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CENTRE TECNOLÒGIC FORESTAL DE CATALUNYA

Soil hydrology in the Ribera Salada Catchment (Catalan Pre Pyrenees) Application of hydrologic models for the estimation of hydrologic transitional regimes

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Promoter

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Contents

RESUM

El principal objectiu d'aquesta investigació és estudiar la dinàmica hidrològica d'una conca Mediterrània afectada per canvis d'ús del sòl, mitjançant el monitoreig d'aquest i de l'aigua superficial. Aquest objectiu s'ha treballat a partir mesuraments de components del balanç hídric pels diferents tipus de cobertura i sòl, amb règims d'humitat i temperatura de transició.

Aquest estudi s'ha realitzat a la conca de la Ribera Salada (Prepirineu meridional Català, al NE d'Espanya), amb una extensió de 222.5 km^2, i un interval altitudinal de 420 a 2385 m i predomini de pendents entre 12 - 25 % i 25 - 50 %. El substrat consisteix en conglomerats calcaris massius, calcilutites i llims. La precipitació es de 507 i 763 mm. Amb sòls poc profunds, calcaris i pedregosos, essent majoritàriament Inceptisòls (Typic Calciusteps, Typic Haploustepts) i Entisòls (Typic Ustifluvents, Typic Udorthortents). A les zones més elevades de la conca, els sòls són més humits, degut a l'augment de la precipitació, on es produeixen processos de descarbonatació del sòl. L'ús del sòl és majoritàriament forestal, amb presència d'ecosistemes de ribera, subalpins i vegetació submediterrània. Algunes àrees es troben amb cultius de patata, cereal i pastures. Una de les característiques més importants d'aquesta conca són els canvis d'ús del sòl que ha patit en els últims 50 anys degut a l'abandó dels masos i cultius tradicionals. Es seleccionaren vuit llocs de mostreig considerant les següents cobertes: *Quercus ilex*, bosc de ribera, *Pinus sylvestris*, pastures, cultius (cereal-patata) i *Pinus uncinata*. A partir de l'any 1997 fins el 2005, s'han anat monitorejant el contingut d'humitat del sòl, l'escolament i els cabals. Des del 2004 s'han anat anotant dades de drenatge. Les variables meteorològiques es mesuren a l'estació de Lladurs de la XAC (Xarxa Agrometeorològica de Catalunya).

Els resultats obtenguts durant tres anys mostren una domini del règim d'humitat ústic (SSS, 2006), o xèric en aquells anys més secs. En la modelització de règims d'humitat i temperatura del sòl, s'utilitzaren els models de simulació NSM "Newhall simulation model" (Newhall, 1976) i JSM "Jarauta simulation model" (Jarauta 1989). NSM (Newhall,1976) tendeix a sobre estimar el règim d'humitat del sòl, però JSM (Jarauta, 1989) simula correctament el règim d'humitat del sòl (SSS, 2006) de la conca, funcionant millor en condicions intermitges d'humitat del sòl. Ambdós models simulen correctament el règim de temperatura dels sòls. Predomina un règim de temperatura mèsic-tèrmic, amb tendència a tèrmic els anys secs. A petita escala la profunditat del sòl, pendent, pedregositat i una alta porositat del sòl són factores que varien el règim d'humitat del sòl. La informació de sòl i clima, complementada mitjançant SIG, va permetre l'obtenció de mapes de règim d'humitat del sòl de la conca, a escala 1:50000, els quals permeten establir mediante simució els règims d'humitat del sòl en diferents escenaris de canvis meteorològics.

El model TOPLATS ha sigut utilitzat en l'estimació de l'humitat del sòl en diferents usos del sòl. Aquest model fou calibrat amb les equacions del filtre Kalman estès (EKF), que deriven de la minimització del quadrat de la diferència entre els valors reals i els estimats (Goegebeur & Pauwels, 2007). Aquesta metodologia interrelaciona correctament els valors de pluja, humitat del sòl, escolament i infiltració, essent els valors d'humitat els que més s'aproximen als reals. Els resultats mostren que aquest filtre és una eina útil per estimar el volum d'aigua del sòl emmagatzemada en conques a escala puntual, assegurant una aplicació correcta del model hidrològic.

Per la modelització del comportament de l'humitat del sòl i diferents components del balanç hídric s'utilitzà el modelo TOPLATS (Famiglietti & Wood, 1994). El model de simulació TOPLATS permite simulà acceptablement el comportament de l'humitat del sòl. Els resultats de infiltració, escolament, intercepció, evapotranspiració de referència i temperatura del sòl són correctes. Les diferències existents entre valors simulats i observats són: l'humitat del sòl no sobrepassa el 5%, la infiltració fluctua entre 4% i 15%, la diferència entre els valors reals i simulats d'evapotranspiració, depèn de l'estació de l'any, essent 1mm a l'hivern i 2.7 mm a l'estiu. La temperatura varia entre 0.01ºC i 3.5ºC. El model calibrat prediu amb precisió el comportament de les diferents components del balanç hídric. Respecte als valors mesurats d'aigua de drenatge correspon al 11-41 % de la pluja total.

Respecte al balanç d'aigua en el sòl (ΔSW), els valors són negatius durant cert període de l'any, arribant a valors crítics els mesos secs. La recuperació de humitat del sòl durant la resta de mesos succeeix de manera parcial. A la part mitja de la conca, alguns mesos els valors d'humitat del sòl s'acosten a condicions de punt de marchites (ecosistema submediterrani). A la part alta de la conca el sòl conserva humitat (ecosistema subalpí). Els valors de cabal trobats corresponen a aportacions per escolament el

cuals són molt baixos. La majoria de les sortides es deuen a evapotranspiració, intercepció, infiltració i drenatge (en ordre de importància).

RESUMEN

El principal objetivo de esta investigación es estudiar la dinámica hidrológica de una cuenca Mediterránea afectada por los cambios de uso del suelo, mediante el monitoreo del suelo y el agua superficial. Dicho objetivo se ha abordado a partir de la medición de componentes del balance hídrico para diferentes tipos de cobertura y suelo, considerando regimenes de humedad y temperatura de transición.

Este estudio se ha realizado en la cuenca de la Ribera Salada (Prepirineo meridional Catalán, NE España) de 222.5 km^2, con un intervalo altitudinal de 420 a 2385 m y predominio de pendientes entre 12 - 25 % y 25 - 50 %. El sustrato consiste en conglomerados calcáreos masivos, calcilutitas y limos. La precipitación anual es de 507 y 763 mm. Los suelos són poco profundos, calcáreos y pedregosos, siendo en su mayoría Inceptisols (Typic Calciusteps, Typic Haploustepts) y Entisols (Typic Ustifluvents, Typic Udorthortents). En las partes altas de la cuenca los suelos son más húmedos, debido al aumento de la precipitación, allí ocurren procesos de descarbonatación del suelo. Predomina el uso forestal, con ecosistemas de ribera, subalpinos y vegetación submediterránea. Algunas áreas se dedican al cultivo de patatas, cereal y pastos. Una de las características más importantes de esta cuenca es los importantes cambios de uso del suelo sufridos en los últimos 50 años, debido al abandono de las masías y cultivos tradicionales.

Se seleccionaron ocho sitios de muestreo, considerando las siguientes coberturas: *Quercus ilex*, bosque de ribera, *Pinus sylvestris*, pastos, cultivo (cereal-patata) y *Pinus uncinata*. A partir del año 1997 hasta 2005, se han venido monitoreando el contenido de humedad del suelo, escorrentía y caudales. Desde 2004 se vienen tomando datos drenaje. Las variables meteorológicas se miden la estación Lladurs perteneciente a la XAC (Xarxa Agrometeorológica de Cataluña).

Los resultados obtenidos par un period de tres años muestran una predominancia del regimen de humedad ústico (SSS, 2006), o xérico en los años más secos. Se utilizaron los modelos de simulación NSM "Newhall simulation model" (Newhall, 1976) y JSM "Jarauta simulation model" (Jarauta 1989) en la modelización de regimenes de humedad y temperatura del suelo. NSM (Newhall,1976) tiende a sobre estimar el régimen de humedad del suelo. Por contra, JSM (Jarauta, 1989) simula de forma correcta el régimen de humedad del suelo (SSS, 2006) presente en la cuenca, funcionando mejor bajo condiciones medias de humedad del suelo. Ambos modelos simulan de forma correcta el régimen de temperatura de los suelos. Predomina un régimen de temperatura mésico-térmico, con tendencia a térmico para los años secos. A pequeña escala la profundidad del suelo, pendiente, pedregosidad y alta porosidad del suelo son factores que hacen variar el régimen de humedad del suelo. La información de suelo y clima, complementada mediante SIG, permitió obtener mapas de régimen de humedad del suelo para la cuenca, a una escala 1:50000, los cuales permiten establecer mediante simulación los regimenes de humedad en el suelo bajo diferentes escenarios de cambios meteorológicos.

El modelo TOPLATS ha sido utilizado en la estimación de la humedad en el suelo para diferentes usos del suelo. Este modelo fue calibrado con las ecuaciones del filtro Kalman extendido (EKF), que se derivan de la minimización del cuadrado de la diferencia entre los valores reales y los estimados (Goegebeur & Pauwels, 2007). Esta metodología interrelaciona correctamente los valores de lluvia, humedad en el suelo, escorrentía y infiltración, siendo los valores de humedad los mas ajustados a los valores reales. Los resultados muestran que este filtro es una herramienta para estimar el volumen de agua en el suelo almacenada en las cuencas a escala puntual, asegurando una aplicación correcta del modelo hidrológico.

Para la modelización del comportamiento de la humedad del suelo y los diferentes componentes del balance hídrico se utilizó el modelo TOPLATS (Famiglietti & Wood, 1994). El modelo de simulación TOPLATS permite simular aceptablemente el comportamiento de la humedad del suelo. Los resultados para infiltración, escorrentía, intercepción, evapotranspiración de referencia y temperatura del suelo son correctos. Las diferencias existentes entre valores simulados y observados son: la humedad del suelo no sobrepasa el 5%, la infiltración fluctúa entre 4% y 15%, la diferencia entre los valores reales y simulados de evapotranspiración, depende de la estación del año, siendo 1mm en invierno y 2.7 mm en verano, la temperatura varia entre 0.01 ºC y 3.5ºC. El modelo calibrado predice con precisión el comportamiento de las diferentes componentes del balance hídrico. Respecto a los valores medidos para agua de drenaje corresponde al 11-41 % de la lluvia total.

Respecto al balance de agua en el suelo (ΔSW), los valores son negativos para un corto periodo del año, alcanzando valores críticos en meses secos. La recuperación de humedad del suelo para el resto de los meses ocurre de manera parcial. En la parte media de la cuenca, para algunos meses los valores de humedad del suelo son cercanos a condiciones de punto de marchites permanente (ecosistema submediterráneo). En la parte alta de la cuenca el suelo conserva condiciones intermedias de humedad (ecosistema subalpino). Los valores de caudal encontrados corresponden a los aportes por escorrentía, los cuales son muy bajos. La mayor parte de las salidas ocurren por evapotranspiración, intercepción, infiltración y drenaje (en orden de importancia).

ABSTRACT

The main aim of this research is to study the hydrological dynamics of a Mediterranean mountain basin affected by land use changes, by means of the monitoring of soil and surface water. This aim has been reached by measuring and simulating hydric balance components of different soils and under different vegetational types, considering water and temperature transition regimes.

This research was done in Ribera Salada basin (Catalan Pre Pyrenees, NE Spain), with an area of 222.5 km^2, altitudes between 420 and 2385 m, with predominance slopes between 12 - 25 % and 25 - 50 %. The substrate consists of massive calcareous conglomerates, calcilutites and limestones. Main annual precipitation are 507 to 763 mm. Soils are shallow, calcareous and stony, being most of them Inceptisols (Typic Calciusteps, Typic Haploustepts) and Entisols (Typic Ustifluvents, Typic Udorthortents). In the upper and moister part of the basin soil decarbonatation takes place. Forest use is predominant, going from brook forest environments to subalpine and submediterranean vegetation. Agricultural uses include mainly the growing of cereals, potatoes and pastures. One of the most important characteristics in this basin are the significant soil use changes in the last 50 years, due to the abandonment of farms and traditional crops.

Eight sites were studied, corresponding to soils under *Quercus ilex*, brook forest, *Pinus sylvestris*, pasture, crops (cereal-potatoes) and *Pinus uncinata*. From 1997 until 2005, soil moisture, run-off, water flow and interception were monitored. From 2004 on, drainage data has been recorded. Meteorological variables were measured by means of a complete Lladurs meteorological station, belonging to XAC (Catalan Agrometeorological Network).

The obtained results to three years show the predominance of ustic moisture regime (SSS, 2006), or xeric during the driest years. The simulation models NSM "Newhall simulation model" (Newhall, 1976) and JSM "Jarauta simulation model" (Jarauta 1989) were used to represent soil moisture and temperature regimes. NSM estimates a higher level of soil moisture regimes than observed. On the contrary, JSM simulates correctly soil moisture regimes, working better under intermediate soil moisture conditions. Both models simulate correctly the soil temperature regimes, being mesic-thermic to thermic during the driest years. At detailed scale (plot observation), soil depth, slope, stone amount and high soil porosity are factors that affect the soil moisture regimes. Soil and climate information, implemented through a GIS, allowed us to obtain soil moisture regime maps of the basin at a 1:50000 scale, which are very useful to simulate soil moisture regimes in different scenarios of meteorological changes.

The TOPLATS model, when used to estimate soil moisture under different cover types, was calibrated with Extend Kalman filter (EKF) equations derived through a minimization of the square difference between the true and estimated model state (Goegebeur & Pauwels, 2007). This methodology interrelates correctly rainfall, soil moisture, runoff and infiltration. Among them, the obtained soil moisture values corresponded the best to observed data. The results show that it is a useful tool to estimate soil water volume stored in basins at a point scale, ensuring a correct application of this hydrological model.

To model soil moisture behaviour and the different hydric balance components, the TOPLATS model (Famiglietti & Wood, 1994) was used. TOPLATS model simulates correctly the soil moisture behaviour. The differences between observed and simulated values are the following: soil moisture does not surpass 5%; the infiltration fluctuates between 4% to 15%; in evapotraspiration depends on the season being between 1 mm in winter to 2.7 mm in summer, soil temperature values difference fluctuates between 0.01ºC and 3.5ºC.The calibrated model predicts precisely the behaviour of different hydric balance components. The measured water drainage amount is 11-41 % of total rain.

The observed and simulated soil water storage in the basin (ΔSW), has negative values during the driest months. Soil moisture recovery during the rest of the months is only partial. In the medium part of the basin, occupied by submediterranean ecosystems, soil moisture values are closer to drought conditions during some months of the year. In the highest part of the basin (subalpine ecosystems) there are intermediate soil moisture conditions in dry periods. Most part of water outputs are due to evapotranspiration, interception, infiltration and drainage, in decreasing order of importance. Run-off values are very low.

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Chapter 1

GENERAL INTRODUCTION

1.1 Background

The main aims in watershed management are to preserve water resources in the watershed itself and downstream, as well as minimizing hazards related to water and soils. Soils and vegetation are perhaps the natural components of the watershed most affected by human activities, which in turn determine its hydrologic budget.

Mediterranean mountain areas are potential water accumulation zones to generate energy and to store water for human consumption, agriculture and industrial use. In the Pyrenees, the socio-economic evolution has lead to an abandonment of rural zones, resulting in an increase of forestry areas at the expense of a decrease of agricultural zones and pastures. Nowadays, in Catalonia, a 60% of the total surface area is under forestry use.

These land use changes modify the hydrologic response of the basins. An increase of forest diminishes the available water in soil due to a high consumption of water and losses because of interception and thus diminishing water flow and water availability in rivers due to runoff (Batalla & Poch, 2004). This results in changes of hydric regimes of the basins, which affect production, transference and water availability, and which influence reservoirs, wells and aquifers. The hydrological study of these areas can be useful to predict not only the consequences of cover type alteration, but also to assess changes due to climate variations. At the same time it is a good tool to design strategies to mitigate these changes.

Different water simulation models have been used to predict the relation between soil, vegetation and atmosphere in drainage basins. The most frequently used are SWAT (Soil and Water Assessment Tool), SVATS (Soil Vegetation Atmosphere Transfer Schemes), IHACRES, TOPMODEL, and HEC-1. These models have a great potential for monitoring soil water dynamics in the catchments. The TOPLATS model (Famiglietti & Wood, 1994a and Peters-Lidard et al., 1997) incorporates a TOPMODEL framework (Beven and Kirkby, 1979 and Sivapalan et al., 1987) to account for lateral redistribution of subsurface water based on local topography and soil transmissivity, using the equation for conservation of mass "inflow rate minus outflow rate equals rate of change of storage" (Hornberger et al., 1998). Spatial heterogeneities in soil moisture, which are manifestations of heterogeneity in topography, soils and vegetation, were proven to be important controls on aggregated fluxes and boundary layer development.

Soil water regimes can be used to characterize soils for taxonomic purposes. According to USDA (1975, 2006), they can be estimated through climatic data, which determine the annual evolution of the soil moisture content. This is a statistical concept, since it refers to an average year. In theory, these SWR are homogeneous in a given land unit, but the topographical situation associated with the soil depth and the geomorphology has an important role in the spatial soil moisture variation.

Soil moisture regimes can be determined using models based in climatic data. The most widely used is the Newhall simulation model (NSM), but others, such as Jarauta simulation model (JSM), include other soil variables that improve its precision. Using measured data of soil moisture and NSM (Newhall, 1976), JSM (Jarauta, 1989a,b) and TOPLATS simulation models, we will gain knowledge on soil water behaviour under different land use and soil type in a Mediterranean catchment, characterized by a wide variation of temperature and moisture conditions.

The use of field collected data and the simulation models will allow us to know the behaviour of the different hydric balance components. This information corresponds to soil type and use prevailing in the basin. Collected and simulated data will provide us with knowledge on the water dynamic in the basin and also in the different subbasins of the Ribera Salada, with special emphasis in the Canalda and Cogulers basins, because these are the most representative. From water flow information we will deduct water contributions from basin to reservoirs and the most important fluxes types.

1.2 Objectives

The objectives of this research are:

1. To know the different moisture and temperature regimes in the basin and its spatial and temporal variations, associated to changes in relief or soil morphology.

2. To study soil moisture behaviour under different land uses and soil types, representative of Mediterranean zones.

3. To analyze the behaviour of the hydric balance components under different soil combinations and soil uses in Mediterranean mountain basins.

4. To analyze the applicability of several simulation models, in the hydric balance, and the soil moisture regimes, according to Soil Taxonomy, in a Mediterranean forest basin.

5. To generate a procedure applicable to predict soil moisture behaviour to the Ribera Salada catchment.

6. To create a methodology that allows to predict hydric balance components in the Ribera Salada catchment and subcatchments.

7. To calibrate the TOPLATS model by means of the use of EKF equations for the estimation of soil water in the study area, so that it can be used for other Mediterranean basins.

1.3 Thesis outline

This work begins with the introductory Chapter 1, which contains an abstract of the study background, exposed objectives, used methodologies to calculate field data and an explanation of the used models to predict soil moisture behaviour and hydrologic variables.

Chapter 2 deals with the difficulties to determine soil moisture regimes, according to Soil Taxonomy criteria (SSS, 1975, 2006) using the Newhall and Jarauta soil moisture simulation models. This chapter also discusses their validity in Mediterranean mountain zones, as a tool to predict the effects of soil use and rainfall changes. Using characteristical land use and soil type, it is possible to know the soil moisture spatial dynamics, depending on land use and the main soil hydric conditions; generating a methodology which allows to predict later soil moisture behaviour in Ribera Salada basin.

In the subsequent three chapters the used methodologies with the TOPLATS simulation model calibrated with Extend Kalman Filter (EKF) equations and the subsequent predictions of the catchment hydrological variables are discussed.

Chapter 3 consists in the calibration of the TOPLATS model using soil moisture simulated values, by means of Kalman equations (Goegebeur and Pauwels, 2007). Chapter 4 analyzes a very large data set of soil moisture measurements in the Ribera Salada catchment, allowing to know the evolution of soil water under different soil and soil uses. Soil moisture simulation results show that it is possible to use the TOPLATS model to predict soil moisture conditions. In this chapter a comparison is established between simulated results and field data of different hydric balance components such as soil moisture, infiltration, run-off, soil temperature and evapotranspiration. A methodology that allows to predict the soil moisture behaviour on the different soil combinations and land use; is generated allowing to know the present and future hydric conditions existent in the basin and subbasins. This information is useful not only to manage the basin but also to work in smaller basins and to plan the water contributed to the Rialb reservoir.

Chapter 5 study the behaviour of all the hydric balance components using TOPLATS as a tool to quantify water fluxes under the soil uses in the basin. To end with there is a conclusion of the advantages of the simulation model and indications how to ameliorate its applicability in these type of basins. Finally, chapter 6 to summarize the main conclusions and recommendations of the thesis.

1.4 Material and methods

1.4.1 Description of the catchment

The Ribera Salada basin is located in the Pre-Pyrenees a mountainous area at the NE of Spain. The Ribera Salada river belongs to the Ebro basin (fig 1.1). The relief is tabular with a predominance slopes rank between 12 - 25 % and 25 - 50 % and with an altitude between 2385m and 420 m. The substrate consists of massive conglomerates and calcareous sandstones merging to calcareous siltstones. Soils are shallow, calcareous and stony. More information about the geology of the basin can be consulted at the following references; Solé (1973), Masachs (1981), IGME (1994, 2001) and ICC (2002). Most soils are classified as Lithic and Typic Ustorthents (SSS, 1993, 2006). The complete soil survey information can be found in Estruch (2001); Orozco (2003) and Loaiza (2004).

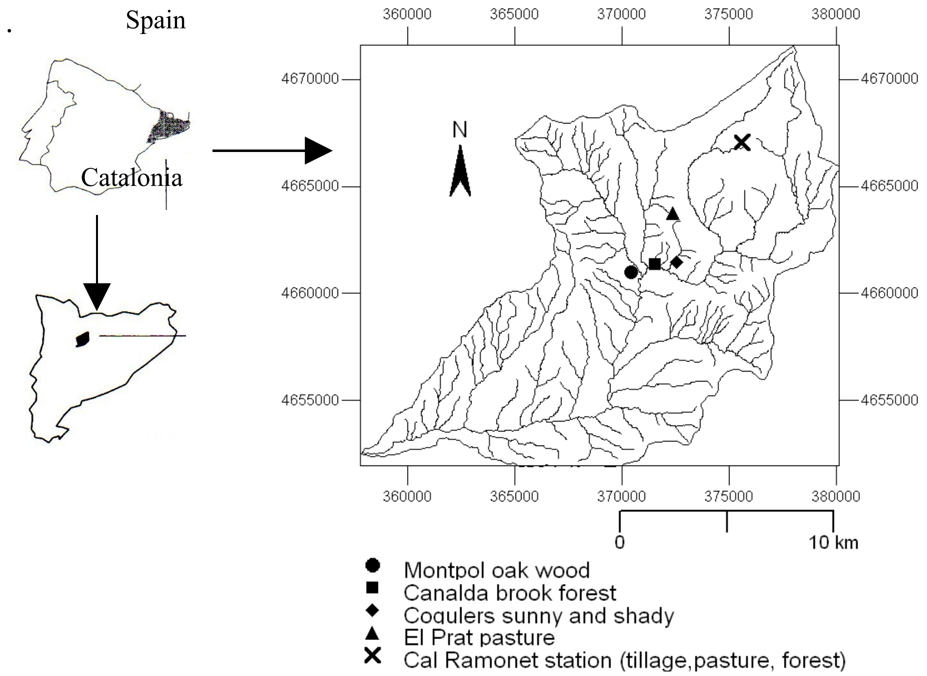


Fig 1.1 Map of the field site, Ribera salada catchment

The basin covers an area of 222,5 km², and the predominant land use is forestry, from brook forest to subalpine and submediterranean vegetation. The agricultural zone is mainly to sow 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 (MAPA 1989a, 1989b, Aldomà et al., 1987, Ubalde, 1997, Ubalde et al., 1999). A detailed composition of these ecosystems can be found at to García (2004). Fig 1.2 shows soil types and land uses of the catchment. The preliminary hydrological behaviour in the catchment is studied by Alisedo (1998) and Batalla & Poch (2004). Table 1.1 shows soil type and land use existent in the sampled sites.

