43.49	19.26	51	51.59	1.06	Loam-clay loam

Upper boundary: Ub, Lower boundary: Lb, Saturated Hydraulic Conductivity: SHC, Soil Moisture at Field Capacity: FC, Soil Moisture at Wilting point: WP, Stone Content: SC, Bulk Density: BD.

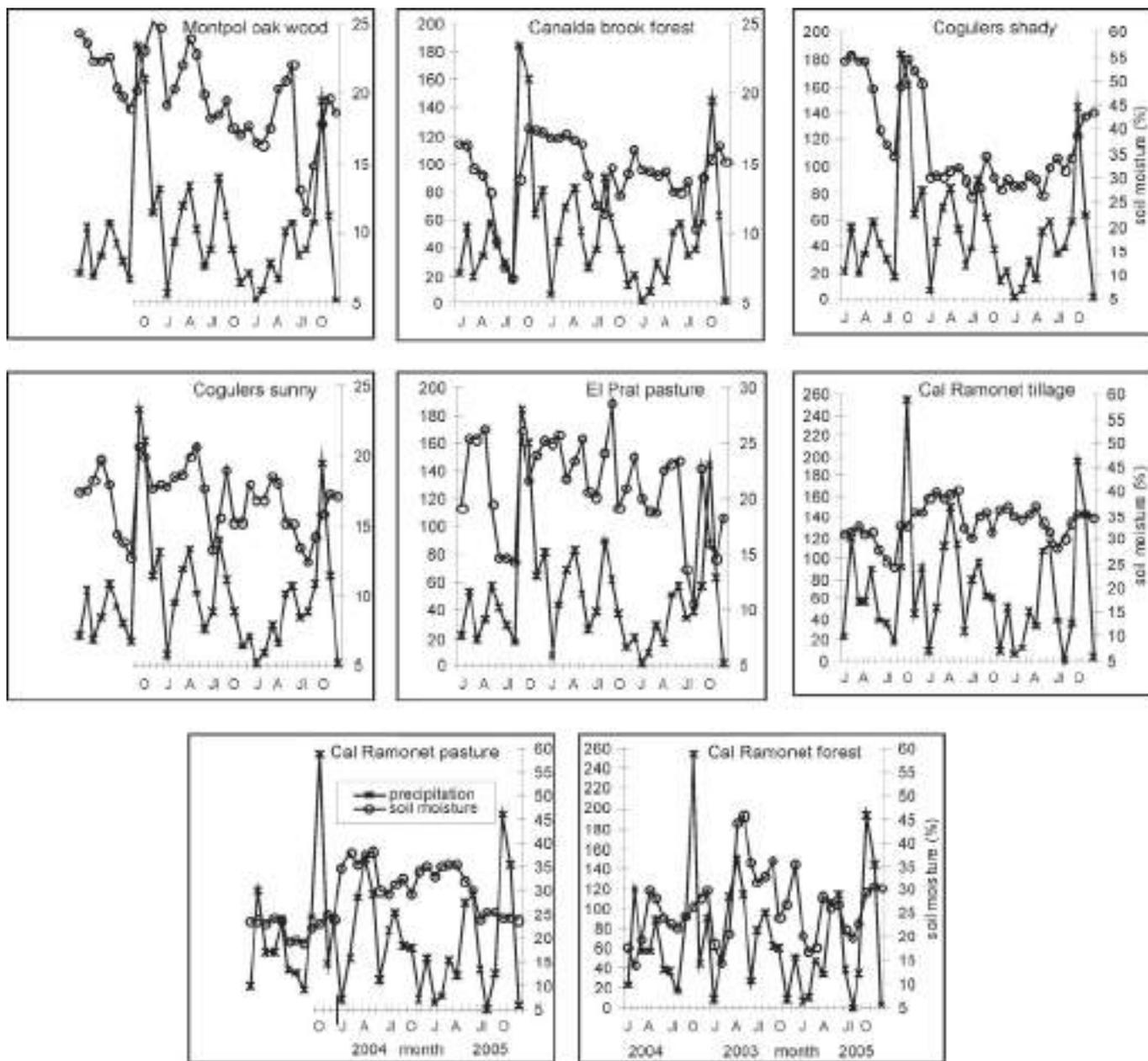


Figure 2. Monthly average precipitation and soil moisture for the different study sites during the period 2003-2005.