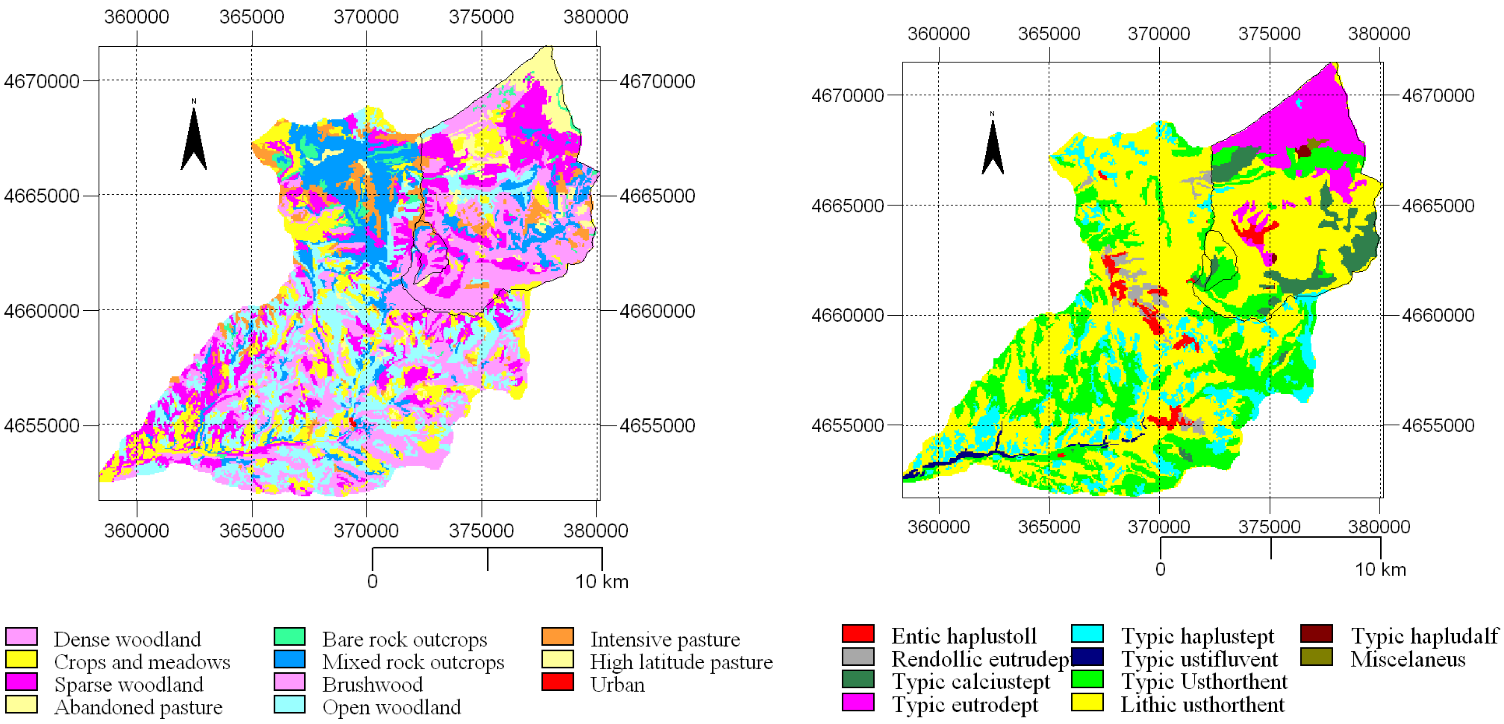


Fig 1.2 Representative land uses and soil types of the catchment (Orozco, 2003)

Table 1.1 Soil and land use of the plots located in the Ribera Salada catchment

Station	Soil use	Soils (SSS 2006)
Montpol oak wood	*Quercus Ilex* forest	*Typic Calciustepts*
Canalda brook forest	brook forest	*Typic Ustifluvents*
Cogulers shady		*Typic Ustorthortents*
Cogulers sunny	*Pinus Sylvestris* forest	*Typic Calciustepts*
El Prat pasture	Pasture	*Typic Haploustepts*
Cal Ramonet Tillage	tillage	
Cal Ramonet pasture	mountain Pasture	*Typic Calciudolls*
Cal Ramonet pine forest	*Pinus uncinata* forest	
	Miscellaneous (Rock)	*Miscellaneous*

Fig 1.3a, 1.3b show the different altitudinal existent ranks in the basin and the moisture regimes found by Estruch (2001) and according to the rainfall altitudinal distribution, the soil moisture regime is moister from 1400m.

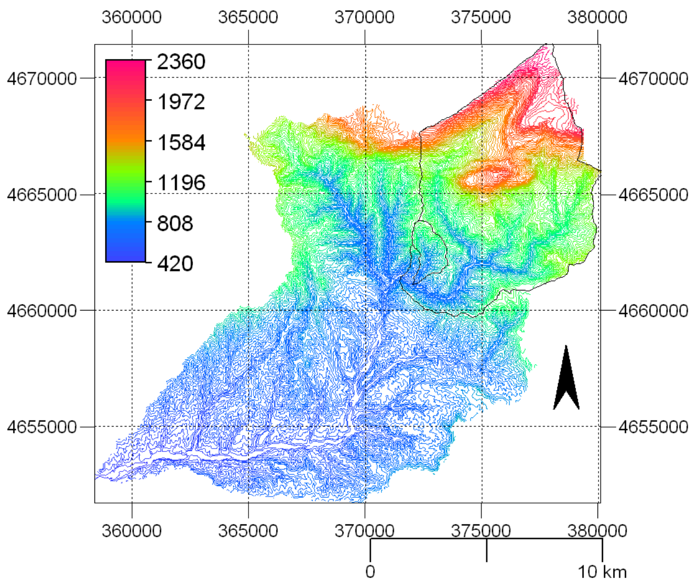


Fig 1.3a Hypsometric map of the catchment

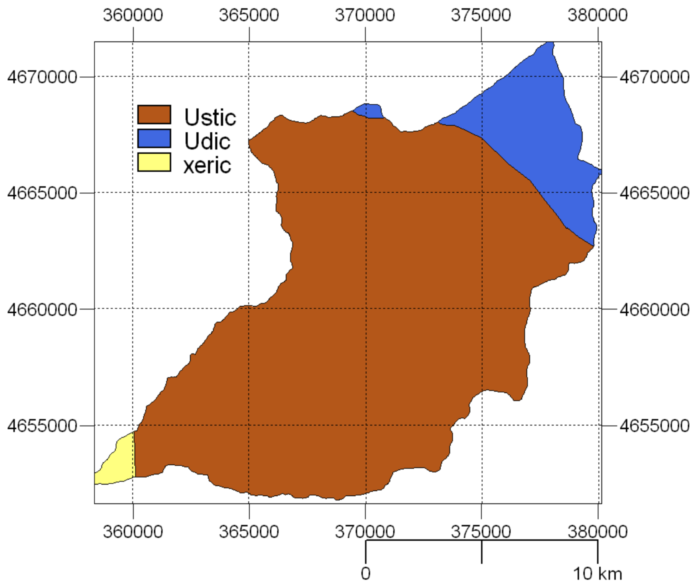


Fig 1.3b Soil moisture regimes in the catchment (Estruch, 2001)

The climate is mainly Mediterranean to Subalpine in the highest parts according to Ubalde (1997). The average temperature in the basin is 5.1 ºC in winter and 20 ºC in summer. During summer, high values of accumulated global radiation are reached: a total of 2102 Mj/m^2, net radiation is 999 Mj/m^2 and evapotranspiration is 400 mm. In winter these parameters reach the lowest values: accumulated global radiation 780 Mj/m^2, net radiation 262 Mj/m^2 and the lowest evapotranspiration is in autumn: 108 mm. Climatic characteristics are shown at table 1.2.

Table 1.2 Meteorological data 1999 - 2005 Lladurs station

	T	Tmax	Tmin	STmax	STmin	RH	Wv	Rt	ETo		
Year			ºC			%	m/s	mm		Rd	Fd
1999	11,7	17,8	6,5	14,4	14,1	67	1,2	676	875	141	84
2000	11,9	17,9	6,6	14,5	14,2	67	1,1	703	879	128	64
2001	12,0	18,2	6,7	14,6	14,4	65	1,2	516	927	118	67
2002	11,8	17,7	6,7	14,3	14,0	67	1,1	644	953	149	37
2003	12,5	18,3	7,4	17,3	16,8	65	1,2	763	903	131	66
2004	11,4	17,6	6,3	18,6	18,3	68	1,1	544	870	124	76
2005	12,0	17,9	6,1	16,4	16,1	64	0,9	507	947	131	66

T: temperature; Tmax: absolute maximum temperature; Tmin: absolute minimum temperature; STmax: absolute maximum soil temperature; STmin: absolute minimum soil temperature; RH: relative humidity; Wv: Wind velocity; Rt: total rain; ETo: evapotranspiration; Rd: rainy days; Fd: Frozen days.

The socio-economic characteristics of the area are marked by depopulation. During the fifties, farmers were attracted by the best salaries the industry and service sectors, turning into urban habitants. The existent plots of land were small, and farmers could not meet with the expensive technology costs with the low inputs obtained. This crisis became worse in the seventies, resulting in a severe agricultural recession. In the Solsonès region, this tendency is increasing nowadays, agricultural population has been reduced to 50% in the last 30 years (Aldomà, 1987; Pounds, 1987; DARP, 1996, 1999; Cantera, 1997; Ubalde, 1997, 1999).

1.4.2 Experimental design

From 1997 to present, Ribera Salada catchment has been the subject of several hydrological researches. In this research five locations were selected based on representative soil types and land uses of the catchment, fig 1.4.

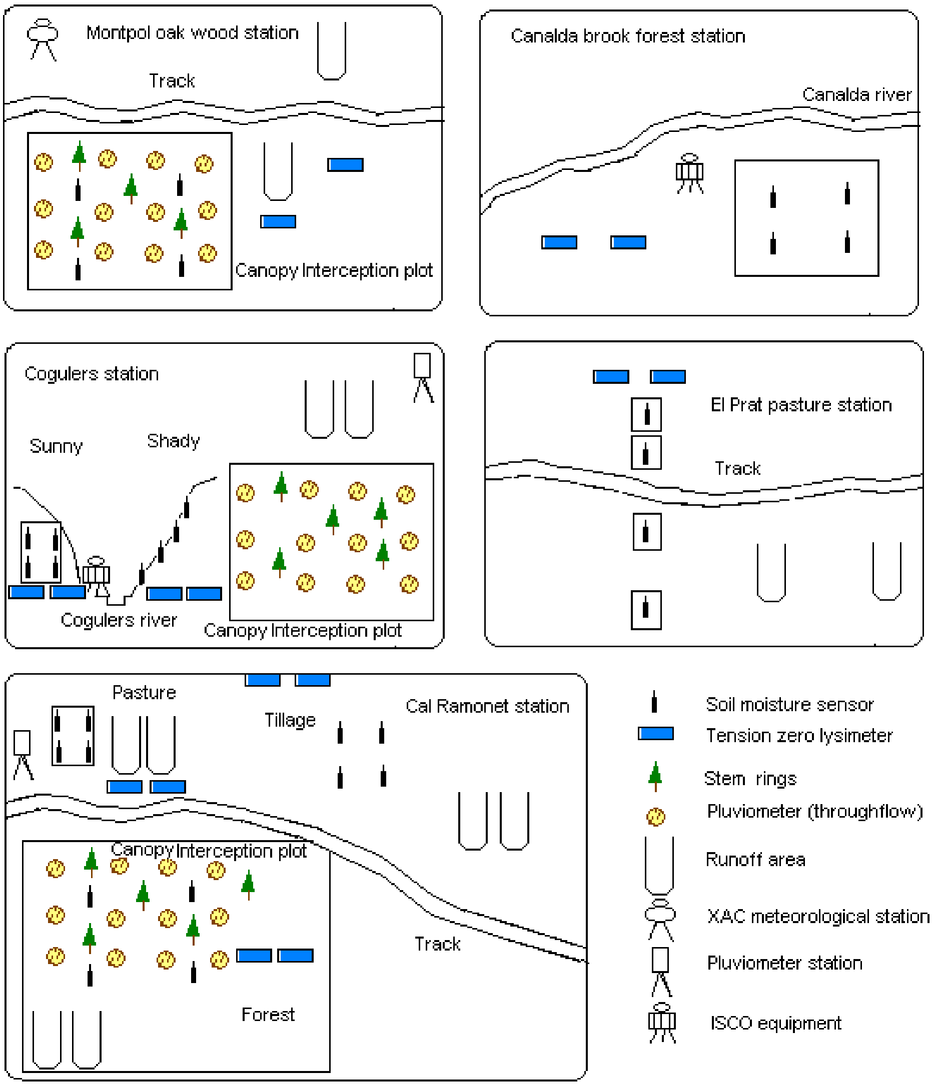


Figure 1.4 Ribera Salada plots of study

Table 1.3 shows soil water sensors calibration equations at each location. It was done according to the guidelines of the manufacturer Decagon®. Moisture percentages were obtained from soil sampled on the plots and analyzed at the laboratory. Comparing these results with the volumetric moisture data, registered by the sensors ECH_2O, we obtained linear calibration equations for the different soils, with R^2 ranging from 0,74 to 0,92. More information related to the soil moisture calibration and soil physical characteristics can be found in Loaiza (2004). The soil temperature values were registered every hour and stored in the agrometeorological data base of the Catalan Agrometeorological Network (XAC).

Table 1.3 Results of sensor calibration equations (y = bx + c)

Sensors Plot	b	c	R^2
Montpol oak wood	0,817	4,741	0,90
Canalda brook forest	0,944	5,256	0,92
Cogulers shady	0,9	20,604	0,81
Cogulers sunny	0,798	9,949	0,82
El Prat pasture	1,201	5,961	0,77
Cal Ramonet tillage	0,590	20,125	0,75
Cal Ramonet pasture	0,364	15,571	0,80
Cal Ramonet pine forest	0,597	18,609	0,74

y: Values obtained in the field, x: Data registered by the sensor, b: slope of the calibration line, c: calibration constant depending on specific conditions of sensors and plots.

Hydrologic variables monitoring was done from 21/04/2004 to 28/06/2005 with a weekly sampling frequency during rainy periods and biweekly during dry periods. The equipment installed in the different sampling sites can be observed in fig 1.4.

Two tension zero lysimeters were installed by the site at different depth between 20 - 50cm, according to soil characteristics, (table 1.4). A lysimeter consists of a square metal plate with 20cm x 30 cm dimensions and its function is to collect soil infiltrated water.

Table 1.4 Lysimeters installation depth

	Montpol	Canalda	Cogulers		El Prat	Cal Ramonet		
Lysimeter	oak wood	brook forest	shady	sunny	pasture	pasture	Tillage	pine forest
Depth (cm)	20	22	25	30	20	50	40	30

To measure superficial run-off, Gerlach's boxes were used, having two boxes by site due to the high spatial and temporal variability. When the run-off area is limited by galvanized plates (100cm x 20cm), the parcels are named closed stations. When the plot does not have a delimited run-off area, it is named an open station. Runoff water from Gerlach boxes was stored into 30 liter plastic containers. The characteristics of each Gerlach plot can be seen at table 1.5.

Table 1.5 Gerlach's boxes set up

Plot	Montpol oak wood	Cogulers *Altes*	El Prat pasture	Cal Ramonet pasture	 tillage	 pine forest
Type	Open	Closed	Closed	Closed	Open	Closed
Area average (m^2)	10,2	36,75	29	17,3	47,5	11,13
Slope (%)	45	30	24	22	22	29
Box dimensions (cm)	100x20x30	100x20x30	100x20x30	100x20x30	50x32x18	50x25x7

Canopy interception was measured for three canopy types in interception plots during the period. They consisted of 12 pluviometers under the canopy to measure throughflow, measured each 5 minutes. Stemflow was measured by 4 to 5 stem rings under each canopy type, that was collected in containers and measured after each rainfall period. Regression equations between rainfall from Montpol, Cogulers and Can Ramonet stations, and measured interception were obtained by Solsona (2005). The equations are the following:

Quercus ilex: Interception (mm) = 0,1680* Rainfall (mm) + 1,7541 (R^2= 0.9998)
Pinus nigra: Interception (mm) = 0,1942* Rainfall (mm) + 4,5887 (R^2= 0.9946) [1]
Pinus sylvestris: Interception (mm) = 0,4699 * Rainfall (mm)+ 3,7643 (R^2= 0.9998)

Table 1.6 shows the soil parameters measured in each station, being hydraulic conductivity (Ks) measured by the disk infiltrometer (Perroux & White, 1988); particle distribution using hydrometer methodology and soil moisture between -33 and -1500 kPa (SSS, 1992). A soil control section was established according to the criteria of Jarauta (1989a). Soil moisture regimes determination was done according to established criteria by Soil Taxonomy (SSS, 1975, 2006).

Table 1.6 Soil control section and selected soil hydrological properties

Station	**Upper boundary (cm)**	**Lower boundary (cm)**	**Ks (mm/h)**	**-33kPa (%)**	**-1500kPa (%)**	**Texture**
Montpol oak wood	5	62	6.75	27.15	11.63	sandy loam
Canalda brook forest	4	64	7.75	29.50	13.20	Loam
Cogulers shady	4	64	4.88	25.03	13.16	Loam
Cogulers sunny	5	40	8.92	21.48	16.35	sandy loam
El Prat pasture	5	40	10.93	38.05	15.04	loam-loamy sand
Cal Ramonet station	5	60	11.21	43.49	19.26	loam-clay loam

The meteorological data needed to run the Jarauta, Newhall and TOPLATS model, were obtained from the XAC complete meteorological station named Lladurs and from Cal Ramonet meteorological station of Centre Tecnològic Forestal de Catalunya (CTFC). The first station is located at same site as Montpol station and the second one is located at the Cal Ramonet site. Meteorological data were measured at 1.5m height, yet the wind at 10m height. Main climatic characteristics are found in table 1.2.

A continuous hourly meteorological dataset was used from 1998 to 2005 based on daily observations of the Lladurs meteorological station. Air temperatures and relative humidity parameters data were collected every second in a *Vaisala HMP45* sensor, then they were averaged and recorded. Soil temperatures were measured using a Campbell 107 sensor set up into the soil (50 cm depth) and connected directly to Campbell Scientific datalogger. Wind speed was obtained by a RM Young 05103. Rainfall information was obtained using an ARG100 raingauge, measured every second.

Evapotranspiration was calculated using Penman - Monteith equation (Doorenbos & Pruitt, 1977) evaluated by Llasat & Snyder (1998) in XAC network from measures of solar radiation by means of a Q7 Campbell sensor, which generates one signal proportional to the net radiation. Global radiation was also measured by the SKY SKS1110 sensor.

The process to calculate hourly ETo is the following:

If h sun ≥ 10

$$\text{ETo (mm)} = \frac{0.408\Delta(Rn - G) + \gamma(37/Ta)\, dh\_VV_2 dif\_pv}{\Delta + \gamma\,(1+0.34 dh\_VV_2)} \qquad \text{Eq [1]}$$

Rn: net radiation, G: earth heat transmission, γ: psicometric constant, Ta: air temperature, VV: wind speed, Δ: variation vapour pressure sat, dif_pv = difference vapour pressure

Where : $Ta = dh\_temp + 273$ Eq [2]

dh_ temp is hourly temperature in ºC, dh VV_2 hourly wind speed at 2 meters high expressed in (m/s)

To calculate Δ

Δ is the variation of saturate vapor pressure (P vapor sat en kPa) according to temperature in kPa/ºC

$$\Delta = \frac{4098*P\_vapor\_sat}{(dh\_temp+237.3)^2} \quad \text{Eq [3]}$$

$$P\_vapor\_sat = 0.6108 \exp^{(17.27dh\_temp/\ dh\_temp+237.3)} \quad \text{Eq [4]}$$

To calculate Rn

Rn is the net radiation estimated from grass soil cover at 10 cm high in Mj/m^2

$$Rn = Rn\_s - Rn\_l \quad \text{Eq [5]}$$

$$Rn\_s = (1-0.023)dh\_rsun\ 3.6*10^{-3} \quad \text{Eq [6]}$$

The value 3.6* 10^{-3} is a converser factor from W/m^2 to Mj/m^2

$$Rn\_l = 2.403*10^{-10}Ta[0.34-0.14(0.34-0.14(P\text{-}vapor)^{1/2}]\left[1.35(dh\_rsol3.6*10^{-3}/R_{50})\right] \quad \text{Eq [7]}$$

$$P\_vapor = dh\_mois*P\_vapor\_sat\ /100 \quad \text{Eq [8]}$$

P vapor is vapor pressure (kPa) while dh_rsun and dh_mois are global radiation (W/m^2) and hourly relative moisture (%).

To calculate G

G is earth heat transmission in Mj/m^2

$$G = 0.1Rn \quad \text{Eq [9]}$$

To calculate γ

γ is a psicometric constant in kPa/ºC

$$\gamma = 0.665 * 10^{-3} \text{ Pressure} \qquad \text{Eq [10]}$$

$$\text{Pressure} = 101.3\ (293 - 0.0065 \text{ height} / 293)^{5.26} \qquad \text{Eq [11]}$$

Height is expressed in meters.

The instrument signals were collected by a CR10X datalogger (Campbell Scientific ®). All this information is available in hourly scale in the XAC data base. The emissivity parameters, minimum and maximum stomatal resistance (s/m), radiation parameters, vapor pressure deficit, temperature adjustment and ground heat flux under vegetation were determined following Peters-Lidard et al. (1997).

Soil moisture was measured during the period 2003 - 2004. In this period there are available data of all the stations without any gap, therefore any comparison between plots is possible.

Cartographic information of land use and soils at a scale 1:50000 were obtained from Ubalde et al. (1999) and Orozco et al. (2006). Soil information use SSS (1993) criteria. The topographic information at a 1: 50000 scale, was obtained from the Catalan Cartographic Institute (ICC,1994, 1996), being equidistance between curves 20m.

1.5 Newhall Model

Simulation models for soil moisture regimes used in this research are NSM (Newhall,1976) and JSM (Jarauta, 1989a, 1989b). The NSM was originally developed to simulate soil moisture changes and identify soil moisture regimes based on monthly rainfall and temperature data. NSM monthly input data is restricted to a period of one year (a year consisting of monthly averages of several years or a normal typical year). NSM uses longitude and latitude information to obtain potential evapotranspiration in accordance with the Thornthwaite equation. This model has long been used by the SSS to determinate soil moisture regimes as defined in Soil Taxonomy (SSS, 1975, 2006). Winter's and summer's soil temperature average is evaluated by means of the monthly air temperature average in this period, using Soil Taxonomy criteria. NSM also assumes that all precipitation events are effective unless soil moisture control is saturated. NSM classifies soil moisture and soil temperature regimes. Three water state classes (dry, moist, wet) are used (SSS, 2001), which consider the soil moisture status as dry (<-1500 kPa); moist (-33≥ x ≥-1500 kPa) and wet (>-33 kPa). The outputs obtained only cover 360 days of the year and all months last 30 days (Waltman et al., 1997, 2003; Van Wambeke, 2000; Trnka et al., 2002; Costantini et al., 2002). This model has been used in Spain by Tavernier & Van Wambeke (1976a), Lázaro et al. (1978), Ibáñez & Gascó (1983) and Jarauta (1988, 1989a, 1989b, 1993). All these authors admit that there exists a restriction in the use of this model, which is necessary to gain field data of several years.

1.5.1 The Preliminary Assumptions of the Newhall Model

According to Van Wambeke (2000), are the following:

1.5.1.1 The soil moisture profile

The soil moisture profile considered by the model extends from the surface down wards 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 80,01 cm in a well-structured clay to 200 cm in a light sandy loam; in a wide range of medium-textured soils, the required depth 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 the Moisture Control Section defined by Soil Taxonomy as the layer having an upper boundary at the depth where a dry with a tension of more than 1500 kPa, but not air dry soil will be moistened by 25 mm of water moving downwards 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 downwards from the surface within 48 hours. Figure 1.5 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 water's tension at which water is held in the profile decreases.

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 1.8. Each slot of the soil moisture diagram 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 a water holding capacity of 200 mm.

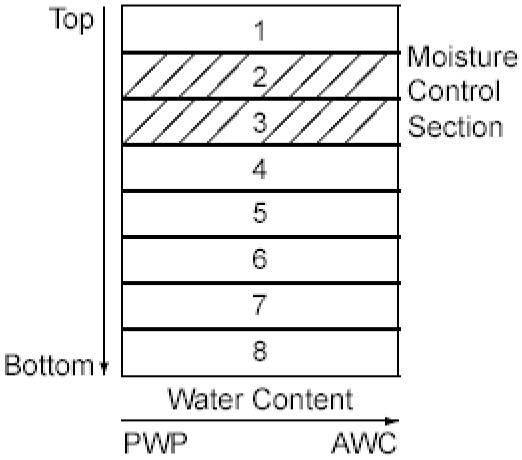


Figure 1.5 Newhall's Soil Moisture Profile

1.5.1.2. 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 moved downwards by the wetting front depends on the amount of water needed to bring all the soil above the front 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 at which the water is removed out of the soil, in other words *depletion*, depends on the energy available for moisture extraction, expressed in terms of *potential evapotranspiration* (PE) which influences 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. The model uses less energy 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 reached at the 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.

1.5.1.3. Distribution of monthly climatic factors

a) Precipitation: The monthly precipitation (MP) is distributed according to the following sequence:

I. 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.

II. 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.

b) 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 following Thornthwaite.

1.5.2 The Time-Step Progression of the Model

According to Van Wambeke (2000), 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 period (HP) which occurs at midnight between the 15th and 16th of the month, and the third period 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 this has 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 that is 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.

1.5.2.1 Processing sequence during one month

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

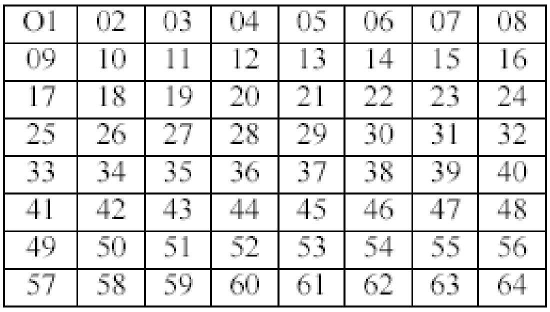
I. compute light precipitation, where LP = MP/2
II. compute the net potential evapotranspiration (NPE), where
NPE = (LP - PE)/2If NPE > 0, accretion will take place during this period; otherwise, water will be extracted from the profile.

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.

1.5.2.2 Changes in Water Content during each Period

I. Accretion: To simulate the additions of moisture to the profile, water is added to the soil, each non-full slot following a specific order shown in the soil moisture diagram of Table 1.7

Table 1.7 Slot Sequence during Accretion

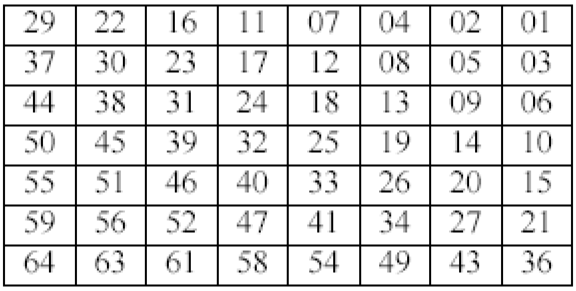


O1	02	03	04	05	06	07	08
09	10	11	12	13	14	15	16
17	18	19	20	21	22	23	24
25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

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. In this way, the accretion procedures simulate the downward movement of a wetting front.