of low soil moisture the volume and intensity of the precipitation is low, which can be observed. The results shows that in the highest part of the basin (the Cal Ramonet stations), where the climate is sub-alpine, the soil moisture content is higher than in the other stations, except for the Coguliers shady site. In this station the topographical conditions (converging stream lines), combined with the dense structure of the vegetation lead to consistently high

soil moisture values. Figure 2 shows that the soil moisture values are lower in the intermediate and lowest parts of the basin, where sub-Mediterranean climate conditions prevail. The soil moisture values are strongly influenced by the presence of orographic precipitation. For the study period, the average precipitation in the Winter months (DJF) was 30 mm. For Spring (MAM) this average was 45 mm, for Summer (JJA) 46 mm, and for fall (SON) 78 mm. While the

precipitation is slightly higher in Summer than in Winter, the soil moisture contents are lower. This can be explained by the effect of evapotranspiration. In summary, the soil moisture values in the different sites show an annual cycle. The soil moisture profile is exhausted at the end of the Summer, after which it is replenished by the Fall precipitation. During the Winter the low precipitation values lead to a decrease in soil moisture, but to a lesser extent than in the Summer. The variations of this behaviour are regulated by the altitudinal distribution of the precipitation and the physical and topographical characteristics of the soil control section.

6.2. Simulations using JSM

For each test site three year with no missing daily soil moisture data was used for the parameter estimation. Only soil moisture values were used in the parameter estimation. The in-situ measured parameters were used as initial guess. Table 2 lists these parameter values. Using the observations of soil temperature, and soil moisture content during the remainder of the study period was then used for model validation. **Jarauta et al.** (1993) demonstrated that the model is capable of reproducing all these soil moisture

behaviour, and concluded that the model can be used to simulate the soil moisture regime in dry environments. Table 3 shows the results of this model application. A number of conclusions can be drawn from this table. First, the JSM simulations have a very low bias with respect to the observations. The Root Mean Square Error between the observations and simulations is below 2% for the majority of the annual results. This RMSE is calculated as:

$$RMSE = \frac{\sqrt{\sum_{n=1}^N [\theta_o(n) - \theta_s(n)]^2}}{N} \quad (1)$$

N is the number of observations, and θ_o and θ_s are the observed and simulated soil moisture (-), respectively. In general, the number of dry days has been simulated with reasonable accuracy. However, in some cases a relatively large difference in the number of dry days has been obtained. This can be explained by the structure of the hydrologic model. JSM provides daily time series of soil moisture, while the number of dry days is a threshold value. For example, for the Canalda brook site RMSE in the order of 1.25% has been obtained. However, the amount of dry days has been overestimated by a factor of two. This

Table 3. Average observed and simulated soil moisture behaviour (2003 – 2005) for the different test sites. O stands for observations, JSM for Jarauta simulation model, NSM for Newhall simulation model.