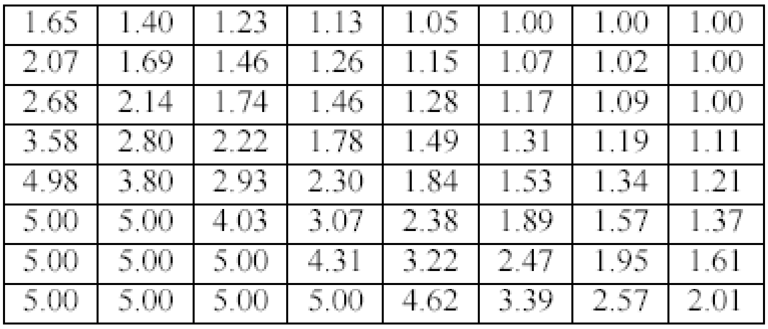
II. Depletion: The sequence for the extraction of water from the profile starts with the top right-hand slot and scans the slots in successive right-downwards diagonals, as shown in table 1.8. During the sequence each slot is examined, and if water is present, it is removed from this slot it. The depletion 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 of the depletion requirement diagram which indicates the 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 1.9.

Table 1.8 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

Table 1.9 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.

1.5.2.3 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*. This is also called *completely dry*, referring to a completely dry soil. The Newhall model accepts this condition when the leftmost slots numbered 09, 17, and 25 in Table 1.8 are all empty.

2. The moisture control section is *moist in all parts*, or *completely moist*. Newhall model defines this condition when none of the leftmost slots numbered 09, 17, 25 in Table 1.8 are empty.

3. The moisture control section is *dry in some parts* or *moist in some parts*. This soil is also referred to as *partly dry* or *partly moist*. The Newhall model considers this condition only when the moisture control section does not fulfill the requirements for (1) nor (2), e.g. when it is neither completely dry nor completely moist.

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 partly for the fact that the model ignores all upward movements of water in the soil which in reality participate in the moisture supply to the MCS.

1.5.2.4 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:

$$DX = 15 \cdot RPEX/NPE \qquad \text{Eq [12]}$$

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

$$DE = 15 - DX - DX2 \qquad \text{Eq [13]}$$

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.

1.5.2.5 Changes in Soil Temperature

The definitions of both soil moisture regime and temperature regime require the calculation of the periods when soil temperature is above or below certain critical values, e.g. 6ºC or 8ºC, 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 main monthly temperatures. The average annual soil temperature is estimated to increase 1.5ºC to the annual average air temperature. At 50 cm depth the average temperatures during winter and summer are evaluated by adding the same value to the air temperature and reducing the difference in 1/3. The onset of a period in which 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 which 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 results to be about half of the lag of when the soil is warming up. The reason is that the soil is usually wetter when warming up than when cooling down, and therefore has a higher thermal capacity.

1.6 Jarauta Model

JSM makes it possible to daily or hourly rainfall data in the prediction of soil moisture regime. The Jarauta model considers, the rainfall infiltration efficiency into the soil, 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. 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.

Subsequently 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 (Jarauta, 1988, 1989a, 1989b, 1993).

The factors considered are those modified by Jarauta (1989a) to applied to his simulation model.

1.6.1 The soil moisture profile

Soils may have lithic or paralithic contacts or other limitations that can diminish both the soil water capacity and the infiltrating water into deeper layers. The Jarauta model uses seven different soil profiles to simulate several possible situations.

The reference profile has 200 mm of AWC. The numeration of the matrix is the same as used in the Newhall methodology (table 1.8). The different profiles considered by the Jarauta model are boxes: 1 - 64, 1 - 56, 1 - 48, 1 - 40, 1 - 32, 1 - 24, 1 - 16. Each box contains a capacity of 3.125 mm; the soil moisture control section is located between boxes 9 - 24.

1.6.2 Profile accretion

1.6.2.1 Precipitation data: The model uses daily and monthly rainfall data. If the daily data are used, 75 mm of water is set as the maximum water amount that can be infiltrated in one day. If daily rainfall is more than 75 mm, the excess is considered to be surface runoff. If monthly data is used, a rainfall intensity coefficient is calculated from the following parameters: N (average number of rainy days), P (average of annual rainfall, in percentage), Ki (indicative index of penetrability average efficiency).

$$(P/N)\ aver = 1/12 \sum_{i=1}^{12} (P/N)i \qquad \text{Eq [14]}$$

Ki is defined as:

$$Ki = 1 \qquad \text{si } (P/N)\ aver \geq (P/N)i \qquad \text{Eq [15]}$$

$$Ki = (P/N)aver/(P/N)i \qquad \text{si } (P/N)\ aver < (P/N)i$$

To obtain corrected monthly precipitation (PMc).

$$PMc = Ki * PM \qquad \text{Eq [16]}$$

If Ki is unknown, monthly precipitations are taken without correction, considering systematically Ki=1 in each month.

1.6.2.2 Water inputs: When daily precipitation is taken, the limitation of 75 mm/day has to be considered. In the case of monthly precipitation PMc is calculated, and used to estimate strong rainfall (PS) which is entered each 15th day of every month.

$$PS = PMc/ 2 \qquad \text{Eq[17]}$$

The other part of PMc is named light precipitation (PL).

$$PL = PMc/2(n-1) \qquad \text{Eq [18]}$$

"n" expresses the day of the month

1.6.2.3 Sequence of water entrance into the profile: The reference sequence of water entrance into the soil corresponds to table 1.8.

1.6.3 Soil water depletion

1.6.3.1 Evapotranspiration calculation: 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 monthly average temperature in ºC (t) and the percentage of daily hours of the month (p), estimated by Doorenbos and Pruitt (1977), are considered as initial variables, from which the consumptive use factor (f) and the reference evapotranspiration (ETo, mm/day) of Blaney-Criddle are calculated:

$$f = p(0.46t + 8.13) \qquad \text{Eq [19]}$$

$$ETo = \phi\ (f) \qquad \text{Eq [20]}$$

This function (Doorenbos and Pruitt, 1977) is a straight line that depends on values of relative minimum moisture (HR min), relative insolation hours (n/N) and average daily wind speed (U).

To calculate tillage evapotranspiration (ETc) in optimal conditions of water availability Eq [21] is used:

$$ETc\ (mm/day) = Kc \cdot ETo\ (mm/day) \qquad \text{Eq [21]}$$

Kc is a tillage coefficient that depends on soil cover. This coefficient can be consulted at Doorenbos and Pruitt (1977) or determined experimentally. In soils under tillage, actual evapotranspiration (ETr) is determined according the following criteria:

ETr = ETc if there is not water limitation in the soil
ETr < ETc if there is a water limitation in the soil

In the second case, the water extract from the soil is calculated according to different forms:

Where the variables are: S(t) is the available water in the soil at the moment t, Sa total is the amount of water available in the soil, q the available water fraction, D the root depth. As a definition, the water amount that is released from a soil controlled volume, whose water retention capacity is SaD, is calculated by:

$$Etr = - d(DS(t))/dt \qquad \text{Eq [22]}$$

Achieving:

$$ETr = ETc \qquad \text{if } DS(t) \geq (1-q)\ SaD \qquad \text{Eq [23]}$$
$$ETr = DS(t)/(1-q)SaD\ .\ ETc \qquad \text{if } DS(t) < (1-q)\ SaD \qquad \text{Eq [24]}$$

Replacing Eq 23 in Eq 21, the following equation is obtained:

$$- d/dt\ (D\ S(t)) = ETc/(1-q)Sa\ D\ .\ D\ S(t) = \lambda\ D\ S(t) \qquad \text{Eq [25]}$$

That can be written as

$$d(D\ S(t))/\ D\ S(t) = -\lambda\ dt \qquad \text{Eq [26]}$$

Integrating this equation, results:

$$In\ (D\ S(t)) = - \lambda\ t + C1 \qquad \text{Eq [27]}$$

C1: integration coefficient

And then:

$$D\ S(t) = K_1\ e^{-\lambda t} \qquad \text{Eq [28]}$$

K1: integration constant

If S(t) is designed as St and S(t-1) as S_{t-1}, and if S_{t-1} is considered initially:

$$D\ S_{t-1} = K_1\ e^{-\lambda\,(t-1)} \qquad \text{Eq [29]}$$

Then:

$$K_1 = e^{-\lambda\,(t-1)} \qquad D\ S_{t-1} \qquad \text{Eq [30]}$$

Replacing K_1 according to eq [28] in eq [27], is obtained:

$$D\ St = e^{\lambda(t-1)}\ D\ S_{t-1}\ e^{-\lambda\, t} = e^{-\lambda}\ D\ S_{t-1} \qquad \text{Eq [31]}$$

Consequently, replacing D S_t in Eq [23], we obtain the reference evapotranspiration value:

$$ETr\ (t) = e^{-\lambda}\ D\ S_{t-1} / (1-q)SaD\ \ .\ ETc = \lambda\ e^{-\lambda}\ D\ S_{t-1} \qquad \text{Eq [32]}$$

If D S_{t-1} < (1-q)Sa D

If the soil does not have vegetal cover, soil evapotranspiration (Es) is determined as:

$\text{Es (mm/day)} = \text{Kc} \cdot \text{ETo (mm/day)}$ Eq [33]

Where Kc is a coeficient that depends on ETo, soil texture (TX) and rain frequency (F), then:

$\text{Kc} = \phi\,(\text{ETo, TX, F})$ Eq [34]

This is an exponential function:

$\text{Kc} = a\, e^{-b.\text{ETo}}$ Eq [35]

F is a parameter adjusted according to Doorenbos and Pruitt (1977) calculations.

1.6.3.2 Changes in Soil Temperature:

Were measured the annual soil temperature series at 50 cm depth, with a thermometer every 1,10, 20 and 30 of each month, calculating an average value through the expression:

$t(\text{average}) = 0.17(t(1)+2t(10)+2t(20)+t(30))$ Eq [36]

The annual average soil temperature were determined every year (Ta), average summer soil temperature (Ts) and average winter soil temperature (Tw). The air temperatures were measured at the same intervals. With these values, the following equations were found:

$\text{Tw} = \text{Tw (air)} - 1.6$ Eq [37]
$\text{Ts} = \text{Ts (air)} + 1.56$ Eq [38]
$\text{Ta} = \text{Ta (air)} + 0.15$ Eq [39]
$D = \text{Tv} - \text{Ti}$ Eq [40]
D: Temperature increase

Soil temperature regime determinations use the parameters:

$\text{Tm} < 22^{\circ}\text{C}$ and $D \geq 5^{\circ}\text{C}$

Table 1.10 shows a summary of characteristics and main differences between the Jarauta and the Newhall model.

Table 1.10 Newhall model characteristics and Jarauta model characteristics (Jarauta 1989a, 1989b, 1993)

Characteristic	Newhall model	Jarauta model
Soil profile modelled	Soil homogeneous and isotropic, well drained, 200mm AWC	Soil homogeneous, well drained with AWC variable
Water infiltrated amount	Monthly rainfall	Monthly rainfall corrected according to rainfall efficiency. Possibility to use of daily rainfall data.
Filled sequence of the soil profile	Fixed for all soils	Adaptation to different types of soil

Inputs water in the soil profile	Fixed for monthly rainfall with three data per month	Adapted for daily rainfall or monthly rainfall with daily rainfall inputs
Evapotranspiration calculations	Tornthwaite formula	Blaney- Criddle model adaptation according to Doorenbos and Pruitt (1977)
Water extraction sequence	Universal, by diagonals of profile	Possible adaptations of soil characteristics
Soil moisture regimes calculations	Soil Taxonomy principles	Soil Taxonomy principles (SSS,1975, 2006) removing subtypes coincident

1.7 TOPLATS simulation model

Among the numerous water simulation models in catchments, the most frequently used are SWAT (Soil and Water Assessment Tool), SVATS (Soil Vegetation Atmosphere Transfer Schemes), IHACRES, TOPMODEL, E2D, EUROSEM and HEC-1. The application of the SWAT model has the tendency to overpredict the amount of soil water, under relatively dry soil conditions, and to underpredict the amount of soil water under wet conditions. However, the model performed satisfactorily in Canada, simulating soil water, and has a great potential for monitoring soil water resources in small watersheds (Mapfumo et al., 2004).

SVATS has errors due to oversimplifications in the formulation of the model physics and the meteorological data. Other reasons are a lack of soil, vegetation and topographic data at a sufficiently high resolution (Pauwels & De Lannoy, 2006). The IHACRES uses rainfall and temperature to estimate catchment wetness, being impossible to calibrate moisture variation at depth, only at 5 - 15 cm depth (Robinson & Stam, 1993). TOPMODEL simulates soil water indirectly, because its main purpose is to quantify runoff and base flow (Holko & Lepistö, 1997).

The E2D model overestimates soil moisture values and infiltration rates and is not suitable for studies recording low magnitude natural events or high porosity soils. EUROSEM creates mistakes systematically in low or high intensity rainfall. This model underpredicts runoff and base flow, increasing the water infiltrated into the soil (Quinton & Morgan, 1996; Verdú, 1998 and Verdú et al., 2000). HEC-1 model works with general topographic data in small scales, without considering soil and vegetation characteristics of the catchment. In the Canalda catchment there were limitations to simulate the base flow and runoff using this model (Estruch et al., 2001, 2003).

The Vallcebre Catchment is an example of a neighbouring Pre-Pyrenean area where five different hydrological models were compared and tested: i) TOPCAT, a simplification of The TOPMODEL approach, which provided acceptable results during wet periods, but underestimates of flow under other conditions. ii) the TOPKAPI model which overestimated flow, especially during dry conditions, presumably owing to an over simplistic parameterisation. iii) the BROOK model which underestimated most of the events although it showed an acceptable consistence. iv) SACRAMENTO provided the worst results attributed to the complex parameterisation related with scale. v) SHETRAN underestimated runoff and flow, producing soil moisture excess. In the catchment scale, soil water reserve was reasonably well reproduced (Gallart et al., 2005).

According to Famiglietti and Wood (1994a) the land surface is partitioned into bare-soil and vegetated components. The vegetated component is assumed to be distributed uniformly over the surface. An interception store is maintained within the canopy so that wet and dry canopy are recognized. Evaporation and transpiration are computed for the wet and dry canopy. Evapotranspiration and transpiration are computed for the bare soil component of the surface. The sensible and ground heat fluxes are also computed for the wet canopy, the dry canopy, and the bare soil. Infiltration and surface runoff are computed for the bare soil and vegetated components of the land surface. In the model occurs runoff generation by both the infiltration excess and saturation excess mechanisms (fig 1.6).

The surface runoff and energy fluxes depend strongly on surface soil moisture. Consequently, the subsurface soil column is partitioned into two layers. An upper, more active root zone is modelled, which supplies the bare soil and vegetation with soil moisture for evapotranspiration. Its state of wetness also affects the magnitude of the infiltration and runoff fluxes. In addition to infiltration and evapotranspiration, two other root zone soil water fluxes are modelled. A drainage flux exists from the base of the root zone and enters the transmission zone. An upward flux of soil water from the water table due to capillary forces is modelled as well. Roots are assumed to extend uniformly throughout the root zone. Beneath the root zone a lower, less active transmission zone is modelled. This zone extends from the base of the root zone to the top of the capillary fringe, which overlies the water table. Soil water fluxes that flow through the transmission zone include the drainage flux from the root zone, which enters through the top of the transmission zone, and the drainage flux out of the transmission zone. The upward capillary flux from the water table passes through the transmission zone and into the root zone.

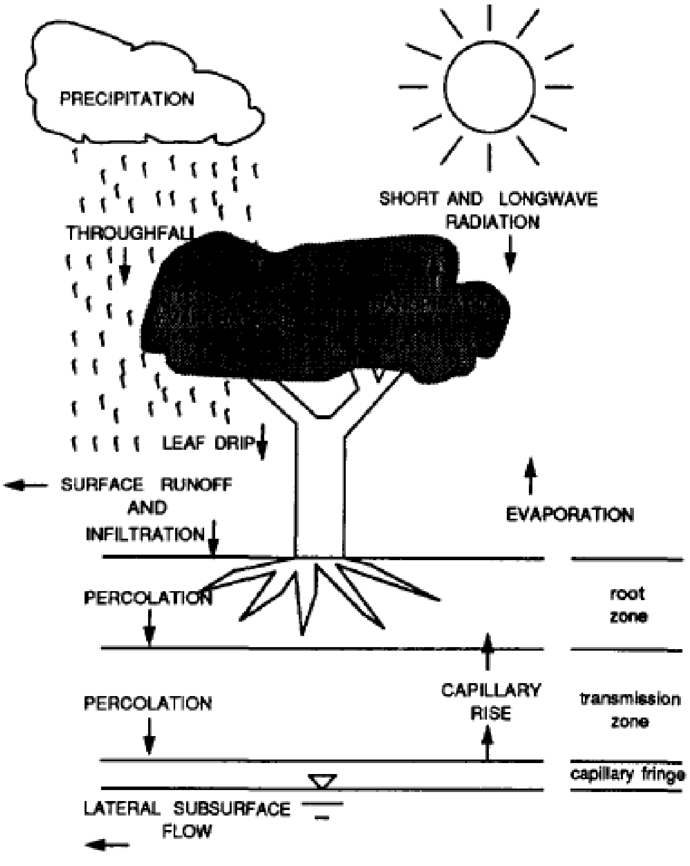


Figure 1.6 Hydrological processes represented in the soil-vegetation-atmosphere models

(Famiglietti and Wood, 1994a)

The local water balance equations following to Famiglietti and Wood (1994a), in other words the prognostics equations for the model states are given below:

1.7.1 Interception storage water balance equations: the water balance for the canopy is given by

$$dw_c/dt = p - e_{wc} - p_{net} \qquad 0 \leq w_c \leq w_{sc} \qquad \text{Eq [41]}$$

$$e_{wc} = \omega_{wc} e_{wct} \qquad \text{Eq [42]}$$

Where p is the precipitation rate, e_{wc} is the wet canopy evaporation rate, p_{net} is the net precipitation that occurs when the canopy water storage capacity W_{sc} has been exceeded, e_{wct} is the rate of evaporation from the entire wet canopy and ω_{wc} is the areal fraction of wet canopy, which is determined from Deardorff (1978) as

$\omega_{wc} = (w_c/w_{sc})^{(2/3)} \qquad e_{wct} > 0$ Eq [43]

$\omega_{wc} = 1 \qquad e_{wct} \leq 0$ Eq [44]

The canopy water storage capacity is calculated after Dickinson (1984) as a function of the leaf area index LAI

$w_{sc} = 0.0002\ \mathrm{LAI}$ Eq [45]

1.7.2 Soil description: soil properties are modelled using the description proposed by Brooks and Corey (1964). The five parameters utilized in this description include the satured hydraulic conductivity Ks, the saturation moisture content θ_s, the residual moisture content θ_r, the pore size distribution index B, and the air entry suction head ψ_c. Soil moisture and hydraulic conductivity in unsaturated soils can be described in terms of the matric head ψ as

$\theta(\psi) = \theta_r + (\theta_s - \theta_r)(\psi_c/\psi)^B \qquad \psi > \psi_c$ Eq [46]

$K(\psi) = K_s(\psi_c/\psi)^{2+3B} \qquad \psi > \psi_c$ Eq [47]

$K(\psi) = K_s \qquad \theta(\psi) = \theta_s \qquad \psi \leq \psi_c$ Eq [48]

1.7.3 Soil water balance equations: To derive the soil water balance equations for the root and transmission zones, two specific cases of local water table depth are considered. In the first case the top of the capillary fringe lies beneath the bottom of the root zone at a depth z - ψ_c. The unsaturated zone is partitioned into a root zone of depth Z_{rz} and an underlying transmission zone. The vertical distance between the top of the capillary fringe and the base of the root zone is defined as the transmission zone length Z_{tz}. In second case the top of the capillary fringe lies within the root zone; there is no transmission zone in this case. The root zone water balance equation for the first case is:

$z_{rz}\dfrac{d\theta_{rz}}{dt} = f_{bs}i_{bs} + f_v i_v + w - f_{bs}e_{bs} - f_v e_{dc} - g_{rz}$ Eq [49]

for

$$z - \psi_c \geq z_{rz} \qquad \theta_r \leq \theta_{rz} \leq \theta_s$$

Where f_{bs} is the fraction of bare soil land surface, i_{bs} is the infiltration rate into bare soils, f_v is the fraction of vegetated land surface (equal to 1- f_{bs}), i_v is the infiltration rate into vegetated soils, w is the rate of capillary rise from the water table, e_{bs} is the evaporation rate from bare soils, e_{dc} is the dry canopy transpiration rate, g_{rz} is the downward soil water flux from the base of the root zone, and the remaining variables have been previously defined. The water balance equation for the transmission zone is

$$z_{tz}\, d\theta_{tz}/dt = g_{rz} - g_{tz} \qquad z_{tz} > 0$$

Eq [50]

for

$$z_{tz} = z - \psi_c - z_{rz} \qquad \theta_r \le \theta_{tz} \le \theta_s$$

Where g_{tz} is the downward soil water flux from the base of transmission zone. The root zone water balance equation for the second case is:

$$z^*_{rz} \frac{d\theta_{rz}}{dt} = f_{bs} i_{bs} + f_v i_v + w - f_{bs} e_{bs} - f_v e_{dc} - g_{rz}$$

Eq [51]

for

$$z^*_{rz} = z - \psi_c \qquad z_{rz} > z - \psi_c \ge 0 \qquad \theta_r \le \theta_{rz} \le \theta_s$$

Where θ_{rz} is the uniform moisture content which extends from the top of the capillary fringe to the land surface. The actual infiltration rate for bare soil is taken as the minimum of an infiltration capacity $i^*(I)$, or the precipitation rate, so that

$$i_{bs} = \min\,[i^*(I),\ p]$$

Eq [52]

Actual infiltration into vegetated soils is the minimum of the infiltration capacity or the net rate of precipitation, so that

$$i_v = \min\,[i^*(I),\ p_{\mathrm{net}}]$$

Eq [53]

The infiltration capacity for bare and vegetated soils is given by Milly (1986) in terms of cumulative infiltration I, soil properties, and the root zone moisture content at the start of each storm event. The rate of capillary rise is based on the result of Gardner (1958) for steady upward flow from a water table

$$w = Ca/(z - \psi_c)^b$$

Eq [54]

Where the parameters C, a, and b are functions of soil type and are given by Eagleson (1978) in terms of the Brooks and Corey (1964) soil parameters. The actual rate of bare-soil evaporation is taken as the minimum of a soil -controlled exfiltration capacity $e^*(Ec)$, or the atmospherically controlled potential evaporation rate e_{pe}

$$\mathbf{e_{bs} = mm\ [e^*(Ec),\ e_{pe}]}$$

Eq [55]

The bare-soil exfiltration capacity is given by Milly (1986) as a function of cumulative exfiltration E_c, root zone moisture content at the start of an interstorm period, and soil properties. The actual rate of transpiration from the dry canopy is obtained from the minimum of the vegetation - controlled transpiration capacity τ^*, or the atmospherically controlled unstressed transpiration rate t_{unst}, as

$$e_{dc} = \omega_{dc} \min [\tau^*, t_{unst}] \qquad \text{Eq [56]}$$

Where ω_{dc} is a canopy water balance variable which expresses the current areal fraction of dry canopy (equal to 1- ω_{wc}). Thus the term vegetation control refers to a state of increased stomatal resistance beyond unstressed levels. The transpiration capacity is based on the soil water extraction model of Feyen et al (1980), and is a function of the matric potential of the soil ψ_s; the critical leaf water potential ψ_{crit}; the hydraulic resistance of the soil Rs; and the hydraulic resistance of the plant R_p. Drainage from the base of the root zone and transmission zone is assumed to proceed at gravity driven rates. These fluxes are described by

$$g_{rz} = K_S \left[\frac{\theta_{rz} - \theta_r}{\theta_s - \theta_r} \right]^{\eta} \qquad \text{Eq [57]}$$

Where

$$\eta = \frac{2 + 3B}{B} \qquad \text{Eq [58]}$$

and g_{tz} is given by replacing θ_{rz} above. Both saturation excess runoff and infiltration excess runoff are computed within the model. The bare soil and vegetated runoff fluxes are

$$q_{bs} = p \qquad \theta_{rz} = \theta_s \qquad \text{Eq [59]}$$

$$q_{bs} = p - i^*(I) \qquad \theta_{rz} < \theta_s \qquad p > i^*(I) \qquad \text{Eq [60]}$$

$$q_v = p_{net} \qquad \theta_{rz} = \theta_s \qquad \text{Eq [61]}$$

$$q_v = p_{net} - i^*(I) \qquad \theta_{rz} < \theta_s \qquad p_{net} > i^*(I) \qquad \text{Eq [62]}$$

1.7.4 Local energy balance equations, potential evapotranspiration and surface temperature: To determine the evapotranspiration rates e_{wc}, e_{dc}, and e_{bs}, the rate of evaporation from the entire wet canopy, the unstressed transpiration rate, and the potential evaporation rate for bare soils must first be computed. These potential rates of evapotranspiration are determined from energy balances for the wet canopy, dry canopy and bare soils respectively. The horizontally homogeneous, one-dimensional form of the energy balance equation is

$$R_n = \rho_w LE + H + G \qquad \text{Eq [63]}$$

Where R_n is the net radiation, $\rho_w$is the density of liquid water, $\rho_w LE$ is the latent heat flux into the atmosphere, H is the sensible heat flux into the atmosphere, and G is the heat flux into the ground. Net radiation is given as

$$R_n = R_{sd}(1 - \alpha) + \varepsilon R_{ld} - \varepsilon \sigma T_l^4 \qquad \text{Eq [64]}$$

Where $\mathbf{R}_{sd}$ is downward shortwave radiation, α is the albedo, ε is the emissivity, $\mathbf{R}_{ld}$ is the downward longwave radiation, σ is the Stefan-Boltzmann constant, and T_l is the temperature of the wet canopy, dry canopy, or bare-soil surface. Latent heat flux is given by Milly (1991) as

$$\rho_w LE = \frac{\rho c_p}{\gamma(r_c + r_{av})}(e^*(T_l) - e_a) \qquad \text{Eq [65]}$$

Where ρ is the air density, the C_p is the specific heat of air at constant pressure, γ is the psychometric constant, r_c is the canopy resistance, r_{av} is the aerodynamic resistance, $e^*(T_l)$ is the saturation vapor pressure at some level above the canopy or soil surface Za. The heat flux of sensible heat is described by

$$H = (\rho c_p / r_{ah})(T_l - T_a) \qquad \text{Eq [66]}$$

Where r_{ah} is the aerodynamic resistance to the heat flow, and Ta is the air temperature at Za. Ignoring the effects of heat storage in the surface soil layer, heat flux into the surface, G, is assumed to be a linear function of the subsurface temperature gradient and is given by

$$G = (\kappa / D)(T_l - T_2) \qquad \text{Eq [67]}$$

Where k is the thermal conductivity, D is the damping depth of diurnal temperature oscillations, and T_2 is temperature at depth D. The expression employed for thermal conductivity is dependent on the matric head and is described by Mccumber and Pielke(1981). The temperature T_2 is presently prescribed in the model. The aerodynamic resistances are given by:

$$r_{ah} = r_{av} = \frac{1}{k^2 u(z_a)}\left[\ln\left[\frac{(z_a - d)}{z_0}\right]\right]^2 \qquad \text{Eq [68]}$$

Where k is von Kármán's constant, $u(z_a)$ is the wind speed at level z_a, d is the zero plane displacement, and z_o is the roughness length of the canopy or the soil surface. Evaporation from the entire wet canopy e_{wet} is determined by solving (63) - (68) for the temperature of the wet vegetated surface. Setting α, z_o and d consistent with the type of wet vegetation, setting G and r_c equal to zero, and letting T_l represent the temperature of the wet vegetated surface yields the partitioning of R_n into ρ_w LE and H. The unstressed transpiration t_{unst} is calculated in the same manner as e_{wct}, but with r_c representing canopy resistance as $r_c = r_{stmin}/LAI$, where r_{stmin} is a minimum value of stomatal resistance. The potential evaporation e_{pe} for bare soil is calculated using (65) - (63) with r_c equal to zero, α, z_o and d consistent with the particular type of wet soil, and T_l applying to the temperature of the wet bare-soil surface. The temperatures and fluxes thus determined are for potential or unstressed conditions. When stomatal resistance increases above its minimum level and the actual transpiration rate is less than the unstressed rate, e_{dc} substituted for E in (65), and (63) is resolved for the correct dry canopy temperature and fluxes. When bare-soil evaporation proceeds at soil-controlled rates, e_{bs} is substituted by E in (65), and (63) is resolved for the correct bare-soil temperature and energy fluxes.

1.7.5 Local water and energy balance fluxes: The local rates of evapotranspiration E and runoff Q are determined by summing the bare-soil and vegetated components, weighted by their corresponding areal fractions:

$$E = f_{bs}e_{bs} + f_v(e_{dc} + e_{wc}) \qquad \text{Eq [69]}$$

$$Q = f_{bs}q_{bs} + f_vq_v \qquad \text{Eq [70]}$$

The remaining energy fluxes and surface temperature are determined as in (69)

1.8 Extend Kalman Filter (EKF)

The original Kalman filter is a relatively recent development in filtering Kalman (1960); Maybeck (1979); Welch & Bishop (1995) and Aubert et al., (2003). Although it has its roots as far back as Gauss. Kalman filtering has been applied in areas as diverse as aerospace, marine navigation, nuclear power plant instrumentation, demographic modelling, manufacturing, hydrology and many others. These types of equations are being used increasingly by different authors to simulate and calibrate hydrological models for water and energy fluxes, which is confirmed by the realized works by Crow & Wood (2003); Kumar & Kaleita (2003); Schuurmans et al (2003); Aubert et al (2003). The methodology used to calibrate the model was developed by Goegebeur and Pauwels (2007). The methodology is based on the equations of the Extended Kalman Filter. The equations are applied iteratively throughout an iteration process, based on which the methodology can be referred to as weight-adaptive recursive parameter estimation. Only a short description will be given here, for a full description we refer to Goegebeur and Pauwels (2007). In the algorithm, all calibrated parameters are stored in a vector **X$_k$**. This vector is propagated from iteration **k** to iteration **k+1** as follows, taking into account the process noise **W$_k$**:

$$\mathrm{x}_{k+1} = \mathrm{x}_k + \mathrm{w}_k \qquad \text{Eq [71]}$$

The observation vector at iteration **k** (**y$_k$**, with m observations) is related to the system parameters as follows:

$$\mathrm{y}_k = c\left(\mathrm{x}_k, \mathrm{v}_k\right) \qquad \text{Eq [72]}$$

V$_k$ is the measurement noise. **C** is a nonlinear function, which relates the observation at iteration **k** to the parameter values at iteration **k**. **V$_k$** and **W$_k$** are assumed to be independent of each other, to be white, with covariances **R$_k$** and **Q$_k$**, respectively. The Jacobian matrices **H$_k$** (m rows and n columns), and **V$_k$** (n rows and columns) are calculated as follows:

Eq [73]

$$\begin{cases} \mathrm{H}_k[i,j] & = & \dfrac{\partial c\left(\hat{\mathrm{x}}_k^{\,-}, \mathbf{0}\right)[i]}{\partial \mathrm{x}[j]} \\ \mathrm{V}_k[i,j] & = & \dfrac{\partial c\left(\hat{\mathrm{x}}_k^{\,-}, \mathbf{0}\right)[i]}{\partial \mathrm{v}[j]} \end{cases}$$

The **0** means that for the calculation of these partial derivatives a noise level of zero is assumed. **V$_k$** is assumed to be the identity matrix, and **H$_k$** is calculated numerically. The algorithm works as follows. For each iteration level **k**, the model is applied for the entire simulation period. The model simulations are stored in the vector $\hat{y}_k^-$, and the corresponding observations are stored in the vector **y**. The system parameter vector $\hat{\mathrm{x}}_k$ is propagated from iteration **k-1** to iteration **k** as follows:

$$\hat{\mathrm{x}}_k^- = \hat{\mathrm{x}}_{k-1}^+ \qquad \text{Eq [74]}$$

Then, using the a posteriori (after the parameter update) error covariance from the previous iteration, the a priori error covariance at the current iteration $\mathbf{P}_k^-$ is calculated:

$$\mathbf{P}_k^- = \mathbf{P}_{k-1} + \mathbf{Q}_{k-1} \qquad \text{Eq [75]}$$

The parameter vector and the error covariance are updated as follows:

$$\begin{cases} \mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^{\mathrm{T}} \left[\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^{\mathrm{T}} + \mathbf{R}_k \right]^{-1} \\ \hat{\mathbf{x}}_k^+ = \hat{\mathbf{x}}_k^- + \mathbf{K}_k \left(\mathbf{y}_k - \hat{\mathbf{y}}_k^- \right) \\ \mathbf{P}_k = \left[\mathbf{I} - \mathbf{K}_k \mathbf{H}_k \right] \mathbf{P}_k^- \end{cases}$$ Eq [76]

K_k is the Kalman Gain Factor, and has been obtained by a minimization of the square of the difference between the true (correct) parameters and the a posteriori estimate of these parameters. $\hat{\mathbf{x}}_k^+$ is the a posteriori estimate of the parameter vector. The values of $\hat{\mathbf{x}}_k^+$ are then stored into the parameter vector $\hat{\mathbf{x}}_{k+1}^-$, and the algorithm is repeated until convergence is achieved or when a predefined number of iterations has been reached.

Chapter 2

ESTIMATION OF SOIL MOISTURE REGIMES IN TRANSITION ZONES ON MOUNTAIN REGIONS. Ribera Salada catchment, Catalan Pre-pyrenees (NE Spain)

2.1 Introduction

The determination of soil moisture regimes is a way to provide relevant information about the soil water availability for plants in a probabilistic way. Soil moisture regimes are defined in terms of the level of groundwater and in terms of the seasonal presence or absence of water held at a tension of less than -1500 kPa in the moisture control section. It is assumed that the soil supports whatever vegetation it is capable of, being crops, grass or native vegetation, and that the amount of stored moisture is not being increased by irrigation or cultural practices (SSS, 2006).

According to Soil taxonomy criteria, the term "regime" represents the normal succession of moisture and drought estates along the time, expressing the percentage of soil moisture variation. The change of soil use to tillages with a higher evapotranspirative demand, can lead conduct to drier regimes; or to leave the land fallow can increase the moisture content. Because of these possible managements, Soil Taxonomy introduced the concept “normal year and cultural practices”. Soil moisture regimes are closely correlated with the agricultural use and the plants growth (SSS, 2006).

Soil taxonomy (SSS, 2006) defines five classes of soil moisture regime alongside five principal classes of soil temperature regimes. These soil moisture regimes are: **aquic** (L. *aqua*, water), **udic** (L. *udus*, humid), **ustic** (L. *ustus*, burnt; implying dryness), **xeric** (Gr, *xeros,* dry), **aridic** and **torric** (L. *aridus*, and L. *torridus*, hot). The soil temperature regimes are: **cryc** (Gr, *kryos*, coldness; meaning very cold soils, 0 ºC< x < 8 ºC in summer is very cold), **frigid** (0 ºC< x < 8 ºC warmer in summer than a cryc regime), **mesic** (8 ºC < x < 15 ºC the difference between mean summer and mean winter soil temperatures is more than 6 ºC), **thermic** (15 ºC< x < 22 ºC the difference between main summer and main winter soil temperatures is more than 6 ºC), **hyperthermic** (x ≥ 22 ºC the difference between main summer and main winter soil temperatures is more than 6 ºC). These classes are used with soil classification parameters.

The moisture control section consist of the zone where the plants have the largest portion of roots; therefore it is the most important area affecting their development. The moisture control section constitutes the central zone in the soil profile and it is there where the moisture is the most representative. Its determination considers the following factors: texture, structure, porosity, factors of water flow and water retention and thickness. Knowledge on the soil moisture regime is important to infer factors of soil processes and the availability of water for plants (under forest, pasture, etc), also to infer vegetation type and condition, nutrient cycling and other ecological relations, allowing to establish the geographical distribution of wetlands and arid regions.

Several researchers have used environmental information in soil moisture regime prediction. As Waltman et al. (1997, 2002) in USA; Trnka et al. (2002); Kapler et al. (2006) in Czech Republic; Constantini et al. (2002) in Italy; Tavernier & Van Wambeke (1976a, 1976b) in Spain and Marroco; Van Wambeke (1976, 1981, 1982, 1985, 2000) in Syria, Lebanon, South America, Africa, Asia and North America.

Basic information such as soil type and soil use (scale 1:50000) in combination with soil moisture information, makes it possible to obtain a correct management of land planning, development, research; and a knowledge of ecological relations and physiological processes. Studing soil moisture regimes, we will gain truthful information on the number of days in a year that there is moist soil and dry soil, and with this information we can predict and manage the crops and possible reforestations, with a high probability of success (Jeutong et al., 2000).

The obtained predictions by soil moisture regime simulation models provide an historical context of drought events, which can be mapped at multiple scales to identify counties and ecological regions with higher possibilities of drought events of polyclimatic environments (Waltman et al., 2002, 2003). 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 specifics regions (Waltman et al., 1997, 2002). In Italy, Constantini et al. (2002) used the soil moisture simulation model to predict soil regimes and soil moisture and correlated it with potential soil erosion.

In the USA, USDA (United State Department of Agriculture) has the national agricultural decision support system (NADSS) database entries of soil moisture status by state stations for a period of 30 years (1971 - 2000). This information is used for interpretations related to crop growth, installation of conservation practices, susceptibility to compaction, ease of excavation, hydric soils, agricultural waste, and many others. The classification of soils often depends on an inference of soil climate based on vegetation and/or atmospheric climate. Soil moisture data can also be used to separate series. Crop insurance agencies use this information for risk management (SSS, 2001).

One of the most frequently used simulation models is the Newhall simulation model (NSM). This model is an at length accepted methodology to estimate moisture regimes and soil temperature (chapter 1); in a direct and indirect way according to Soil Taxonomy. This model simulates the downward movement of moisture into the soil as the progression of a wetting front. The soil moisture profile considered by the model extends from the surface down to the depth of an available water holding capacity (AWC) of 200mm. The soil depth needed to achieve this AWC depends basically on the porosity. The soil profile is divided into 8 layers, each of which retains 25mm of available water; the second and the third layer form the moisture control section (Van Wambeke, 2000).

Other models take into account soil parameters, like the Jarauta simulation model (JSM) (Jarauta, 1989), this model added modifications to NSM like complete meteorological information, daily rainfall and monthly rainfall and vegetation and soil data. The model mentioned above corrects the mistakes found by Tavernier & Van Wambeke (1976a, 1976b), Ibáñez & Gascó (1983), Lázaro et al. (1978), Elías & Ibáñez (1979) for soils in Spain.

The main soil forming factor determining the soil water regime in the climate. In large regions with low variability of the rest of forming factors (relief, parent material, soil cover, management), there will be a unique relation between climate and soil water regime, since the soil available water capacity and hydrological characteristics will be constant. In other situations, where the rest of the soil forming factors have a higher spatial variability, soil hydrological behaviour will also vary, and thus it is possible that under the same climate, different soil water regimes coexist at short distances. This may be very relevant in those places with a strong climatic gradient that span among two or three soil water regimes. In these cases soil and land characteristics will affect the spatial distribution of soil water regimes.

This was already observed by Jarauta (1989a, 1989b) who in a xeric-aridic transitional region found that aridic SWR corresponded to soils with AWC less than 50 mm. In regions with dry climates plant available water capacity is affected by a number factors such as physical barriers, chemical barriers and nutrients distributions. When soil physical properties such as porosity, pore sizes, strength and root channels are unfavorale to water availability (Zhang et al., 2001). Acording to Chanasyk et al. (2004) to grassland watersheds in Alberta, grazing topographic position were upperslope, midslope and lowerslope show differences in soil moisture content.

In the study area three soil water regimes were determined for soil mapping purposes at a scale of 1:50000: udic (above 1200m), ustic (between 480 - 1200m) and xeric (below 480m) (Estruch, 2001; Orozco, 2006). Altitudinal rainfall gradients were calculated by Pipó (2000) and Esteban (2003), finding that the annual rainfall volume difference between the lowest point and highest point in the catchment is 175 mm. Soil temperature regimes were mesic and frigid. Nevertheless, the high diversity of ecosystems in the area suggest that the actual soil climate regimes are by far more complex and other factors than climate have a strong influence on them.

The main aim of this research is to examine the soil moisture content and soil moisture regimes under different soils uses in a Mediterranean model catchment, using measured data of soil moisture and simulation models. The particular aims are: (i) to know the soil moisture regimes under different soil uses in the Ribera Salada and study the soil moisture tendency in the course of the seasons,(ii) to verify the reliability of the NSM and JSM soil moisture content outputs comparing them with measured data, (iii) to extrapolate the results attained to spatially estimate the Ribera Salada soil climate regimes.

2.1 Materials and methods

The general properties of the analyzed models, site studied characteristics and the different measurements done and used methodologies can be checked at Chapter 1.

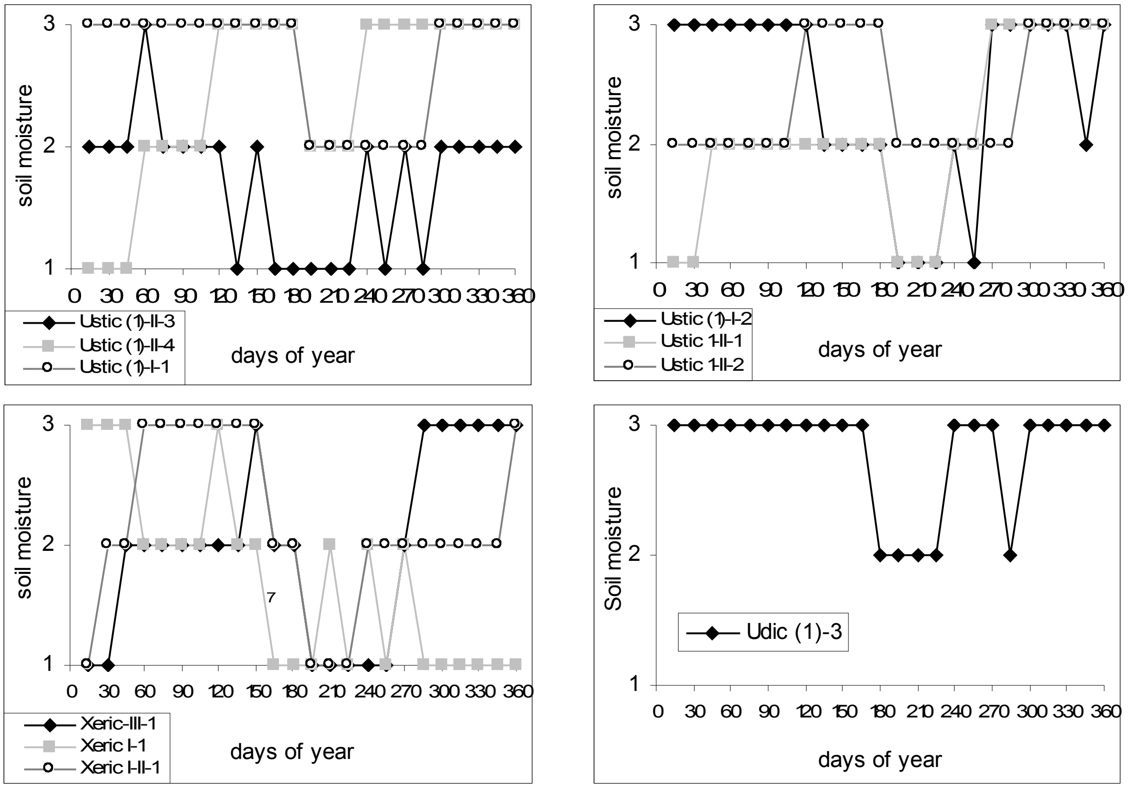
The soil moisture regimes determination follows the established criteria by Soil Taxonomy (SSS, 1975, 2006), (table 5.3). To establish the difference between two moisture regimes, the soil moisture conditions and soil temperature regime are considered. The established criteria to define the last soil moisture regime (point 2.1) are expressed in table 2.1.

Table 2.1 Soil taxonomy criterion (SSS, 1975, 2006)

Soil Taxonomy criteria	Characteristics
A	Soil is totally dry, more than half of the time (accumulated), when the soil temperature at 50 cm depth is higher than 5ºC
B	Soil is partially moist, almost 90 consecutively days, when the soil temperature at 50 cm depth is higher than 8ºC
C	Soil is total or partially dry, during 90 (or more) accumulated days
D	Soil is totally dry during 45 (or more) consecutive days, in the 4 following months to summer solstice (21 June)
E	Soil is totally moist during 45 (or more) consecutive days in the 4 following months to winter solstice (21 December)

Some criteria refer to the inexistence of water in the soil (A,C, D) and the others refer to the presence of water (B, E).

Fig. 2.1 shows the soil moisture behaviour along the year, under different soil moisture regimes existent in the basin. Moisture regimes of different simulated years can be observed at table 2.2. For example Ustic (1)-II-3, means: Ustic (soil moisture regime, point 2.1), (1)- II- 3 defines the moisture subregime, which is associated to specific soil moisture conditions during the year seasons; this behaviour can be observed at fig 2.1 (Jarauta, 1989a).



(1) Dry, (2) Moist, (3) Wet

Fig 2.1 Daily behaviour of soil moisture regimes in the Ribera Salada Catchment

Fig 2.2 shows the monthly rainfall and accumulated rainfall in the studied period (2003 to 2005) compared to the average rainfall from 1998 to 2007. We can observe that the three years studied are drier than the average. This is mainly caused by less precipitation in spring months (April, May and June).

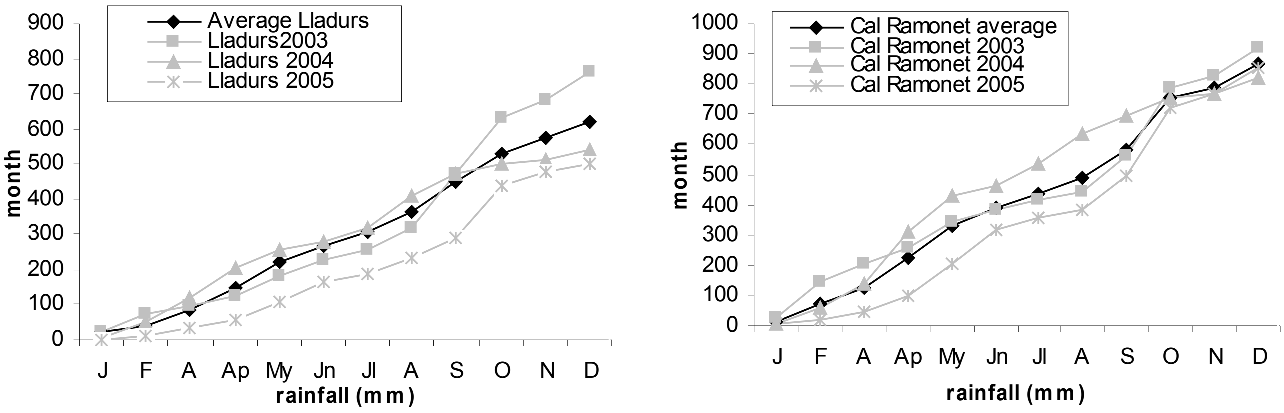


Fig 2.2 Rainfall Lladurs and Ramonet station 2003 to 2005 and average.

Soil moisture data have been measured in the different sampling plots (Chapter 1). The comparison between measured and simulated values in NSM and JSM is held in each plot, as it has been done with soil moisture behaviour analysis. Acuña & Poch (2001) selected two soil mapping units(19 and 43 hectares) to measure hydrologic and soil physical properties according to a nested sampling. The two units were located at a distance of more than 200m from each other. The sampling distances within each unit were 200, 50, 12 and 3 m with a total of 48 sampling points per plot. These authors found that properties such as hydraulic conductivity and soil moisture content had low variability within distances higher than 300 m. The results shown in fig 2.7 correspond to an extrapolation, (scale 1:50000) bearing into account the different soil-soil use combinations present in the basin, according to works by Ubalde (1997) and Acuña & Poch (2001).

2.3 Results

2.3.1 Soil moisture regimes

The evolution of soil moisture during the 3 years studied is shown in fig 2.3.

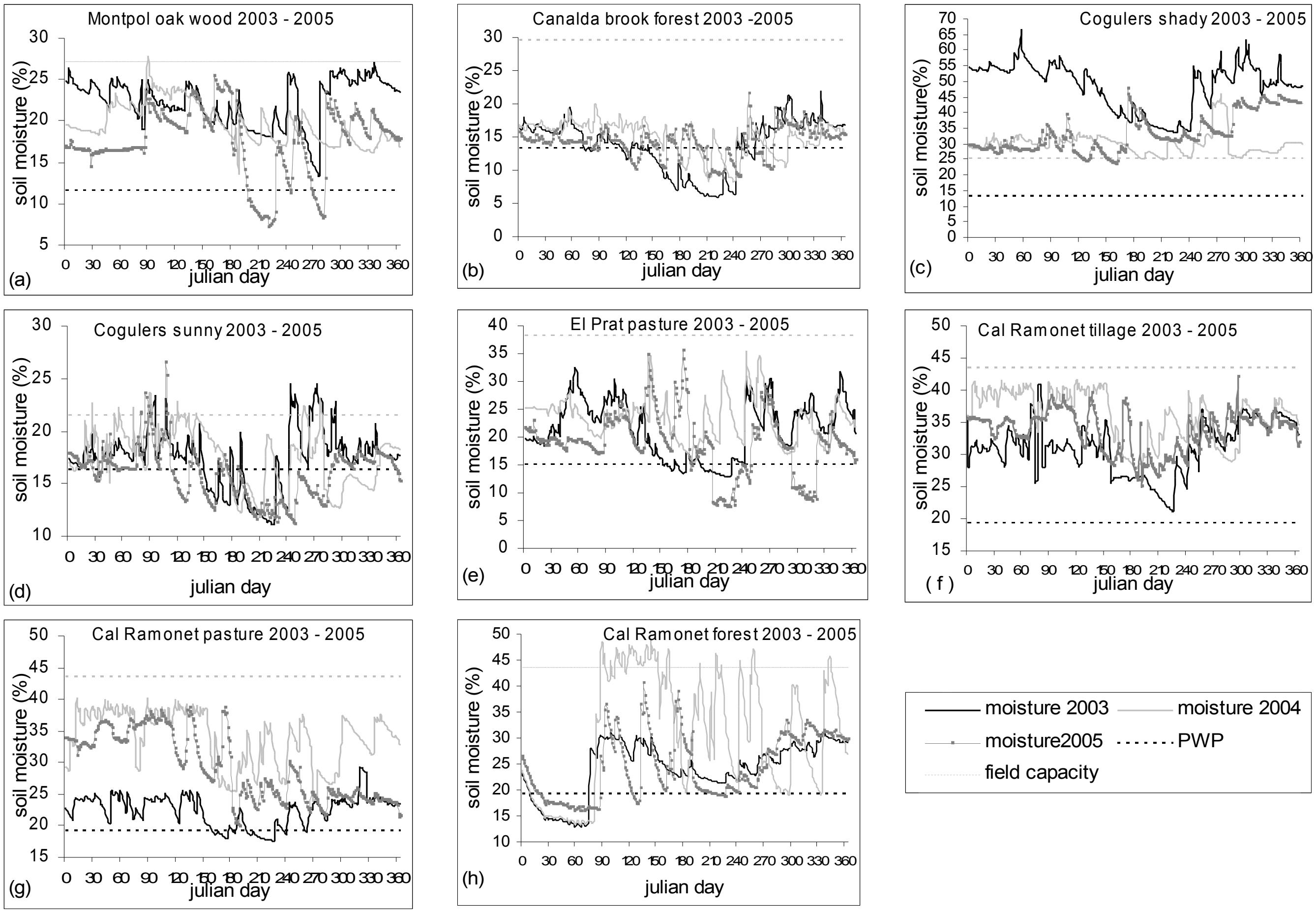


Fig 2.3 Daily real soil moisture for the different field soil moisture stations in the Ribera Salada catchment

We observe a decrease in soil moisture content (x ≤-1500 kPa) in summer in all plots and a decrease in winter in the plots: Montpol oak wood, Canalda brook forest, Cogulers sunny, El Prat pasture and Cal Ramonet forest. Spring and autumn are the moistest seasons (x ≤-33 kPa) in all plots.