Station		Montpol oak wood	Canalda brook forest	Cogulers shady	Cogulers sunny	El Prat pasture	Forest	Cal Ramonet pasture	tillage
Soil dry * (days)	O	10	155	0	140	55	40	30	0
	JSM	10	55	0	118	85	20	20	0
	NSM	30	30	30	30	30	0	0	0
Soil moist (days)	O	350	40	0	130	295	300	330	360
	JSM	208	135	78	165	157	150	135	105
	NSM	195	195	195	195	195	50	50	50
Soil wet (days)	O	0	170	365	95	15	20	0	0
	JSM	147	175	287	88	123	195	210	260
	NSM	140	140	140	140	140	315	315	315
Average soil moisture (%)	O	19.8	14.2	37.2	16.89	21.02	26.35	28.45	33.57
	JSM	22.3	24.03	23.76	18.66	27.75	37.18	37.68	40
	NSM	21.73	23.81	20.88	19.69	30.01	41.83	41.83	41.83
Soil moisture regime	O	ustic	ustic/xeric	udic	ustic	ustic	ustic/xeric	ustic	ustic
	JSM	ustic	ustic/xeric	udic	ustic	ustic	ustic/xeric	ustic	ustic
	NSM	ustic/xeric	ustic	ustic/udic	ustic/xeric	ustic/xeric	ustic/udic	ustic/udic	ustic/udic
RMSE**	JSM	1.47	1.25	2.02	1.36	1.52	1.69	1.76	1.91
	NSM	1.47	1.25	3.46	4	0.04	1.69	1.76	1.91

* number of days with soil moisture percentage less than wilting point values, ** RMSE: Root Mean Square Error, moist: average soil moisture percentage between field capacity and wilting point values, wet: average soil moisture percentage higher than field capacity values.

indicates that, while JSM clearly simulates the soil moisture behaviour in this case, the number of dry days is not a good criterion to evaluate the model performance. However, for all test sites and for all years, the soil moisture regime has been simulated without any errors.

6.3. Simulations using NSM

While in a number of cases the model correctly estimates the soil moisture regime, a relatively large number of erroneous model predictions have been obtained, Table 2. For a number of simulations, an udic regime has been obtained, while in reality the soil moisture regime is ustic. The Root Mean Square Error between the observations and simulations are between 1.25 to 4% for the annual results. This can be explained by the average soil moisture state, which has been simulated as wet, while in reality it is moist. Further, ustic regimes have in some cases been simulated as xeric, which can be explained by the erroneous prediction of the number of consecutive dry days. Also, udic regimes have in some cases been simulated as ustic or xeric, which can again be explained by errors in the modeled number of dry days and/or the average soil moisture state. As a summary, it can be concluded that one must be very careful when using the predicted soil moisture regime by the NSM.

6.4. Comparison between both models

In The Ribera Salada catchment simulated NSM soil moisture values in the Cal Ramonet station (higher altitudes) and Lladurs station (lower altitudes) are higher than the actual values, giving moister soil water regimes. The differences depend on altitudes: the results are lower than the actual ones in Summer and in the beginning of Autumn in the lower parts of the catchment. Also, on higher altitudes, the actual moisture values are lower in Summer. The real and the NSM values differ to 90%, in some cases NSM overestimates the soil moisture content. According to **Jarauta et al.** (1993) and **Porta et al.** (2003), NSM does not model very well the variability of water available for plants, because it considers all the efficient rain, and therefore excluding Mediterranean showers with high intensities. Moreover, it models the evapotranspiration very simply, and does not take into account other rain types or orographic characteristics that may favor slope runoff.

The simulation according to the JSM gives three different soil moisture regimes: udic, ustic and xeric, with two different patterns: i) a biannual one, with two dry periods (winter and summer) with a recharge at the end of spring and autumn; and ii) an annual one, with a single

summer drought. The simulated values are closer to the observed ones in dry periods, coinciding in their duration, time and seasonal behavior; thus it is possible to predict the total days and the state of moisture content. The real and simulated regimes and subtypes coincide almost completely, between 90 - 100%, both in determining the soil moisture regime. The RMSE results in Montpol, Canalda and Cal Ramonet sites in both models have been similar. However, in the other sites the JSM predictions is more accurately than NSM. The prediction improves when the real measured regimes are ustic or udic, because this model is better adjusted to partly dry soil conditions.