The recorded analysis of the soil water content shows that soils under forest cover are drier than pasture, tillage and shady areas. This is due to differences in rainfall interception and infiltration (higher in forest), soil water retention capacity and soil profile localization. Underneath forest, soil moisture is lower than pasture and shady sites, due to the fact that interception and water uptake by roots is high. This dry condition is accentuated in shallower soils. Soils under pastures are drier than soils in shady forest, because pastures take water from the superficial soil layers, whereas trees can take water from deeper horizons, this event draining quickly the water reserves in pastures. Soil profile thickness and evapotranspiration volume are important factors which affect soil water availability.

According to Zhang et al (2001), who studied 250 catchments around the world, the forest sustained a higher evapotranspiration rate than the pasture in dry seasons, and the difference was attributed to the ability of the trees to access soil moisture from greater depth. Plants extract most water from shallow layers where the root density is the highest. The available water depends more on the rooting depth, the average maximum rooting depth being about 7 m for trees and 2.6 m for herbaceous plants.

The different soil use is shown in fig 2.3, which reflects that spatial soil moisture variability is high during intermediate wetness conditions and decreases during both wet and dry conditions; Rius et al. (2001), Llorens et al. (2003) and Gallart et al. (2005) found the same in the Mediterranean mountains. Under extreme wet and extreme dry conditions, the variability is much lower, since reaching these points soil moisture can hardly decrease or increase.

Four representative sites were selected for a more detailed analysis of soil moisture regime. The first site is Montpol oak wood, located in a mid-slope position, covered by oak woods. The second site is Cogulers shady, a frequently saturated area near the bank, covered by moss and pine trees. The third and fourth are located in Cal Ramonet station, covered by tillage and forest, respectively.

The first site shows a less pronounced intra-annual variability (between 13% and 27% soil moisture). Soil water content decreases after December and does not increase until the end of February or May. Summer drought includes the second fortnight of July and August (soil have values of -1500 kPa). Finally, there is a progressive wetting-up of the soil from June to November, with two peaks of soil moisture throughout the year.

The second site shows a marked intra-annual variability (between 25 and 66% of soil moisture). All along the year the soil profile is always saturated. In the second fortnight of June, the soil water content decreases gradually, due to the evapotranspiration demand increase and the ceasement of the subsurface water transfer. The lowest soil water content is reached at the end of August. Later on, the content of soil water tends to increase until the end of November. The soil saturation conditions (θ_m>-33 kPa) last until late June when the water content decreases.

The other two profiles show a marked intra-annual variability (soil moisture between 15 - 48 %). The soil water content decreases after January (Cal Ramonet forest) and does not increase again until the end of March. The progressive wetting-up of soils starts the first fortnight of September to continue, to the end of the year. The inter-annual variability is greater in Cal Ramonet forest than Cal Ramonet tillage. The Cal Ramonet forest has two dry episodes (winter and summer), whilst the Cal Ramonet tillage has only one dry episode (summer). Forest soil is shallower, therefore the AWC is lower and water is spent more quickly.

To summarize, the seasonal tendency of the stations described, illustrates a catchment hydrodynamics characterized by summer droughts except in Cogulers shady (shady forest).

In all sites, autumn and spring are recharge seasons, and winter is the season when a progressive drying occurs until early spring. Two sites form an exception: the Cogulers shady, with wet soil all the year long, which suffer a progressive drying in summer and the Cal Ramonet tillage with a short low soil water content period in summer.

In the Cogulers shady, these moist conditions are due to the presence of wet microclimate special conditions and a water source close to the plot. In the Cal Ramonet tillage besides the low slope, soil moisture content is influenced by tillage management as plowing, the addition of tillage residues and furrows, which increase the soil moisture retention capacity. In winter, precipitation occurs as snow, and is stored more efficiently than rain. Furthermore, evapotranspiration expenses are low in winter.

2.3.2 Simulation of soil temperature

The soil temperature is the result of the interaction of several factors, according to Malagon & Montenegro (1990). The edaphic temperature variability depends on soil characteristics, moisture and cover type, which has a direct influence on evapotranspiration and consequently on heat flux of the soil. These heat fluxes into the soil are an answer to the changes in solar radiation intensity, conductivity and thermal diffusivity. These phenomena are guided by complex transport processes.

Regarding soil moisture, a moister soil has higher heat capacity, due to the high heat capacity of the water. Preliminary, soil temperature regimes in the Ribera Salada catchment are estimated with Lladurs station information (XAC), from air temperatures, considered to be between Mesic and Thermic, depending on the severity of winter temperatures. Both simulation models coincide in a Mesic regime. The result of both models is satisfactory as a first approximation, but do not predict punctual changes in soil temperature.

The monthly averages of soil temperature in the Lladurs station are shown in fig 2.4a, and fig 2.4b represents the observed soil temperature compared with JSM and NSM results.

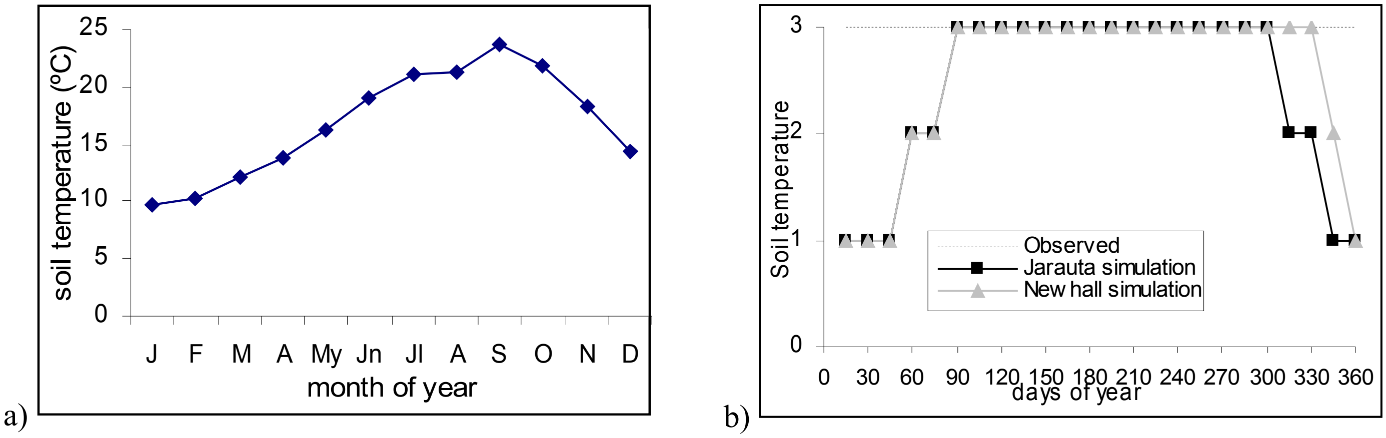


Fig 2.4. a) Soil temperature monthly in Lladurs station (1998 - 2005)

b) Observed Soil temperature vs Jarauta and Newhall model simulation results. Soil temperature levels (1: T<5 ºC; 2: T<5>8 ºC; 3: T>8 ºC).

Examining the observed soil temperature we can see that in winter soil temperature is ≤10ºC, and in the other seasons the values fluctuate between 15 to 25ºC. The highest temperature in the soil is recorded in August.

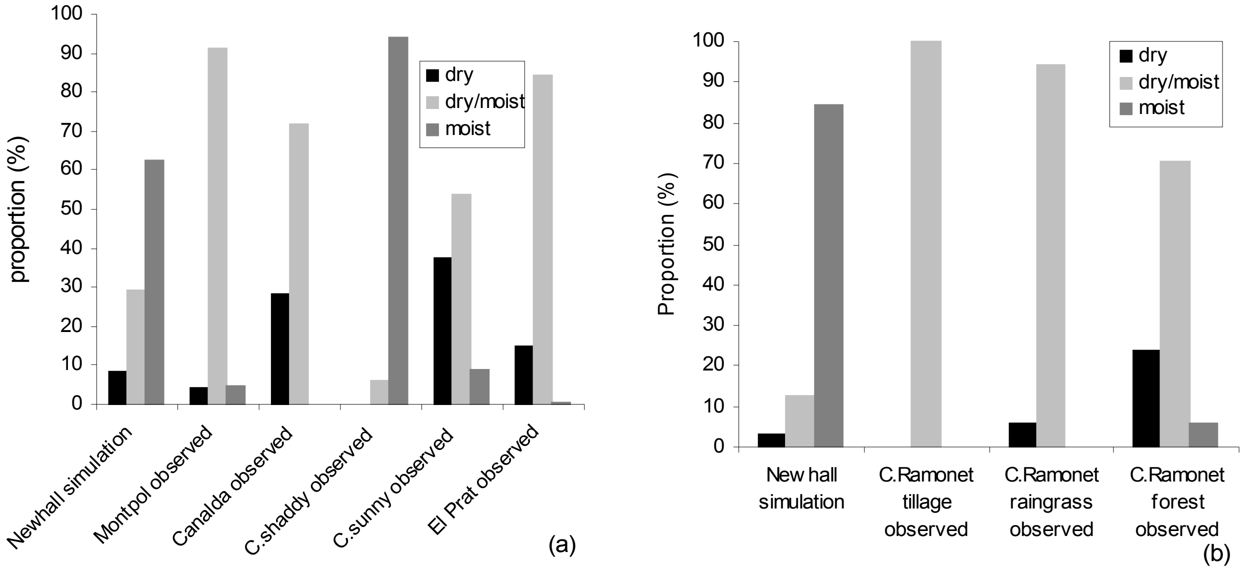
Soil temperature simulated values show a high similarity with observed values in NSM as well as JSM. Only in winter and in the last period of autumn, the model shows a slight difference between the observed and the simulated values. The simulated values are lower than the actual values because both NSM and JSM calculate the soil temperature according to air temperature by means of a very general equation (chapter 1). This simplistic procedure is the reason why in Spain, several authors report very different soil temperature regimes as thermic, mesic and cryic regimes [Tavernier & Van Wambeke (1976), Lazaro et al.,(1978), Arrue et al., (1984)].

2.3.3 Simulation of soil moisture regimes

2.3.3.1 Newhall model

The application of NSM to the different sites is shown in fig 2.7, table 2.2. The simulated NSM soil moisture values in the Cal Ramonet station (highlands) and the Lladurs station (lowlands) are higher than the actual values, (fig 2.5). The simulated soil moisture values in lowlands are lower in summer months and at the beginning of autumn, than in the rest of the year. In highlands, the moisture values fall in summer and are high during the rest of the year, except in 2004 when soil was moist along the entire year.

Fig 2.5 shows soil moisture at different locations and conditions in average years, both simulated using NSM and observed. In these graphs soil moisture saturation values are expressed in three levels: i) dry (θ_m < -1500 kPa), ii) partly moist (θ_m "-33 kPa> X >-1500 kPa"), iii) moist (θ_m >-33 kPa). The percentage coincidence between the observed values and NSM can be consulted in table 2.3. The field data and the NSM simulated values differ to 90% in some cases. During most parts of the year, simulated moisture is higher than the real one.



*dry (soil moisture < -1500 kPa), partially moist (soil moisture "-33 kPa> X >-1500 kPa"), moist (soil moisture >-33 kPa).

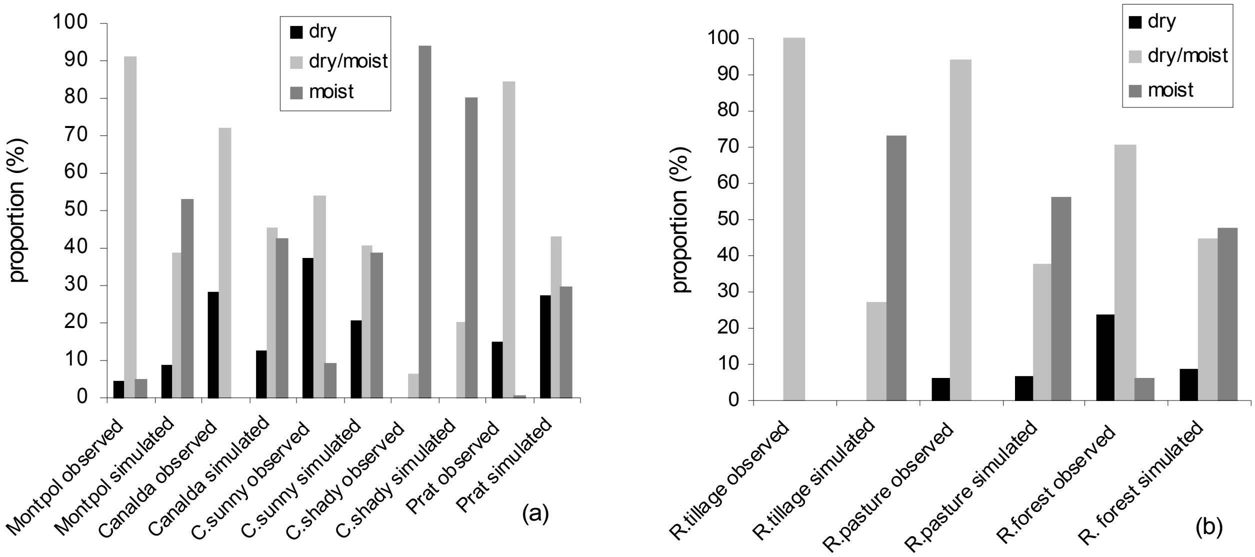
Figure 2.5 Total percentage of soil moisture observed and Newhall simulation values
(a) Soil moisture lowlands, (b) soil moisture highlands

In summary, NSM overestimates the soil moisture content, reaching soil saturated values when the soil control section is drier in the field. These results are caused by the limited input data into the NSM. According to Jarauta (1988,1989), Jarauta et al. (1993), Porta et al. (1994) NSM does not model very well the variability of available water by plants, because it considers all the rain being efficient, which is not the case in Mediterranean showers with high intensities. Moreover, it models the evapotranspiration very simply, and does not take into account other rain and orographic characteristics. All these aspects limit its applicability (chapter 1).

2.3.3.2 Jarauta model

The simulation according to JSM (fig 2.1) gives three different soil moisture regimes being, udic, ustic and xeric (table 2.2). The behavior of the simulated soil moisture in the Jarauta model has two different patterns: i) a biannual one, which gives two dry periods, winter and summer, and a soil moisture content increase at the end of spring and autumn, ii) an annual one, where during summer months the soil is drier, while the rest of the year, it is completely or partially moist.

Fig 2.6 shows the main annual soil moisture content of the simulated vs. observed values for the different locations. JSM allows the estimation of soil moisture for each soil use and soil type.



*dry (soil moisture < -1500 kPa), partially moist (soil moisture "-33 kPa> X >-1500 kPa"), moist (soil moisture >-33 kPa).

Fig 2.6 Total percentage of soil moisture observed and obtained by Jarauta simulation.
(a) Lowlands soil moisture, (b) Highlands soil moisture

The observations are centered in the dry periods percentage, because they determinate the existence of udic or xeric regime in the basin. The simulated values are closer to the observed ones in dry periods, coinciding in their duration, time and their seasonal behavior and thus being capable to predict the total days and the state of moisture content. The model works well under medium and low soil moisture, which is appropriate for Mediterranean conditions. The observations are focused on the dry period percentage, because they deteminate the existence of udic or xeric regimes in the basin.

2.3.4 Determination of soil moisture regimes

The classification of soil moisture regimes in the different stations is represented in table 2.2. Table 2.3 shows the criteria of evaluation and the coincidence with the soil taxonomy formulations in a rang of 0 - 100% with respect to the Soil Taxonomy criterion, described in table 2.1. JSM and NSM accomplishes 100% of the A criterion. JSM only partly complies with the B criterion while NSM complies with it all the time, because in all cases it simulates higher moisture than in the field. JSM complies with the C criterion in 100% of cases, while NSM complies only partially with it and sometimes even does not follow this criterion. JSM follows the D criterion in all plots, except in the Cal Ramonet pasture and the Cal Ramonet forest, where it is partially followed.

NSM doesn't follow the D criterion, except in the Cal Ramonet tillage and the Cal Ramonet forest. JSM tends to give low moisture values, because this model is better adjusted to partially dry soil conditions. NSM tends to simulate higher soil moisture, and does not consider moisture retention, infiltration or evapotranspiration.

JSM tends to simulate better soil moisture conditions because it allows to work under specific CRAD values, soil profile thickness and infiltration conditions; and each soil use allows us to calculate evapotranspiration following the tillage coefficient used in Doorenbos & Pruitt (1977) equations.

Table 2.2 Soil moisture regimes in Ribera Salada stations according to real data observed at field, and Jarauta and Newhall simulation data

Year	**Data**	**Montpol** oak wood	**Canalda** brook forest	**Cogulers** shaddy	**Cogulers** sunny	**El Prat** pasture	**Cal Ramonet**		
							Tillage	Pasture	Forest
2003	Observed	Ustic 1-II-2	Ustic 1-II-1	Udic (1)-3	Ustic 1-II-1	Ustic 1-II-1	Ustic 1-II-2	Ustic 1-II-1	Ustic (1)-II-2
	JSM	Ustic 1-II-2	Ustic(1)-II-2	Udic (1)-3	Ustic 1-II-1	Ustic 1-II-1	Ustic 1-I-1	Ustic 1-I-2	Ustic (1)-II-2
	NSM	Udic (1)-3	Udic (1)-3	Udic (1)-3	Udic (1)-3	Udic (1)-3	Ustic 1-I-1	Ustic 1-I-1	Ustic 1-I-1
2004	Observed	Ustic 1-II-2	Ustic 1-II-1	Udic (1)-3	Ustic 1-II-1	Ustic 1-II-2	Ustic 1-II-2	Ustic 1-II-2	Ustic (1)-II-2
	JSM	Ustic 1-II-4	Ustic(1)-1-2	Udic (1)-3	Ustic 1-I-2	Ustic 1-I-2	Ustic 1-I-1	Ustic 1-I-1	Ustic (1)-I-1
	NSM	Ustic(1)-I-1	Ustic(1)-I-1	Ustic(1)-I-1	Ustic(1)-I-1	Ustic(1)-I-1	Udic (1)-3	Udic (1)-3	Udic (1)-3
2005	Observed	Ustic 1-II-2	Perxeric	Udic (1)-3	Ustic 1-II-2	Ustic 1-II-1	Ustic 1-II-2	Ustic 1-II-2	Ustic (1)-II-2
	JSM	Ustic 1-II-4	Xeric-III-1	Udic (1)-3	Ustic 1-II-3	Ustic 1-II-3	Ustic 1-I-1	Ustic 1-II-2	Ustic (1)-II-1
	NSM	Xeric-III-1	Xeric-III-1	Xeric-III-1	Xeric-III-1	Xeric-III-1	Udic (1)-3	Udic (1)-3	Udic (1)-3

JSM: Jarauta simulation model, NSM: Newhall simulation model, observed: field data

NSM overestimates ustic regimes in all the studied plots. Tavernier & Van Wambeke (1976a) assigned an udic common regime to all Mediterranean mountain zones. These authors defined ustic regimes in the Iberian Peninsula as transitional pedoclimates, between xeric types and udic or aridic regimes. Other authors like Elias et al.(1979) in the Ebro river basin and Jarauta (1991) in the Garrigues region of Spain, found that under xeric and aridic real soil moisture regime, NSM assigns an ustic regime. These Mediterranean ustic regimes does not fit within the concept of tropical ustic regimes, characterized by wet summers and dry winters.

Table 2.3 Soil taxonomy criteria for different stations in Ribera Salada catchment

Station	Data	A	B	C	D	E	Station	Data	A	B	C	D	E
				%							%		
Low land	NSM	0	100	66	66	100	High land	NSM	0	100	33	0	100
Montpol oak wood	JSM	0	100	100	0	66	Cal Ramonet tillage	JSM	0	100	100	0	66
	Observed	0	100	100	0	0		Observed	0	100	100	33	0
Canalda brook forest	JSM	0	66	100	66	66	Cal Ramonet pasture	JSM	0	66	100	0	100
	Observed	0	100	100	100	0		Observed	0	100	100	0	0
Cogulers sunny	JSM	0	66	100	66	66	Cal Ramonet forest	JSM	0	100	100	33	33
	Observed	0	100	100	66	0		Observed	0	100	100	0	0
Cogulers shaddy	JSM	0	100	0	0	100							
	Observed	0	100	0	0	100							
El Prat pasture	JSM	0	33	100	66	33							
	Observed	0	100	100	66	0							

JSM: Jarauta simulation model, NSM: Newhall simulation model, observed: field data, A, B, C, D, E : criteria for moisture regimes explained in table 2.1.

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 determination for 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 (table 2.2).

JSM is more suitable to simulate soil moisture regimes in the different plots, since the real and simulated regimes and subtypes coincide almost completely, between 90 - 100%, both in determining the soil moisture regime and the subtypes. This model has been used in the Lleida southern meridional area by Jarauta (1988) and in the Montpol oak wood in Ribera Salada during 2002 - 2003 by Junyent (2004). In both cases moisture regimes matched reasonably with field data.

2.3.5 Spatial distribution of soil moisture regimes.

Soil moisture regimes were assigned to soil map units, and maps of soil moisture regimes were obtained (fig 2.7) at 1:50.000 scale, according to the methodology by Acuña & Poch (2001). In most parts of the basin, ustic regimes are predominant, with udic regimes in shady areas under specific conditions of high relative moisture and the river bed proximity (Cogulers subcatchment). Some of the mapping units defined by these variables are too small to be included in maps under scale 1:50000. The xeric regime conditions are found in the driest year (2005) under brook forest zones on alluvial materials. NSM simulates adequately the soil moisture regimes in the basin. NSM tends to give moister regimes than real conditions (and some year drier). Due to NSM, particular characteristics of each soil type and soil use are not considered, whereas JSM allows to model specific conditions by site (table 1.8).

JSM simulates correctly the soil moisture regime during the years 2003 and 2004. In 2005, the simulated moisture regime was drier than the real one only in the higher northern part of the basin. In the other parts of the basin simulated and real moisture coincide. NSM shows a udic soil regime from 2003 to 2005 in a part of the basin, having in the rest of the basin a ustic regime between 2003 and 2004 and xeric regime in 2005.

Considering an average year, 100% of the Ribera Salada soil has an ustic moisture regime. In years with a long drought period, such as 2005, 24% of the total soil reaches xeric regime conditions. The udic regime is characteristic for shadowy areas, under exceptional microclimatic conditions, with a high relative moisture and low evapotranspiration and in areas close to riverbeds. These areas are difficult to map due to their small size.