JSM tends to simulate soil moisture in accordance with the ecological conditions of each site because it allows us to work with different available water capacity values, soil profile thicknesses, infiltration conditions and evapotranspiration estimations. NSM overestimates ustic regimes in relation to the ecological conditions of the studied sites. **Tavernier & Van Wambeke** (1976a) assigned an udic common regime to all Pyrenees mountain zones and ustic and aridic regimes in zones with Mediterranean climates in Catalonia. These authors defined ustic regimes in the Iberian Peninsula as transitional pedoclimates, between xeric types and udic or aridic regimes. Other authors like **Elias & Ibañes** (1983) found that in the Ebro river basin, under real xeric and aridic soil moisture regimes, NSM assigns an ustic regime. These Mediterranean ustic regimes do not fit within the concept of tropical ustic regimes, characterized by wet summers and dry winters, except in some areas where the orography affects the water supply during winter, as it happens in some Pyrenean valleys (**Poch & Boixadera**, 2008).

In Italian Mediterranean soils, using NSM, **Costantini et al.** (2002) found xeric soil moisture regimes in years that actually had ustic and udic regimes. In Zimbabwe, **Watson** (1981) also found serious limitations of NSM in the determination of ustic and udic soil moisture regimes. In our research, NSM only coincides with real field values in the simulations of a reduced number of years.

5. Conclusions

In this study, two models to predict soil moisture regimes have been applied to eight test sites located in the Ribera Salada catchment in the Spanish Catalanian pre-Pyrenees. The first model, Jarauta Simulation Model (JSM) considerer an adaptation to different types of soil with drained and AWC variable, corrected monthly rainfall according to rainfall efficiency. On the other hand, the second model, the Newhall Simulation Model (NSM), is a

threshold-based soil moisture regime model, using only precipitation and air temperature as local information. Hourly observations of soil moisture have been used to evaluate the models. The measured soil water contents confirm the prevalence of ustic regimes, while xeric regimes occur in dry years. Udic regimes occur in areas located close to water sources. An example of such a site for this study is the Cogulers shady site. While in many cases the NSM accurately simulates the soil moisture regime, it frequently erroneously predicts these regimes. This can be explained by errors in the prediction of the number of consecutive dry days and/or the average soil moisture state. On the other hand, JSM has been found to predict the soil moisture regime in all cases. The model results of JSM as compared to the NSM can be explained by the theoretical foundation of the model. JSM has been designed to work in very specific conditions (Mediterranean environments), while the NSM uses only basic meteorological information in a number of threshold-based general equations. The estimation of soil moisture regime by JSM hits 100% of the cases, while NSM hits 66% of the cases in relation to the measured data in the field. The results show a 62 % of coincidence between two models.

Since JSM approaches the natural system, it can be expected that, when it is well calibrated, it accurately predicts the soil moisture regime according to the soil taxonomy requirements [SSS, 2006]. As a first approximation the NSM has certainly proven to be useful for soil moisture regime prediction, especially when computational power is limited, and if one is careful in the interpretation of its results. Both simulation models are limited in the daily prediction of soil moisture percentages, due to small variations in initial soil moisture, rain intensity and rain water volume, because the purpose of these models is to estimate in a probabilistic way the soil water regime on a yearly basis, and not the evolution of the daily soil water content. The use of such a model for soil moisture regime predictions is an unexplored subject that, since computational possibilities are continuously increasing, should be given more attention in the future.