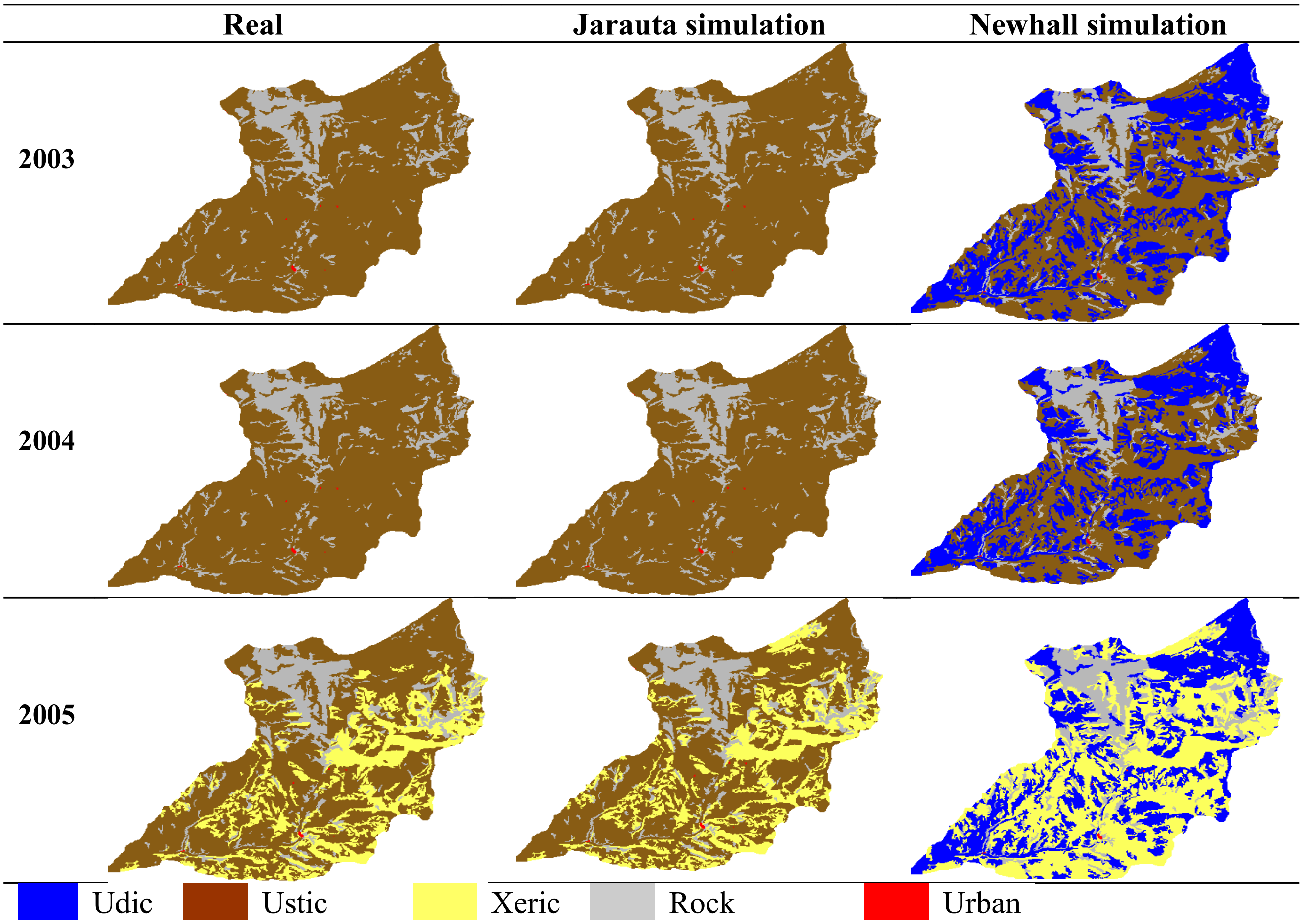


Fig 2.7 Map of soil moisture regimes in the Ribera Salada catchment

In the middle part of the basin, simulation results coincide with the findings of Estruch (2001) and Orozco et al. (2006), agreeing it to be a ustic regime (fig 1.3b). These authors assign udic regime in the highest part of the basin and xeric regime in the lowest part of the basin, based on the altitudinal gradient which affects the rainfall and temperatures regimes, with the highest precipitation and the lowest temperature in high lands.

2.4 Conclusions

The determination of soil moisture regimes has to deal with the probability of several requirements being wet in an average year, and therefore has to be based in a long observation period. The assignment of a SMR to a 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, as it has been done here, and the comparison of modeled and actual regimes gives a first approximation to its probability of occurrence and shows the applicability of the models.

The soil moisture regime is affected by annual rainfall variations, thus it is necessary to select the years with a representative rain volume and distribution, to determine the moisture regime in each plot.

Soil moisture measurement during 3 years allows us to assign soil moisture regimes to different sites that depend on soil use, soil characteristics (stoniness, thickness, and infiltration), soil profile situation and climatic characteristics (rainfall distribution and intensity).

The application of NSM tends to overestimate the soil moisture's percentage, reflecting giving moister regimes than field measurements. This is especially important for meteorological change implications in soils, where an increase of temperature and desert conditions will not be reflected. The JSM is more precise in evaluating regimes under these Mediterranean conditions. JSM can be used to predict more exactly soil moisture regimes in dry conditions, because it can be adapted to different soil type and use, whereas NSM considers a typical soil and soil use, which accentuates the presence of extreme high moisture values. 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.

The dry seasons for both simulation models are summer and winter, with summer as the driest one in all cases. The Ribera Salada soils tend to have a medium moisture status in summer and winter, without reaching a completely moist or dry profile during 45 consecutive days, as it is required in Soil Taxonomy. With respect to Mediterranean mountain basins, like the Ribera Salada, we should bear in mind that in rainy periods soil profile is seldom completely moist, due to high intensity rains with a low infiltration efficiency. JSM results showed high soil moisture values in some periods, which in reality correspond to medium moisture conditions (between -1500 kPa and -33 kPa).

Soil regime maps obtained with JSM results are highly reliable in dry conditions. The prediction of soil moisture regime by JSM hit 100% of the cases, while NSM hit 66% of the cases.

In Ribera Salada, soil use is changing from crops and pastures to forest, which could lead to xeric regimes in underneath forest areas during dry years in the medium part of the basin. In the highest part of the basin, this change of use would extend the area of ustic regimes or xeric in shallow soils in high mountain pastures.

Working on the assumption of a temperature increase under the frame of global climatic change, the obtained results predict a change of soil temperature regime from a transition between mesic-thermic to a thermic temperature regime. Concerning soil moisture regime, the prediction is more approximate, but it would evolve to a xeric moisture regime.

The soil root zone depth, slope orientation and the zone altitude seem to be the predominant characteristics in soil moisture amount, favoring udic and xeric regimes, hardly mapable under a 1:50000 scale; therefore some soils that are under shady conditions or at altitudes above 1400 m, tend to have moister conditions, whilst deep soils at lower altitudes tend to have drier conditions.

Through the use of these models we can to carry out maps under different scales of soil moisture regimes. Other applicability's of simulation models are: to explain temporal behavior of soil moisture content under different cover types; to identify their spatial variability and locate different areas by soil use and ecologic regions with high probability of droughts; or to infer future conditions derived from climatic change, or to predict the evolution of vegetal populations.

Chapter 3

IMPROVEMENT OF SOIL MOISTURE SIMULATION USING EXTEND KALMAN FILTER, IN THE APPLICATION OF TOPLATS MODEL. Ribera Salada catchment, Catalan Pre-Pyrenees (NE Spain).

3.1 Introduction and objectives

The knowledge of water availability in mountain areas is very important when dealing with Mediterranean climates because the seasonal drought obliges us to rely on water reservoirs that are fed by mountain watersheds. Moreover, for land use planning for forest or agriculture we need to be in the know of the soil water variability in space and time. The importance of water in Mediterranean mountains, particularly in the Pyrenees, has been studied multidisciplinarily by several authors (Batalla & Sala, 1993, 1996; Llorens et al., 1997; Ubalde et al., 1999; Verdu et al., 2000; Gallart et al., 2005; Orozco et al., 2006).

Soil moisture is defined as the water stored in the near - surface unsaturated zone. Its content varies continuously in depth, which makes soil moisture measurements expensive and often problematic, partly due to the tremendous natural heterogeneity and scale problems, besides the troubles to describe water processes in soils and watersheds. A good alternative is the use of numerical models of soil moisture. These models can spatially integrate distributed meteorological conditions (rainfall), land use, and topographical information to produce surface soil moisture predictions over large areas. The major difficulty in applying these models is to define the hydrological parameters. Most of them can be measured in the field and others can be estimated through a calibration procedure. These procedures range from simple empirical equations that can be solved analytically, to complex systems of partial differential equations that require sophisticated numerical algorithms and powerful computers (Goegebeur & Pauwels, 2007).

In this research, the TOPLATS simulation model is used to know the soil moisture values for different land uses in the Mediterranean mountains. This model has been given a considerable amount of attention to simulate the soil moisture in different environments (Houser et al., 1998; Pauwels et al., 2001, 2002; Zhao et al., 2004; Bormann, 2005; Crow et al., 2002, 2005). It has been calibrated using the equations of the Extend Kalman Filter (EKF) for TOPLATS, which consist of measuring the parameters difference between measured and simulated values. The calibrated parameters values are calculated considering the slope values of the calibration line. More information about the parameters calculation can be found in Goegebeur & Pauwels (2007). A description of the EKF equations can be found in Maybeck (1979) and Welch & Bishop (1995). Examples of data assimilation studies that are used by the Kalman filter in the hydrological parameter modelation are Crow & Wood (2003); Kumar & Kaleita (2003); Schuurmans et al. (2003) and Aubert et al. (2003).

The main objective of this research is to calibrate TOPLATS in selected soil sites in Mediterranean catchments using the methodology developed by Goegebeur & Pauwels (2007), in which soil moisture has been monitored for different land uses. In this context, we are interested in intend to obtain two specific objetives. The first objective is to develop and calibrate a soil moisture estimation method, by using TOPLATS and EKF tools, so that *in situ* measures are not required. The second objective is to integrate these soil moisture values into an hydrological model, and to quantify the improvement of precision in soil moisture, infiltration and runoff predictions through the assimilation of TOPLATS calibration data.

3.2 Materials and methods

General characteristics, such as model description, study area and experiment design, can be found in Chapter 1. Model simulation with TOPLATS at each site was performed for a period of one year. The specific year depended on the availability of observations from each site. Simulated and measured soil moisture was compared, using 8784 values at each site (fig 3.1). The that corresponded to a daily time step. The land cover parameters were determined following Peters-Lidard et al. (1997). They are described by soil parameters, which are found in Famiglietti & Wood (1994a). To calibrate the soil moisture simulations, Kalman equations were used, which measure the parameter differences between the simulated and measured values. The calibrated parameter is calculated in accordance with the procedure of Goegebeur & Pauwels

(2007) from the calibration line. The original soil parameters used to run TOPLATS can be observed in table 3.2.

The soil parameters were determined from the actual soil texture class following the parameters: Ks (saturated hydraulic conductivity), β (Brooks - Corey pore size distribution index), Ψ_e (air pressure entry), Qo (base flow saturated) and f (change Ks in depth), being calibrated for the studied sites according to Rawls et al. (1982) criteria. The relationships between these parameters allow us to predict water retention volumes for particular tensions and saturated hydraulic conductivities based on soil properties. The Brook and Corey equation provides a reasonably accurate representation of the water retention. Soil moisture and hydraulic conductivity in unsaturated soils can be described in terms of matric head (Famiglietti & Wood, 1994a).

3.3 Results and discussion

3.3.1 Calibration

The calibration starts with an initial estimation of the soil parameters that are inputs of the TOPLATS simulation model, going from as much as possible field measurements, to the other parameters that are taken from literature, which are explained in detail in chapter 4. The calibration procedure searches for parameter values in order to match the model results as good as possible. the calibration results using the EKF algorithm can be observed in table 3.1.

Table 3.1 Results of the calibration parameters soil moisture in the Ribera Salada catchment

Station	Ks * (mm/h)	β (-)	Ψ_e (m)	Qo (m^3/s)	f (-)	RMSE (-)
Montpol oak wood	24. 4	1.556	0.3836	$2.782e^{-8}$	0.7014	0.0189
Canalda brook forest	42.16	0.116	0.6558	$5.565e^{-7}$	0.0118	0.0298
Cogulers shady	0.39	0.633	1.0043	$7.083e^{-7}$	0.7178	0.0395
Cogulers sunny	20.38	1.162	0.3698	$2.928e^{-7}$	1.1792	0.0218
El Prat pasture	9.99	0.829	0.4129	$8.805e^{-8}$	1.1857	0.0546
Cal Ramonet tillage	5.97	0.208	0.4578	$5.129e^{-7}$	0.5548	0.0359
Cal Ramonet pasture	5.97	0.224	1.8859	$5.646e^{-7}$	0.5743	0.0344
Cal Ramonet pine forest	0.31	0.968	0.4407	$5.471e^{-7}$	0.4522	0.0634

(*) parameter measured, RMSE: minimum square.

The values before calibration can be observed in table 3.2. The values of Q_o are for subcatchment to Canalda subcatchment (0.57 m^3/s) and Cogulers subcatchment (0.01 m^3/s), while the f values result 2.7 for all sites

Table 3.2 Parameters soil moisture in the Ribera Salada catchment before calibration

Station	Ks * (mm/h)	β (-)	Ψ_e (m)	RMSE (-)
Montpol oak wood	6.75	0.378	0.3020	0.099
Canalda brook forest	7.75	0.252	0.4012	0.216
Cogulers shady	4.88	0.252	0.4012	0.083
Cogulers sunny	9.92	0.378	0.3020	0.264
El Prat pasture	10.93	0.252	0.4012	0.180
Cal Ramonet (tillage, pasture, forest)	11.21	0.242	0.5643	0.165

(*) parameter measured, RMSE: Root Mean Square Error.

The highest Ks values for calibration data correspond to loam textured soils and in the rest of the basin (Cal Ramonet station and Cogulers shady) soils Ks decreases, being the lowest values those in recent alluvium (Canalda station). Soils underneath a forest cover have Ks values lower than underneath pastures. The RMSE values result to be more reliable after calibration.

These results confirm the findings by Verdú et al. (2000). These authors apply the E2D and EUROSEM models in the Ribera Salada soils, and found that infiltration measured values can difficultly be exceeded by rain intensities, which generates low runoff values that are difficult to model. β values (obtained by Brook and Corey equations, (Rawls et al., 1982)) fluctuate between 0.116 - 1.556, being the lowest values under brook forest (Canalda) and the Cal Ramonet tillage and pasture. The rest of sites have values around 1.

The RMSE (Root Mean Square Error) values are between 0.0189 - 0.0634. In the Cal Ramonet forest and El Prat pasture, there are high RMSE values because in these stations the moisture content is more variable. The others stations have lower values of RMSE, which coincide with the calibration intervals behavior.

The RMSE values tend to be low in those sites where the soil moisture content variation changes regularly with time, without sudden peaks of high or low moisture. Oppositely, when soil moisture content presents peaks of high moisture, the RMSE values are high.

The RMSE would differ if the program would be ran in a different time interval. In this study the RMSE parameters were determined based on the Goegebeur and Pauwels (2007) procedure.

3.3.2 Soil moisture estimation

The average values of the observed (field data), simulated (simulation before calibration) and calibrated (simulation after calibration) data are found in table 3.3. The R^2 values of observed soil moisture vs. simulated and calibrated values are 0.6690 and 0.9967 respectively. From these statistics we can conclude that the calibrated model can simulate the soil moisture behaviour with a sufficient degree of accuracy.

Table 3.3 Observed, simulated and calibrated values of soil moisture

Station	Soil moisture %		
	Observed	Simulated	Calibrated
Montpol oak wood	19.72	31.03	19.80
Canalda brook forest	13.86	22.59	13.68
Cogulers shady	48.1	49.79	47.72
Cogulers sunny	17.48	29.78	17.51
Prat pasture	25.3	17.57	26.24
Cal Ramonet Tillage	34.18	44.94	34
Cal Ramonet pasture	32.65	45.03	31.13
Cal Ramonet pine Forest	34.06	43.44	33.88

The evolution of the daily soil moisture values between simulated, calibrated and measured can be found in fig 3.1 for the eight sites. In all cases, the simulated values are from 10 to 20 % higher than the observed ones, because the model tends to store all the infiltrated water in the soil profile. The moisture percentages are quite high before the calibration (fig 3.1), taking into account that infiltration is quite low (table 3.4) and that the model do not simulate losses by subsurface runoff. It is assumed that the missing water supplies the soil water demands. The soil parameter calibration decreases the differences to values between 3.9 and 8.5%, in this way simulating better the soil water behavior.

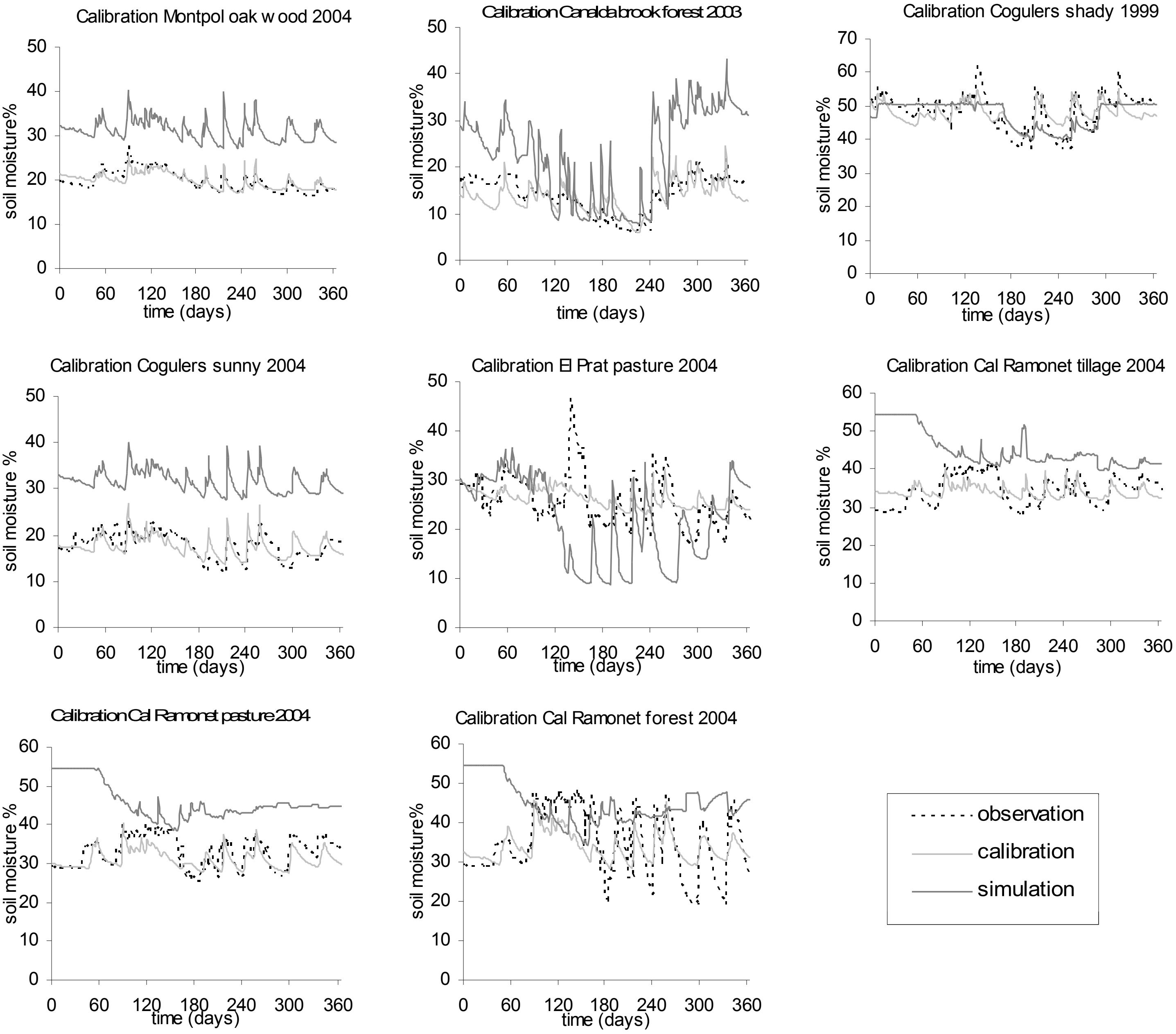


Fig 3.1 Soil moisture calibration (TOPLATS) under different soil uses in the Ribera Salada Catchment

In the Montpol oak Wood, the differences between observed and calibrated soil moisture are between 0 to 3.9%. The calibration values are close to the measured ones, with small differences at the beginning, at the end of the calibration and in some punctual periods in the central part of the graph. In the Canalda brook forest, the soil moisture difference (observed-calibrated) is 0.004 to 6.1%. The lowest values correspond to the summer season. Calibration curve behavior tends to approximate the real behavior, except at the beginning and in punctual cases in the medium part, where the moisture observed values are quite low.

The Cogulers shady has higher moisture values than the other monitored sites. The difference between the observed and calibrated moisture fluctuates from 0.01 to 6.4%. The calibration graph shows a similar behavior as in the observations, predicting correctly natural behavior, even in the moisture peaks. Under sunny conditions (Cogulers sunny), the tendencies of observed and calibrated values are similar to those of the Montpol oak wood station. The soil moisture differences vary from 0.014 to 4.8%. In El Prat pasture, the calibrated graph does not coincide with the observed values in episodes of short time changes. This coincidence does exist in medium soil moisture episodes, while there is a high difference in extreme low or high moisture events with abrupt soil moisture changes. Despite this affirmation, the soil moisture differences (observed-calibrated) range from 0.006 to 5.2%.

In the Ramonet tillage, we can observe quite high soil moisture values, with simulated and observed differences of between 0.015 to 5.3 %. The calibration results are closer to the observed values. Cal Ramonet pasture calibration behaviors simulate quite good the observed soil moisture; the existent differences between the observed and calibrated values go from 0.0047 to 4.7%. In the Cal Ramonet forest, the observed vs. calibrated soil moisture fluctuates between 0.025 and 8.5%, and in episodes of sudden changes, the difference between observed and calibrated is bigger.

The calibration results are in general closer to the observed data, but there are still some problems. The difference between the observed and calibrated data is smaller than 6.4% for a 95% of the calibration data, except in the Cal Ramonet forest, where the difference is a 8.5%. In spite of this, observing fig 3.1, it can be concluded that the calibration does not allow the current simulation of abrupt soil moisture changes (from dry conditions to moist conditions and vice versa). Under saturated soil moisture conditions, the difference between the real and calibrated values is bigger than under other conditions, reaching values from 10 to 15%. The best fits are found under low moisture conditions this difference does not exceed 5%. In episodes with short time changes, the observed vs. calibrated difference is bigger, due to the model which does not consider punctual variations inside the profile and in the soil surface, real root distribution and their depth, the particularities of interception processes, the vegetation distribution or some vegetal physiologic mechanisms, like stomatal closing.

3.3.3 Infiltration and runoff extra model validation

Infiltration and superficial runoff have been measured in the field (explained in chapter 1) and are also components of the model, related with soil moisture, that have been selected to verify the validity of the calibration (table 3.4).

Table 3.4 Total Rainfall, Infiltration and Runoff in the Ribera Salada Catchment site to period study

Stations	Total rainfall (mm)	Infiltration (mm)		Runoff (mm)	
		Observation	Calibration	Observation	Calibration
Montpol oak wood	545	387	424	6.6	0
Cogulers shady	545	346	322	1.9	3.1
El Prat pasture	545	544	517	1.3	2.9
Ramonet tillage	785	783	730	3.5	0
Ramonet pasture	785	751	711	2.14	4
Ramonet forest	785	424	391	2.9	6.5

In this case the Cal Ramonet forest stations real infiltration values are lower than the simulated ones. In the other stations the real values are higher than simulated ones. After calibration, the fit substantially improves. The difference between the real and simulated data can be attributed to a site effect, topographic differences, or soil and vegetation characteristics. Houser et al. (1998) attributed these differences to the model's difficulty to reproduce exactly the natural environment conditions, in this case being the trees and root zone spatial variability.

Regarding runoff, it is difficult to obtain conclusive results, since it accounts only for a 0.3 to 1.2 % of the total rain. Its effect on total hydric balance is not that relevant, and therefore the values are low and can be hardly modeled. However they can be taken into account as a complement of infiltration data.

The TOPLATS simulation model assumes a vertical water movement into the soil and water storage conditions, where excesses are used in runoff and infiltration (Famiglietti & Wood, 1994b; Peters-Lidard et al., 1997). The results presented in this chapter show that the model badly simulates short time changes.

Authors like Llorens et al. (2003) associated abrupt soil moisture changes to a water provision reduction, as a consequence of a higher interception, which varies depending on the vegetation and topographical situation. An the way, under forest cover in

Mediterranean mountains, originate to local conditions with a high hydric stress which are difficult to simulate.

The simulation results of runoff are quite low and in some cases the model result is zero, coinciding with Verdú et al. (2000) findings in the same basin using the E2D and EUROSEM models. The second model systematically generated mistakes under low rainfall intensities, and overestimations of runoff after big events of rain. In the Vallcebre basin, Gallart et al. (2005), the dense vegetation (forest, pastures) and old soil conservation structures impeded significant runoff. The same author identified three main kinds of runoff events, as results of antecedent wetness conditions of varying catchment and characteristics of changing rainfall events (intensity and volume).

3.4 Summary and conclusions

The calibrated TOPLATS model interrelates correctly soil moisture, runoff and infiltration, demonstrating that soil moisture characterization is essential if we want to apply hydrological models in a correct way. Soil moisture values obtained by calibration models are better adjusted in the places where the soil moisture tends to vary progressively in time than in places with abrupt variation which increases the differences between observed and simulated values. In the first case, the difference between the real and simulated values is lower than 5%, while this increases up to 8.5% in the second case. When moisture conditions are extremely dry or wet (caused by sudden changes).

The calibration methodology used to determinate soil moisture under different cover types, using the TOPLATS model, calibrated with KFM equations (Goegebeur & Pauwels, 2007), results to be a useful tool to estimate soil water volume stored in basins at a detailed scale. A correct calibration of model parameters gives relevant information about local dynamics of soil moisture during a rainy event. Combining this information with flow data in the basin, we can know the contribution of water volume to the surface flow and other paths (subsurface flow and aquifers), obtaining a better description of hydrologic basin behavior.

Chapter 4

APPLICABILITY OF *TOPLATS* MODEL FOR SIMULATING SOIL MOISTURE CONTENT IN RELATION TO LAND USE IN MEDITERRANEAN MOUNTAINS. Ribera Salada, Catalan Pre Pyrenees (NE Spain).

4.1 Introduction and objectives

In Mediterranean ecosystems, soils are the largest reservoirs that can supply water for biomass production. This is especially important for the seasonal aridity of these environments. Moreover aquifer water recharge depends on soil water balances and the ability of soils to infiltrate and transmit water to other reservoirs. Due to the fact that Mediterranean ecosystems are fragile, with high risk of degradation, soils have to be protected in order to keep these functions.

The Ribera Salada basin represents a broad, forested, Prepyreneic region that provides water to several reservoirs. The area has experienced notable changes in land use since the 1950s. For instance, the surface occupied by pastures and tillage decreased 3 % and 8 % respectively and forest increased 11% in the period 1957 - 1993 (Ubalde et al., 1999). In the Catalan Mediterranean region, De Bello et al. (2005) suggests that soil use changes can affect the soil water content (grazing is synonymous for dry conditions) and the plant composition (grazing abandonment favors the development of shrubs and trees).

The objective of this research is to know the behaviour of soil moisture in Mediterranean basins based on long-term field measurement and to predict its evolution regarding environmental changes, such as the global climatic change or land use changes. In these zones, water is important for among others, reservoir replenishment, human consumption and crop irrigation. Since this requires the analyses of different scenarios through models, we will evaluate the applicability of a soil moisture simulation model, named TOPLATS, under different soil uses in an experimental basin.

TOPLATS is a model which incorporates TOPMODEL (TOPMODEL- based Land Surface- Atmosphere transfer Scheme). TOPLATS is based on spatial hydrologic water distribution and energy balance. It is a model developed with the specific intention to represent the spatial variability in soil, vegetation, and atmospheric forcing data on the water and energy balance fluxes and states. This model is a framework to account spatial variability and lateral redistribution of subsurface water, based on the local topography and soil transmissivity, a process generally ignored by most soil-vegetation- atmosphere transfer schemes (Famiglietti & Wood, 1994a, 1994b; Peters-Lidard et al., 1997; Pauwels and Wood, 1999a, 1999b).

The results will be applied to a soil and land use map of the basin, in order to calculate the hydric balance of the basin. Current methodologies to measure soil moisture in the field are hard and expensive to maintain. The use of simulation models is, in this sense, very useful for two reasons: (i) to forecast the changes in soil moisture regimes or land use climatic changes and (ii) to extrapolate the results to similar non monitored sites.

The chapter is organized as follows. First a short description of the study area is given. Then there is an overview of the used datasets and the soil moisture information. In the next section the hydrological model is briefly described. And finally the results of the soil moisture, infiltration, evapotranspiration and soil temperature assimilation values are explained.

4.2 Materials and methods

The hydrologic model used in this study is the TOPLATS -Based Land-Atmosphere Transfer Scheme (TOPMODEL), which is founded on the concept that shallow groundwater gradients set up spatial patterns of soil moisture that influence infiltration and runoff during storm events, and evaporation and drainage between these events. The assumption is made that these gradients can be estimated from local topography (through a soil-topographic index [Sivapalan et al., 1987]). From this foundation, the model was expanded to include infiltration and resistance-based evaporation processes, a surface vegetation layer and a surface energy balance equation with an improved ground heat flux parameterization, and the effect of atmospheric stability on energy fluxes (Famiglietti & Wood, 1994a, 1994b; Peters-Lidard et al., 1997). The model was originally developed to simulate the surface water and energy balance for warm seasons (Famiglietti & Wood, 1994a, 1994b; Peters-Lidard et al., 1997). More recently, winter processes (frozen ground and a snow pack); improved water and energy balance scheme for open water bodies, and a two-layer vegetation parameterization was added (Pauwels & Wood, 1999a). For a detailed model description we refer to Famiglietti & Wood (1994a), Peters-Lidard et al. (1997), Pauwels & Wood (1999a).

This model has been applied to the Walnut Gulch watershed in Arizona, Houser et al. (1998), the Zwalm catchment (Pauwels et al., 2001, 2002; Pauwels & De Lannoy, 2006), the Upper Kuparuk River Basin in Alaska (Dery et al., 2004), the Red-Arkansas River Basin (Crow et al., 2001; Crow & Wood, 2002), and to field experiments such as FIFE [Peters-Lidard et al., 1997], BOREAS (Pauwels & Wood, 1999b, 2000), SGP97 (Crow & Wood, 2003), SGP99 (Gao et al., 2005), and SMEX02 (Crow et al., 2005). They have shown that the model can adequately simulate surface energy fluxes, soil temperature, and soil moisture.

The originality of TOPLATS (Famiglietti & Wood, 1994a) consist in its ability to predict water diurnal dynamics and energy fluxes, based on a land - atmosphere transfer scheme. The model simulates soil moisture behavior, infiltration and runoff, during storm events, and evaporation and drainage, in between storm events. These gradients can be estimated from local topography and climatic data. TheTOPLATS model includes infiltration and resistance - based evaporation processes, a surface vegetation layer and a surface energy balance equation. The model also considers winter processes, water improvement and an energy balance scheme for open water bodies and a two layer vegetation parameterization. (Famiglietti & Wood, 1994a; Peters-Lidard et al., 1997; Pauwels & Wood, 1999b; Pauwels et al., 2000, 2001; Pauwels & De Lannoy, 2006).

The soil's type, vegetation and meteorological parameters used by TOPLATS running are detailed. Table 4.1 indicates the origins of the soil and vegetation data, used in the simulation.

Table 4. 1 Determination of parameters

Parameter	Determination
Pore size distibution index (β)	from Rawls et al., 1982
Bubbling pressure (m)	from Rawls et al., 1982
Saturated soil moisture (%)*	porosity with cores 5cm diameter
Residual Soil moisture (%)*	Saturated soil moisture (%) - Critical soil moisture (%)
Surface saturated hydraulic conductivity (mm/h)*	disk infiltrometer (Perroux & White, 1988)
Sand content (%)*	soil samples sieve (SSS. 1992)
Root fraction in layers (%)*	soil description (SSS. 1993)
Leaf area index	from Pauwels and Wood (1999a)
Albedo for dry surface	from Pauwels and Wood (1999a)
Albedo for wet surface	from Pauwels and Wood (1999a)
Momentum roughness length (m)	from Pauwels and Wood (1999a)
Heat roughness length (m)	from Pauwels and Wood (1999a)
Zero plane displacement height (m)	from Pauwels and Wood (1999a)
Critical soil moisture (%)*	Richard metodology (SSS. 1992)
Wilting soil moisture (%)*	Richard metodology (SSS. 1992)

* field and laboratory determination

Table 4.2 and table 4.3 show the soil and vegetation parameters used in the simulations. The soil and vegetation parameters are explained in Famiglietti and Wood (1994a). To calculate the thermal conductivity of the soil parameters we refer to Pauwels and Wood (1999a).

Table 4.2 Soil parameters used for the plots in the Ribera Salada Catchment TOPLATS simulations

Parameters	Montpol oak wood	Canalda brook forest	Cogulers shady	Cogulers sunny	El Prat pasture	Cal Ramonet
Pore size distibution index (β)	0.37	0.25	0.25	0.37	0.25	0.24
Bubbling pressure (m)	30.2	40.12	40.12	30.2	40.12	56.43
Saturated soil moisture (%)	0.39	0.44	0.38	0.46	0.40	0.57
Residual Soil moisture (%)	0.12	0.15	0.13	0.21	0.024	0.14
Surface saturated hydraulic conductivity(mm/h)	6.75	7.75	4.88	8.92	10.93	11.21
Sand content (%)	52.66	49.75	30.4	51.33	55	45

Table 4.3 Vegetation parameters used in the plot simulations at the Ribera Salada Catchment TOPLATS simulations

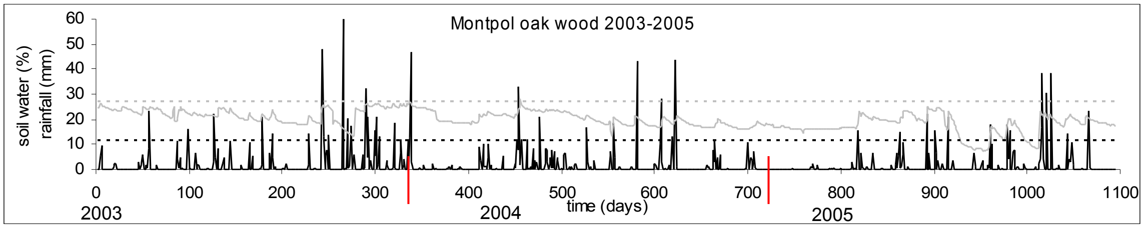
Parameters	Montpol oak wood	Canalda brook forest	Cogulers shady -sunny	El Prat pasture	Cal Ramonet pasture	Cal Ramonet Tillage	Cal Ramonet forest
Root fraction in top layer (%)	0.30	0.40	0.30	0.40	0.40	0.40	0.40
Root fraction in second layer (%)	0.20	0.30	0.20	0.30	0.30	0.30	0.40
Root fraction in third layer (%)	0.20	0.20	0.20	0.10	0.10	0.20	0.20
Leaf area index	4.3	1.1	2.25	0.6	0.6	1	6.6
Albedo for dry surface	0.11	0.15	0.11	0.13	0.13	0.13	0.19
Albedo for wet surface	0.10	0.13	0.10	0.24	0.24	0.24	0.16
Momentum roughness length (m)	1	0.9	1	0.15	0.15	0.05	1.20
Heat roughness length (m)	0.10	0.15	0.10	0.02	0.02	0.01	0.12
Zero plane displacement height (m)	6.7	1	6.7	1	1	0.3	8
Critical soil moisture (%)	0.27	0.29	0.25	0.38	0.43	0.43	0.43
Wilting soil moisture (%)	0.11	0.13	0.13	0.16	0.19	0.19	0.19

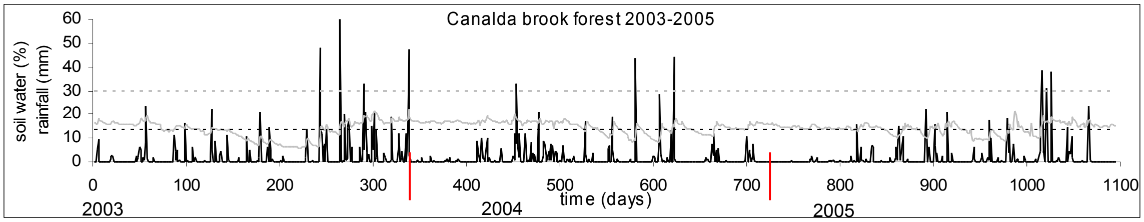
4.3 Results and discussion

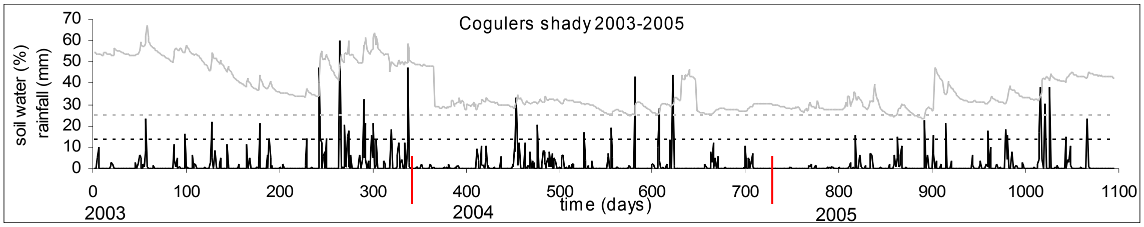
4.3.1 Analysis of field soil moisture

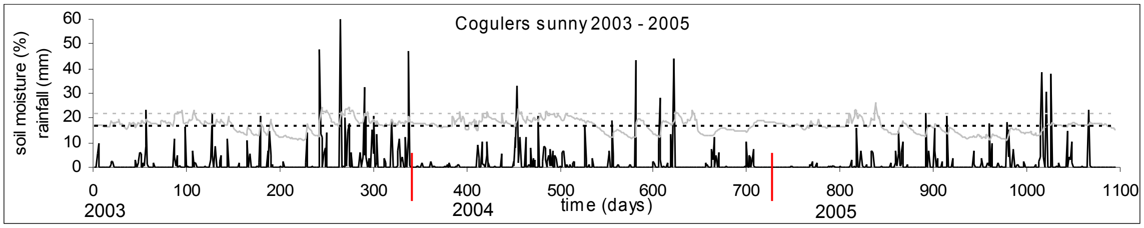
Fig 4.1 shows soil moisture and rainfall from different studied plots. The rainiest months are July and August, and the driest ones are December and January. The maximum moisture values correspond to rainfall peaks in months with long rainfall events characterized by low intensity rainfall. Moisture peaks tend to decrease and be stabilized quickly, varying between 15- 30 %. Except then in the Cogulers shady and Cal Ramonet stations, where soil moisture oscillates between 15 - 60 %. The soil moisture increase percentage agrees with the rainfall occurrence. In Mediterranean zones the soil moistest periods do not all times coincide with high rainfall volumes, having a bigger effect in soil moisture those events with a low intensity and long duration (Gallart et al., 2005; Llorens et al., 2003). Soil recharge depends, besides on rainfall duration and rain intensity, on initial soil moisture, more than on rainfall volume.

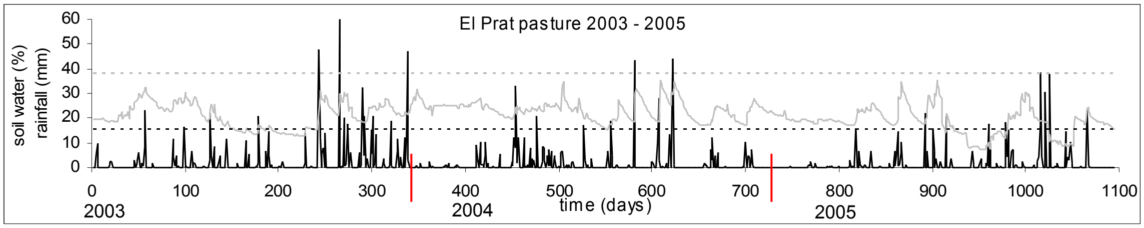
In all sites, the driest periods correspond to both winter and summer. Drought is stronger in winter in the Cal Ramonet station due to the fact that the water falls in the shape of snow. In the other stations the lowest moisture values are recorded in summer due to high evapotranspiration.

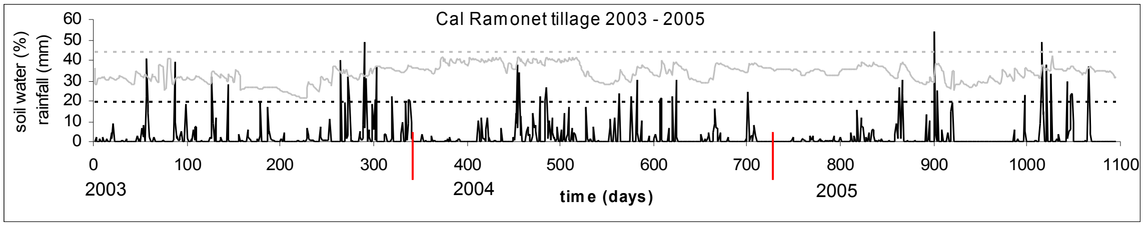

Montpol oak wood 2003-2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
time (days)
2003
2004
2005

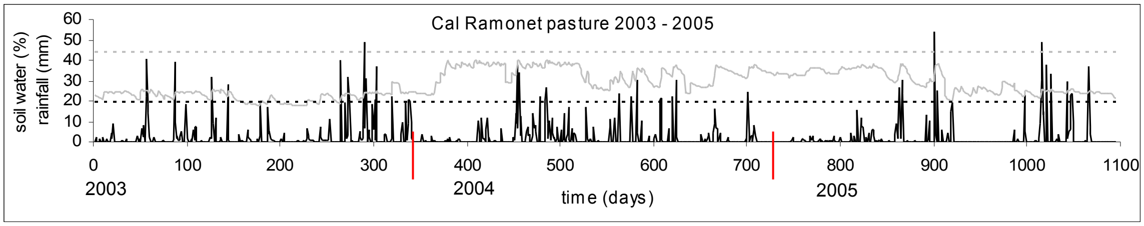

Canalda brook forest 2003-2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
time (days)
2003
2004
2005


Cogulers shady 2003-2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
70
0
100
200
300
400
500
600
700
800
900
1000
1100
time (days)
2003
2004
2005


Cogulers sunny 2003 - 2005
soil moisture (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
time (days)
2003
2004
2005


El Prat pasture 2003 - 2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
time (days)
2003
2004
2005


Cal Ramonet tillage 2003 - 2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
2003
2004
time (days)
2005


Cal Ramonet pasture 2003 - 2005
soil water (%)
rainfall (mm)
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
800
900
1000
1100
2003
2004
time (days)
2005

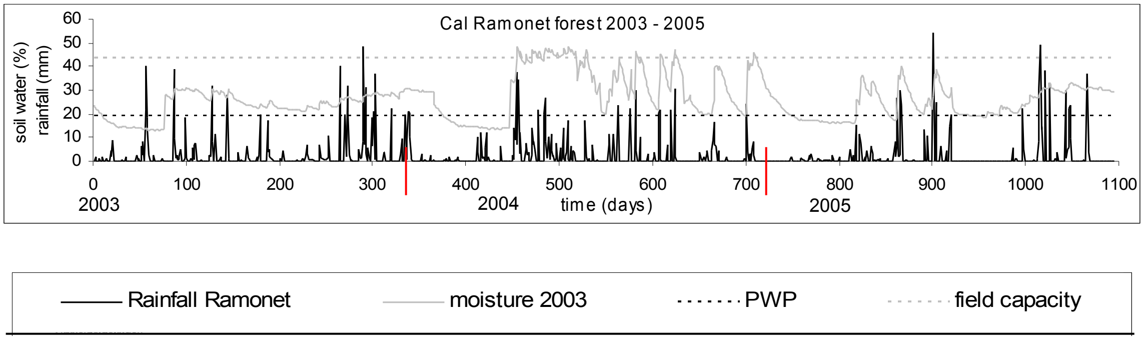


Fig 4.1 Daily evolution of soil moisture and rainfall for different land uses in Ribera Salada Catchment 2003 - 2005.

Averagely, the driest sites result to be soils underneath forest followed by pasture, tillage and shady soils. The differences can be observed in Cal Ramonet (fig 4.1), and are due to higher rainfall interception, higher infiltration and lower soil water retention .

The graphs for the different soil uses show that spatial soil moisture variability is higher under intermediate wetness conditions, because the soil profile wetting and drying reaction is wider. Soil moisture variability decreases under wetter and drier conditions, restricting its reaction and agreeing with Rius et al. (2001), Llorens et al. (2003) and Gallart et al. (2005) in Mediterranean mountains. De Bello et al. (2005) affirms that pastures are characterized by marked dry soil moisture episodes, being grazing and convergent dry conditions. These authors suggest that grazing produces a fast loss of soil moisture due to the fact that pastures in the Pyrenees are found in high mountain zones, in shallow soils, where the water content is quickly exhausted. In some cases, because of the shallow of the pasture roots, the water of the first soil horizons is quickly exhausted. In our case, the dryness of the forest site is due to canopy interception and to the water absorption by deep roots.

Fig 4.1 shows the daily evolution of soil moisture under different soil uses in the catchment in relation to the AWC (available water content) for each soil. Four representative soil moisture sites were selected for a more detailed analysis of soil moisture regime throughout the year. The first site is the Montpol oak wood, located in a mid-slope position, covered by oak woods; the second point is the Cogulers shady, located in a frequently satured area near to the bank, covered by moss and pine trees. The two other plots are located in the Cal Ramonet station in a mid-slope position, covered by tillage and forest, respectively.

The first site (Montpol oak wood) shows a less intra-annual variability (between 13% and 27 % soil moisture). The soil water content decreases after December and increase of the soil water content is noted until the end of February or May. Summer drought is observed the second fortnight of July and August (the soil has values -1500 kPa). Finally, there is a progressive soil wetting-up from June to November, with two peaks of soil moisture throughout the year. The soil profiles located at the Canalda brook forest; Cogulers sunny and El Prat also show this behaviour.

The second site (Cogulers shady) shows a marked intra-annual variability (soil moisture between 25 and 66%). The soil profile is saturated throughout the year. In the second fortnight of June, the soil water content decreases gradually due to the increasing evapotranspiration demand and the interruption of the subsurface water transfer. The lowest soil water content is reached at the end of August. Later on, after the first rainfall inputs of autumn, the soil water content tends to increase until the end of November. The lowest values of soil are observed in late June, when the water content presents low variability (soil moisture oscillations are less pronounced).

The other two profiles show a marked intra-annual variability (soil moisture between 15 - 48 %). the soil water content decreases after January (Cal Ramonet forest) and the recharge does not occur until the end of March. The progressive wetting-up of soils happens from the first fortnight of September to the end of the year. The inter-annual variability is greater in the Cal Ramonet forest than in the Cal Ramonet tillage. The Cal Ramonet forest has two dry episodes (winter and summer), while the Cal Ramonet tillage has only one dry episode (summer). The Cal Ramonet pasture show a similar behaviour as Cal Ramonet tillage.

The moistest soil period corresponds to the rainiest week of spring and autumn, when some of the soils reach matric potentials of -33 kPa conditions. The driest period corresponds to summer in the medium part of the basin (low lands), and winter in the highest part (high lands).

4.3.2 Analysis of modelled soil moisture

Fig 4.2 shows both simulated and measured soil moisture contents from 1998 in the different plots. The simulated soil moisture conducts two different behaviours. The first one applies to soils with a moisture content that changes progressively along the year, with the moisture values decreasing gradually in winter and summer. The second behaviour shows abrupt fluctuations in soil moisture, which are more evident during summer and winter periods. An example of the first case of behaviour can be observed at the Cogulers shady, and the second one in the Cal Ramonet forest. The second type is concluded to be also the main behaviour of the basin.

In the highest part of the basin (Cal Ramonet stations), the real water content is averagely 10%. In the lowest part of the basin (the other stations) this difference reaches 5% in most of the cases (99%). In the Manitoba forest catchment Pauwels and Wood (1999a, 1999b) found differences of 1 - 10 % between the simulated and real soil water content. Other studies such as Crow & Wood (2002) in the Red Arkansas River basin (USA), report values near to 5%. Pauwels & De Lannoy (2006) concluded that in the Zwalm catchment (Belgium) the amount of available soil water increased to approximately 85mm and reduced 150mm per year, and when the precipitation is overestimated and underestimated respectively, in both cases the errors in the modelled soil moisture are basically eliminated, despite the impact of errors on the precipitation.

Maximum and minimum peaks of soil moisture content are difficult to simulate, because these values correspond to particular soil conditions. In the Canalda brook forest these values are caused by a water table level variation, related to the riverbed proximity. In other cases the real moisture values have more marked peaks than the simulated values.

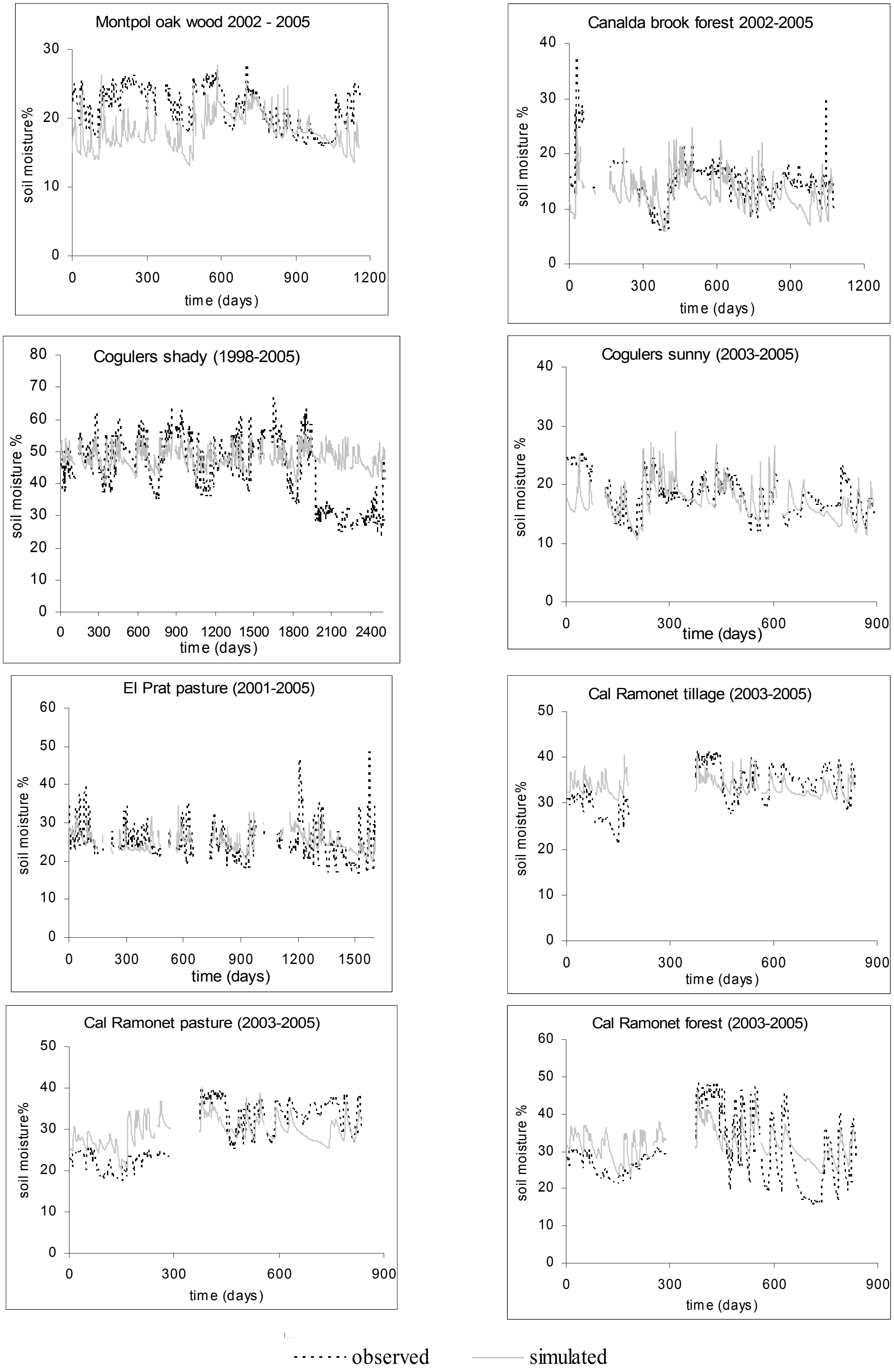


Fig4.2 Daily soil moisture TOPLATS simulation calibrated and observed in the Ribera Salada Catchment.