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References

- Batalla, R. & Sala, M.** 1996. Impact of land use practices on the sediment yield of a partially disturbed Mediterranean catchment. *Z.Geomorph.N.F.* 107: 79-93.
- Bormann, H. & Klaassen, K.** 2008. Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma.* 145: 295-302.
- Bouyoucos, GJ.** 1962. Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal.* 54(3): 464-465.
- Casals P, Romanyà J, Cortina J, Bottner P, Coûteaux MM, Vallejo R.** 2000. CO₂ efflux from a Mediterranean semi-arid forest soil. I. Seasonality and effects of stoniness. *Biogeochemistry.* 48: 261-281.
- Crow, WT & Wood, EF.** 2002. The value of coarse-scale soil moisture observations for regional surface energy balance modelling. *Journal of Hydrometeorology.* 3: 467-482.
- Cantera, ME.** 1997. La agricultura en la edad media. Cuadernos de historia. Arco/libros, sl. Madrid.
- Ceballos BA & Martinez FJ.** 2002. Soil surface water dynamics in different spatial units under dehesa land use system. *Rev G & C.* 16(1-4): 33-42.
- Cescatti, A.** 1992. A computer program for the application of the Newhall model in the classification of the soil moisture regime. *Atti dell Istituto di Ecologia e Silvicultura, Padova* 6: 65-85.
- Costantini, E., Castelli, F. Raimondi, S. & Lorenzoni, P.** 2002. Assessing soil moisture regimes with traditional and new methods. *Soil Sci Soc Am J* 66: 1889-1896.
- Davidoff, B & Selim, HM.** 1988. Correlation between spatially variable soil moisture content and soil temperature. *Soil Science.* 145: 1-10.
- De Bello, F, Leps, J., Sebastià, MT.** 2005. Predictive value of plant traits to grazing along a climatic gradient in the Mediterranean. *J. Appl. Ecol.* 42: 824-833.
- Doorenbos, J., Pruitt, WO.** 1977. Crop water requirements, irrigation and drainage. United Nations. Rome. Irrigation drain, Paper N° 24, 144p.
- Elías, F. & Ibáñez, V.** 1983. Comparison between two mathematical models to the estimation of soil moisture regimes. *INIA.* N° 6. p. 49-60.
- FAO.** 2006. World reference base for soil resources 2006 A framework for international classification, correlation and Communications. Food and Agriculture Organization of the United Nations. Rome. World Soil Sources Reports 103: 132 p.
- Gallart F., Llorens P. & Latron J.** 1994. Studying the role of old agricultural terraces on runoff generation in small Mediterranean mountainous basin. *Journal of hydrology.* 159: 291-3003.
- , **Latron J. & Llorens P.** 2005. Catchment dynamics in a Mediterranean mountain environments. The Vallcebre research basins (Southeaster Pyrenees). I : hydrology. In: Garcia, C., Batalla, R.J (Eds). Catchment dynamics and river processes: Mediterranean and other climate regions. ELSEVIER. p 1-16.

- García-Pausas J., Casals P., Romanya J.** 2004. Litter decomposition and faunal activity in Mediterranean forest soils: effects of N content and the moss layer. *Soil Biology & Biochemistry* 36: 989-997.
- Giertz, S., Junge, B. & Diekkrüger.** 2005. Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa. *Physics and Chemistry of the Earth*. 30: 485-496.
- Ibáñez, V. & Gascó, J.** 1983. Modification in the mathematical model proposed to Newhall .F to the estimation of the soil moisture regimes. Agriculture, fishing and food Ministry. INIA Communications. Natural Resources Series. Nº 18. Madrid. Spain.
- Item, H.** 1978. A model for the water regime of coniferous forest and grassland. *Journal of Hydrology*. 37: 323-332.
- Jarauta, E.** 1989. Models to the estimation the soil moisture regimes. Application to the determination to the soil moisture regimes in agricultural soils in Lleida. Spain. Unpublishing. Ph.D. Thesis. University of Lleida. www.tdx.cat
- , **Porta, J. & Boixadera, J.** 1993. Soil moisture regimes: Interest and problems to the application in the Catalan soils. *Catalan Natural History Institution Bulletin*. Barcelone. Spain. P. 87-96.
- Jeutong, KM., Waltman, WJ. & Smith, OS.** 2000. Comparison of bioclimatic indices for prediction of maize yields. *Crop Science* 40: 1612-1617.
- Kapler, P.** 2006. Newhall model for assessment of agricultural drought event probability under present and changed climatic conditions. European Geosciences Union. *Geophysical Research Abstracts*. Vol. 8.
- Kariklanderud.** 2005. Climate change effects on species interactions in an alpine plant community. *Journal of Ecology* 93: 127-137.
- Lasanta T.** 1988. The process of desertion of cultivated areas in the Central Spanish Pyrenees. *Pirineo*. 132: 15-36.
- Latron, J., Gallart, F.** 2007. Seasonal dynamics of runoff-contributing areas in a small Mediterranean research catchment (Vallecebre, Eastern Pyrenees). *J. Hydrol.* 335(1-2): 194-206.
- Lazaro, F., Elías, F., Nieves, M.** 1978. Soil moisture regimes in Spain. INIA publications. Nº 20. 34 p.
- Loaiza Usuga J.C & Pauwels VRN.** 2008. Use of soil moisture sensors in the determination of soil moisture content (Calibration equations). *Suelos Ecuatoriales*. SCCS. 38(1) 24-33.
- Loaiza Usuga, J.C & Poch, RM.** 2009. Evaluation of soil water balance components under different land uses in a Mediterranean mountain catchment (Catalan Pre-Pyrenees Ne Spain) *Z.Geomorph.N.F.* 53(4): 519-537.
- Llorens, P., Oliveras, I., Poyatos, R.** 2003. Temporal variability of water fluxes in a *Pinus sylvestris* forest patch in Mediterranean mountain conditions. (Vallecebre research catchments, Catalan Pyrenees). In: Servat, E., Najem, W., Leduc, C., Shakeel, A (Eds), *Hydrology of Mediterranean and semiarid regions*, IAHS publication 278, Wallingford, UK. pp. 101-105.
- Newhall, F.** 1976. Calculation of soil moisture regimes from the climatic record. USDA. Soil Conservation Service. 22 p.
- Orozco, M., Poch, RM., Batalla, RJ., Balasch, JC.** 2006. Hydrochemical budget of a Mediterranean mountain basin in relation to land use (The Ribera Salada, Catalan Pre - Pyrenees, NE Spain). *Z.Geomorph. N.F.* 50: 77-94.
- Perroux, KM & White, I.** 1988. Designs for disc permeameters. *Soil. Sci.Soc. Am. J.* 52(5): 1205-1215.
- Poch RM & Boixadera J.** 2008. (Eds) Cerdanya soils. Field manual. DMACS-University of Lleida.
- Pounds, NJ.** 1987. *Historia económica de la Europa medieval*. ed. Critica, Editorial Grijalbo. 500 p.
- Porta, J., López-Acevedo, M., Roquero, C.** 2003. Edaphology to the agriculture and environment. World press editions. 929 p.
- Rius, J, Batalla, VR & Poch, RM.** 2001. Monitoring water and sediment yield in Mediterranean mountains watersheds: preliminary results. 10th international soil conservation organization meeting held may 24-29. Purdue University- USDA-ARS. P. 223-228.
- Robson, JD & Thomasson, AJ.** 1977. Soil water regimes. A study of seasonal waterlogging in English lowland soils. Soil survey. Technical monograph Nº 11. England. 57 p.
- Salas, M^a & Farguell, J.** 2002. Exportación de agua y sedimento en dos pequeñas cuencas Mediterráneas bajo diferentes usos del suelo. *Sistema Costero Catalán. Rev. C. & G.* 16(1-4): 97-109.
- Sebastià, MT.** 2007. Plant guilds drive biomass response to global warming and water availability in subalpine grassland. *Journal of Applied Ecology* 44: 158-167.
- Soil Survey Staff.** 1975. Soil taxonomy. A basic system of soil classification for making and interpretation soil surveys. SSS Soil Conservation Service. Agric, Handbook Nº 436. US Gov printing office. Washington, D.C.
- . 1992. Soil survey laboratory methods manual. Soil Conservation Service. U.S. Dept. of agriculture. Rpt. No. 42. Washington. DC.
- . 1993. Soil Survey Manual. Soil Survey Division Staff. Soil Conservation Service. U.S. Department of Agriculture. Handbook 18.
- . 2006. Keys to Soil taxonomy. Ninth edition. SSS Soil Conservation Service. Agric. US Gov printing office. Washington, D.C.
- Stuart, R, King, J, Van Wambeke A.** 1985. Calculated soil climate regimes of the Yemen Arab Republic Taxonomy and management of vertisols and aridisols. Proceedings of fifth international soil classification workshop, Sudan. p. 27-35.
- Tavernier, R. & Van Wambeke, A.** 1976a. Determination of soil moisture regimes in Spain used the Newhall mathematical model. *Agrochimica*. (In Spanish). 20, Nº 45. p. 407-412.
- & **Van Wambeke, A.** 1976b. Determination of soil moisture regimes in the Maghreb used the Newhall model. *Pedology*. (In French). 26: 168-178.
- Thorntwaite, CW & Mather, JR.** 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Institute of Technology, laboratory of Climatology, Publications in Climatology. 10(3): 311.

- Trnka, M., Semerádová, D., Dubrovský, M., Zalud, Z., Svoboda, M., Hayes, M. & Wilhite, D.** 2002. Drought event probability in the Czech Republic under the present and changed climatic conditions- Unpubl. NATO Science Program. University of Agriculture and Forestry Brno. Czech Republic.
- Ubalde, JM., Rius, J., Poch, RM.** 1999. Monitorización de los cambios del uso del suelo en la cabecera de la Cuenca Ribera Salada mediante fotografía aérea y SIG [El Solsonès, Lleida, España]. Pirineos. 153-154. p. 101-122.
- Van Wambeke, A.** 1976. Computation of soil temperature and moisture regimes in Lebanon and Syria according to F. Newhall's model- Unpubl. Cornell University. Ithaca, NY, USA. 20 p.
- _____. 1981. Calculated soil moisture and temperature regimes of South America. Soil Management Support Services Technical Monograph N° 2. USDA-SCS. Washington, D.C.
- _____. 1982. Calculated soil moisture and temperature regimes of Africa. Soil Management Support Services Technical Monograph n° 3. USDA SCS. Washington, D.C.
- _____. 1985. Calculated soil moisture and temperature regimes of Asia. Soil Management Support Services Technical Monograph n° 9. USDA-SCS. Washington, D.C.
- _____. 2000. The Newhall simulation model for estimating soil moisture and temperature regimes. Department of crop and soil science. Cornell University, Ithaca, NY, USA.
- Verdú, JM., Batalla, RJ., Poch, RM.** 2000. Dinámica erosiva y aplicabilidad de modelos físicos de erosión en una cuenca de montaña mediterránea [Ribera Salada, Cuenca del Segre, Lleida, España]. Pirineos. 155: 37-57. [In Spanish, with English abstract].
- Waltman, W., Ciolkosz, E., Mausbach, M., Svoboda, M., Miller, D. & Kolb, P.** 1997. Soil climate regimes of Pennsylvania. Penn State Agricultural Experiment Station Bulletin 873. Iowa State University. National Soil Survey Centre. Lincoln. Nebraska.
- Waltman, W., Goddard, S., Reichenbach, S., Gu, G., Cottingham, J., Peake, J., Tadesse, T., Harms, S. & Deogun, J.** 2002. Digital government: reviving the Newhall simulation model to understand the patterns and trends of soil climate regimes and drought events- Unpubl. Dept. of Computer Science and Engineering. University of Nebraska. Lincoln.
- Watson, J.** 1981. Estimation of soil moisture regimes for classifying soil according to the United States System. Zimbabwe J. Agric. Res. 19: 229-231.
- Wösten, JHM, Bouma, J, Stoffelsen, GH.** 1985. Use of soil survey data for regional soil water simulation models. Soil. Sci. Soc. Am. J. 49: 1238-1244.

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