This difference can be explained by the presence of extra supplies of water, like a subterranean source. In most cases this difference of percentages is due to the presence of a subsurface flow, and also to a high porosity, which prevents the storage of infiltrated water; these characteristics are not taken into account in the model. Moreover, it depends on the rainfall intensity and initial soil moisture, dry in summer and lightly moist in winter.

Sometimes the simulated moisture is higher than the real moisture, because of a subsurface flux, the existence of karstified calcareous materials and the large amount of aquifers in the zone (a big part of the total water could have the finality to supply these aquifers). According to El Ouazzani (2004), the variability of soil moisture in time and space in a catchment depends on canopy spatial variability, which causes a control in the infiltration and evaporation processes.

In table 4.4 there are the results of the RMSE (Root Mean Square Error) between soil moisture observations and simulations, for all modelled soil moisture content stations. The RMSE values (ranging from 0.0299 - 0.0691) confirm that the model simulates the soil moisture adequately. Values of RMSE of 0.019 to 0.057 were found by Crow et al. (2005) when estimating regional scale soil moisture from observed data.

Table 4.4 RMSE between simulated and measured Soil moisture results in the Ribera Salada Catchment after calibration

Station	RMSE (-)
Montpol oak wood	0.0415
Canalda brook forest	0.0396
Cogulers Sunny	0.0299
Cogulers Shaddy	0.0571
El Prat pasture	0.0386
Cal Ramonet tillage	0.0428
Cal Ramonet pasture	0.0586
Cal Ramonet pine forest	0.0691

In this section we can conclude that the volumetric soil moisture values obtained by a calibrated TOPLATS are similar to be real values. Simulation predicts fairly well the soil moisture behaviour in the different studied plots. The model predicts adequately the seasonal soil moisture on an hourly basis. The largest differences between observed and simulated values occur in periods of short time changes in soil moisture.

4.3.3 Analysis of the modelled infiltration

Fig 4.3 shows averaged values of soil moisture and infiltration for the studied period in all the plots. The correlation between the observed and simulated values is very high, basically a result of the model calibration. R^2 values are highly significant. In the end it shows that a much better fit is obtained after the model calibration. An analysis of Fig 4.3 is given in 5.3.3. Crow et al. (2005) found the R2 value to be 0.68 to 0.95 between the observation and model data for regional scale soil moisture estimation.

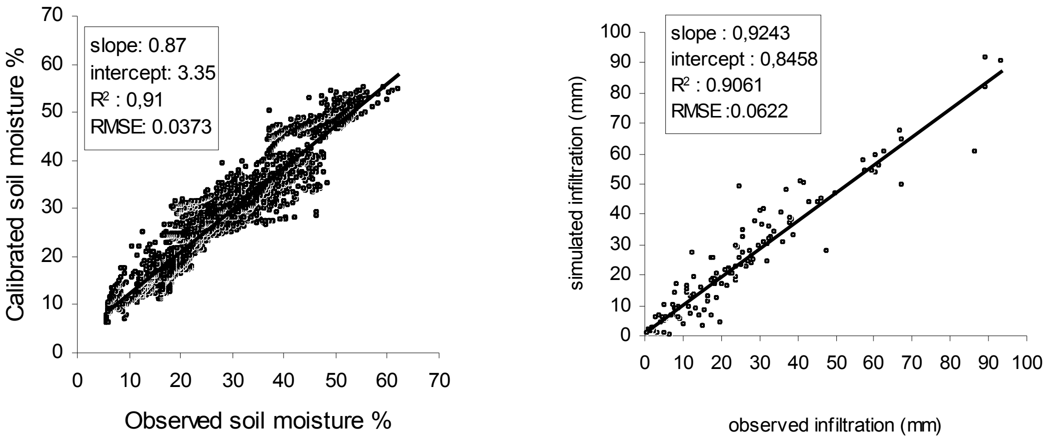


Fig 4.3 Comparison between simulated and observed soil moisture and infiltration in the Ribera Salada Catchment.

Fig 4.4 shows the infiltration behaviour during the observed period (each point represents the total for a time period of rain), together with soil moisture and rainfall, for the predominant soil use in the highest and medium part of the basin. According to Verdú et al. (2000), previous moisture of the soil determines the soil infiltration rate. Gallart et al. (2005) affirms that antecedent wetness conditions change with rainfall events (intensity and volume).

The soil infiltration depends firstly on rainfall volume and intensity (qualitatively observed). Secondly it depends on soil porosity. According to Verdú et al. (2000), in the Ribera Salada infiltration can be exceeded difficultly by rainfall intensities, confirmed by a low relation between runoff/rainfall. Both affirmations confirm the high infiltration values registered at the basin.

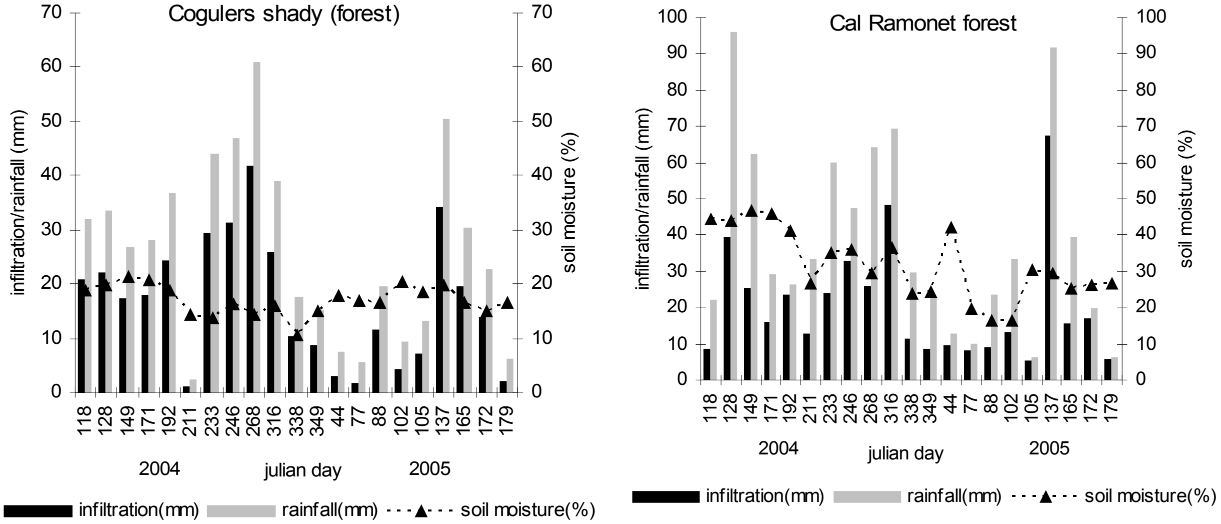


Fig 4.4 Observed soil moisture, infiltration and rainfall

Verdu et al. (2000) stresses the importance of saturation flux in high intensity events or of sporadic saturation in low intensity rainfall events. A typical hortonian flux does not occur, due to the fact that infiltration is important even in medium soil moisture conditions. Under low intensity events and high rainfall volume, we can identify a progressive soil wetting until saturation when the highest soil moisture takes place, and therefore saturated flux prevails.

Under intermediate conditions of soil moisture and high rainfall intensity, non saturated fluxes prevail. Fig 4.4 illustrates a typical soil moisture behaviour and infiltration under the same soil use in the medium and high part of the basin. This behaviour is common in the other studied sites. In both situations, the soil seldom reaches values below -33 kPa in the intermediate part of the basin, which tends to keep medium moisture values (-1500 kPa<x<-33 kPa) in the highest part of the basin. The values at -1500 kPa and -33 kPa can be found at fig 2.3. A more detailed analysis of inputs and outputs of the hydric balance in the different soils and soil uses will be commented at chapter 5, which will allow us to know where the excess rainfall goes to.

4.3.4 Analysis of the modelled evapotranspiration to Lladurs meteorological data

Fig 4.5 shows the evapotranspiration values, measured at the Lladurs station, and calculated using the Penman - Monteith equation (Doorenbos & Pruitt, 1977) evaluated by Llasat & Snyder (1998) and estimated with the TOPLATS simulation model (Famiglietti & Wood, 1994). There is a good correlation between them: during winter and autumn, the difference between them is low, being the minimum difference less than 1 mm/day in winter. During summer, the difference between both parameters can reach 2.7 mm/day. The differences between both are due to the effect of soil moisture deficit associated to soil stones and high porosity.

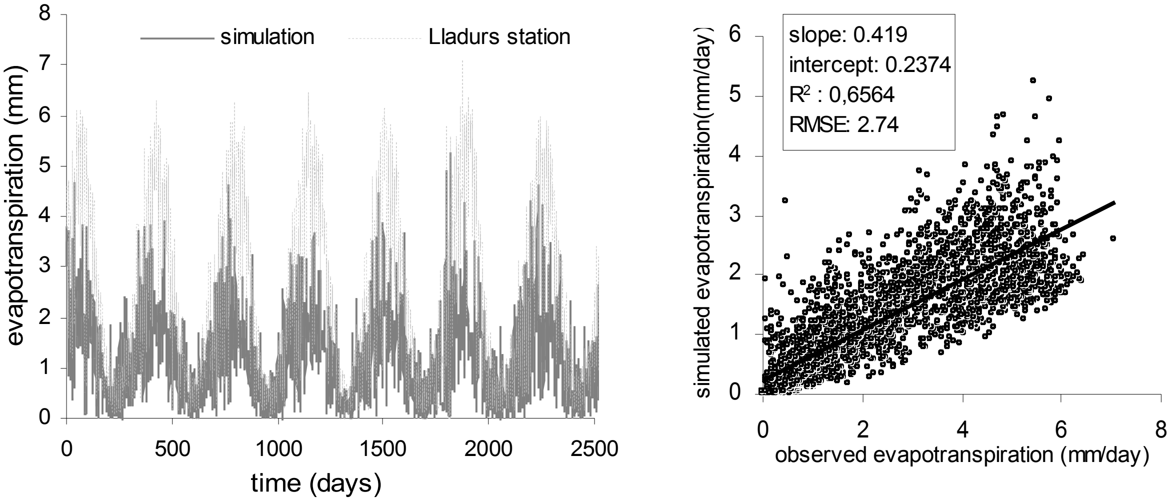


Fig 4.5 Observed and simulated evapotranspiration in the Ribera Salada catchment.
a) Evapotranspiration Lladurs station and TOPLATS simulation 1998 - 2005
b) Scatterplots between simulated and observed evapotranspiration in Lladurs station (1998 - 2005)

The high R^2 and RMSE values confirm the precision of the evapotranspiration model and validate the model to predict evapotranspiration in the Lladurs station. The differences with real data are similar to the finding by Famiglietti & Wood (1994a, 1994b, 1995) applying TOPLATS for energy balances in the King´s Creek catchment in Kansas (USA), with a results of the R^2 values that fluctuate between 70 - 90%.

4.3. 5 Analysis of the modelled soil temperature in Lladurs station

The simulated soil temperature values, shown in fig 4.6a, are lower than the real values, between 0.003ºC and 5ºC. This difference is due to the relative simplicity of modeling the radioactive interactions for the canopy representation and the soil thermal conductivity. This soil temperature difference is higher in winter and autumn. The maximum temperature according to the model is 26ºC, while the observed maximum is 29ºC. The minimum temperature according to the model is -3.1ºC, whilst the observed one is 0ºC. In spite of that, in fig 4.6a we can see how the model keeps the same tendency of temperature increase in summer and decrease in winter during the year.

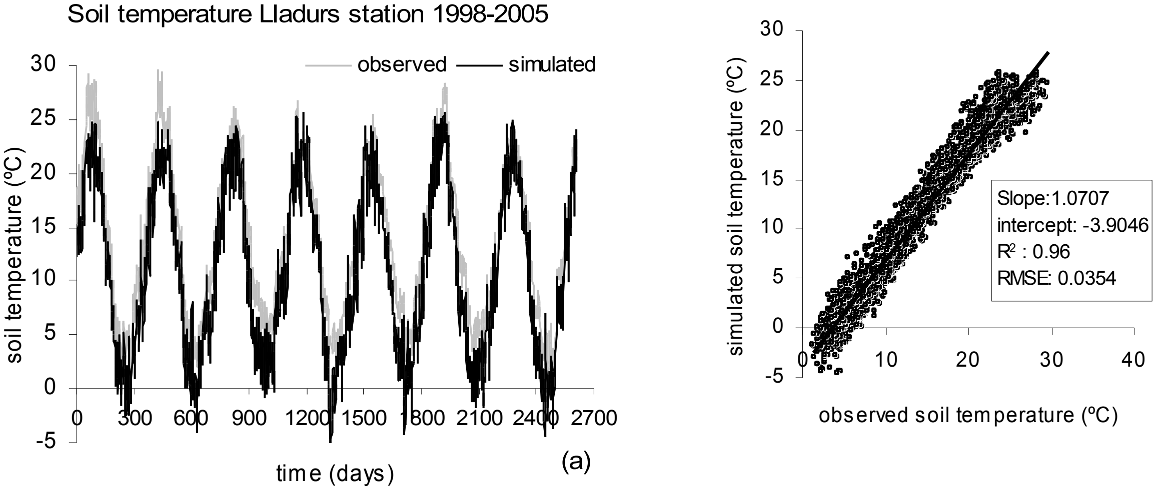


Fig 4.6 Observed and simulated soil temperature in the Ribera Salada catchment.

a) Soil temperature (50cm) Lladurs station and TOPLATS simulation,

b) Scatter plots between simulated and observed daily soil temperature (50cm) in Lladurs station

There is a high correlation between the real soil temperature values and the simulated values. The model simulates correctly the daily soil temperature variation. According to Peters-Lidard et al. (1997) (in International Satellite Land Surface Climatology Project Field Experiment 1987), the TOPLATS model gave very good results reproducing a soil temperature with R^2 0.98 and an RMSE of 1.46 having 5 months of simulation data.

From fig 4.6b it can be concluded that soil temperature is consistent. The observed and simulated temperature have both R^2 0.96, intercept -3.9 ºC and slope 1.07. RMSE values of 3.5ºC are slightly high, but are explained by the high stones content that is very frequent in Mediterranean mountain soils. The presence of microclimates and a transitional temperature regime into the basin (chapter 2) hinder the hydrological model running.

4.4 Conclusions

The modelled soil moisture in all stations predicts acceptably the measured water contents, although single peaks of moisture can be over or underestimated when the soil moisture changes in a short time. Site characteristics as high stoniness, low soil moisture retention and high porosity cause a subsurface flow and preferential flow. The saturation flow occurs punctually into the soil and is responsible of the registered runoff.

The simulation model works better under intermediate moisture conditions, having less precision if moisture conditions are extremely high or extremely low. In brook places, close to water sources or in materials with aquifer contribution, the model has some restrictions, which can be minimized through a model calibration (chapter 3).

Observed data show the importance of the rainfall periods and the soil use type in soil moisture content. Simulated values show a high similarity with observed values at daily scale. In dry places (medium part of the basin), the observed difference in values do not surpass 5%, but in moist places this difference is near to 10% (Cal Ramonet station).

The simulated and observed infiltration conducts a similar behaviour for a long time. For both graphs spring and autumn are the periods with the highest infiltration volume. The best fit is found in the medium moisture values, the difference between simulated and observed infiltration being lower than 8 mm, which counts for 90 % of observed data.

The TOPLATS model represents well the behaviour of evapotranspiration and soil temperature in the Lladurs station, where simulated values and real values are similar. However it was necessary to make a calibration to energy fluxes parameters to adjust the results. The simulated values are closer to the real values in spring and summer, and in autumn and winter the differences are bigger, due to the relative simplicity for modelling the radiative interactions, in spite of the model's limitations, evapotranspiration values and soil temperature simulated. The differences are explained by the stone amount and high porosity in the soil, which modify the behavior of the heat flux into the soil profile.

The TOPLATS model can be applicated to Mediterranean basins. We recommend to work with soil moisture data, runoff and for the reference parameter, to use a calibration of the simulation model.

It is important to characterize the type of flows and the aquifer influence in this type of basins, with limestone substrate, which are partly karstified. The results show that it is possible to estimate soil moisture and infiltration using the TOPLATS model, as long as field data are available to check the results of the simulation.

Despite the fact that we did not consider other flows beside the hortonian, the calibrated model can be easily applicated in Mediterranean mountain areas, whenever reliable information of soil moisture is available at an adequate scale. The model is flexible enough and able to integer the different water balance components for obtaining a good calibration. This model can be applied under different scales, which allows its application to different objectives as: soil conservation, study of soil moisture changes under different meteorological conditions, hydrologic or to assess variations in catchments caused by changes in soil use.

Chapter 5

SOIL WATER COMPONENTS SIMULATION UNDER DIFFERENT SOIL USES IN MEDITERRANEAN MOUNTAINS (TOPLATS model). Ribera Salada catchment, Catalan Pre-Pyrenees (NE Spain)

5.1 Introduction

The knowledge of the hydrological behaviour of the watersheds is important for land use planning and also to predict of natural disasters downstream like torrential floods, drought periods or the expected hydrologic behaviour under different climatic scenarios. To manage the landscape correctly, it is necessary to have information about different hydrologic parameters.

In Mediterranean regions, where rainfall regimes and moisture content are subject to seasonal dry regimes, the knowledge of incoming and outgoing water fluxes into the soil are crucial for a correct management of the water resources. During the last 50 years an abandonment of the traditional crops and rural settlements has been taking place in the Catalan Pre-Pyrenees, which resulted in a decrease of crops and an increase of pastures and forest (Ubalde et al., 1999). These soil use changes lead to hydrological variations in the catchment and also to varying values for the different hydrologic balance components.

A number of studies have focused on the dynamics of the water budget in Mediterranean catchments (Batalla & Salas, 1996; Salas & Farguell, 2002; Llorens et al., 1997, 2003, Verdú et al., 2000; Gallart et al., 1994, 2005; Orozco et al., 2006). Regarding hydrologic behavior in Mediterranean mountain basins, Llorens (1991), Rabadà (1995), Gallart et al. (2005), Latron (2003) and Rubio (2005) performed studies and characterized the behavior of hydrologic balance components.

The quantification of soil water flows is substantially improved by continuous measurements. In this study we will use information compiled from 1998 to 2005, in different plots that represent the predominant soil uses in the Ribera Salada river basin. In order to understand the hydrologic basin behavior we will implement the TOPLATS hydrologic model. This model uses meteorological and soil data to obtain the different variables that take part in the hydrologic processes, and allow this methodology to be extrapolated to non gauged similar basins. This model has been applied in prairies, artic regions and temperate regions for the modelation of water fluxes, with good results. These are reported by Houser et al. (1998), Pauwels et al. (2000, 2001, 2002, 2006), Dery et al. (2004), Crow et al. (2001, 2002, 2003, 2005), Peters-Lidard et al. (1997), Pauwels & Wood (1999b, 2000) and Gao et al. (2005).

This chapter focuses on the interaction of different hydric balance components; this is the reason why some results of chapter 4 are considered in this chapter. The aim is to check the applicability of the TOPLATS model to some water balance components in predicting their behaviour under different soil uses in Mediterranean mountain zones. Real measured values of some water balance components were used to calibrate the TOPLATS model, in order to obtain information about the soil water behaviour. The purposes of this chapter are i) to quantify some components of hydrologic fluxes by means of the elaboration of an hydrologic balance for the different predominant soil uses in the river basin, ii) to examine the behavior of the TOPLATS model in high and low rainfall conditions in the catchment, and iii) to extrapolate the field information through the use of the TOPLATS model to generate an approximation of the hydric balance behaviour in the river basin.

This chapter is organized as follows. First a short description of the study area is given. Then a overview of the datasets used in the TOPLATS simulation model and the hydrological model are briefly described. Then the results to simulation model application in the prediction for the different components of water balance are given. Finally the observed values and simulation values are compared and discussed.

5.2 Materials and methods

Catchment general characteristics and information are found in chapter 1.

5.2.1 Antecedents to field measurements

Regarding the catchment, there are available field measurements of basic hydrologic fluxes such as: rainfall, interception, soil moisture, runoff, infiltration and drainage.

They have been studied at different temporal scales and under different soil uses: *Pinus sylvestris* forest, *Pinus nigra* forest, *Quercus ilex* forest, brook forest and crops (potatoes). The rainfall variability and dynamics where studied by Pipó (2000) and Esteban (2003), the development of equations by these authors allow us to estimate the areal rainfall in the catchment in the Ribera Salada, Cogulers and Canalda basin starting from the Lladurs rainfall data.

$$P_{\text{Lladurs}} = 0.79\, P_{\text{Ribera Salada}} + 5.98 \qquad R^2 = 0.97 \qquad [\text{Eq1}]$$
$$P_{\text{Lladurs}} = 0.60\, P_{\text{Canalda}} + 11.62 \qquad R^2 = 0.84 \qquad [\text{Eq2}]$$
$$P_{\text{Lladurs}} = 0.64\, P_{\text{Cogulers}} + 5.03 \qquad R^2 = 0.96 \qquad [\text{Eq3}]$$

Rosanes (2000), Jiménez (2002) and Solsona (2005) studied the existent correlations between rainfall and interception, stemflow and throughflow by field measurements, under *Quercus ilex* forest, *Pinus sylvestris* and *Pinus nigra* forests. Reig (2004) and Rodríguez (2004) studied the relationships between rainfall, runoff and erosion, finding runoff coefficients lower than 1.4%. More authors such as Verdú et al. (2000), Estruch et al. (2003) and Sanz (2005) used models like EROSION 2D, EUROSEM and HEC-1 to study runoff and sediment production. They concluded that the erosion and runoff were very low. Nevertheless, these simulation models are not sensible for nohortonian flux conditions, and in the studied zone this application results debatable (chapter 4).

Poch et al. (2002) studied the soil water regime based on two data years, 1998 and 1999, using only soil matric potential, under a *Pinus nigra* forest. These authors found that in spring and autumn rainfall provides the biggest water amount of the basin, yet they could not find a clear correlation between soil moisture and meteorology or basin characteristics. Subsequently Junyent (2004) conducted an initial quantification of hydric soil regime, based on 2 data years, considering only soil moisture measurements. This author found that under *Quercus ilex,* during 28% of the year, soil is under witling point; and under *Pinus nigra* low thickness soils reach the field capacity during 60% of the year. The largest reserve of soil water is observed during October, March, April and May.

5.3 Results and discussion

In this section the obtained components of the hydrological cycle will be evaluated, which will provide us with a better knowledge of this hydrological cycle depending on soil type and use. An approximation to the hydrological balance will be studied every fortnightly and in the total time period of study. These results will be used as a base to calibrate and implement the TOPLATS hydrologic simulation model, as a tool to know the behaviour of some hydric balance components for each existent soil use and under different meteorological conditions.

5.3.1 Analysis of rainfall

During the period 2004 - 2005, one hundred rainfall events were recorded in periods of one week approximately for a total of twenty-one weeks observed. Fig 5.1 shows the amount of rainfall durin of these events. The total annual rainfall in this period was 545 mm in Lladurs and 802 mm in Cal Ramonet. The Ribera Salada basin has an altitudinal rainfall gradient (Pipó, 2000), resulting in a close correlation between the Lladurs meteorological station and the Canalda, Cogulers and Ribera Salada rainfall. This correlation permits the use of Lladurs data in the estimation of the areal precipitation for the basin (Pipó, 2000 and Esteban, 2003). The Mediterranean rainfall variation coefficient is 10% in spring, autumn and winter and 50% in summer, according to Latron (2003) and based on Vallcebre basin data, which is located close to Ribera Salada catchment.

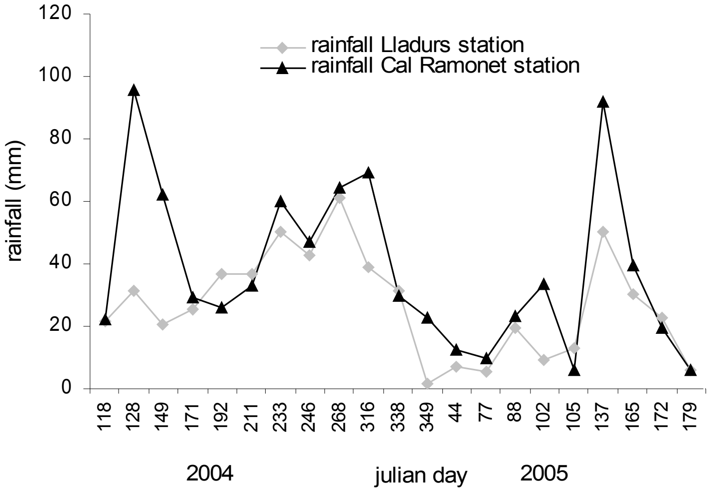


Fig 5.1 Lladurs and Cal Ramonet stations rainfall during the period 21/04/2004 - 28/06/2005.

The rainy period is between May and September, with 77% of the total rain, in agreement with Gallardo & Moreno (1999) who studied the precipitation in the Mediterranean ecosystem in Sierra de Gata (Spain). August and September result to be the rainiest months in the medium part of the basin (Lladurs station), collecting 36% of the total annual rain. On higher altitudes (Ramonet station), the months with most rain are May and June, producing 32% of total rain. The rainiest season in the studied period was summer, collecting 44% of the total rain, and winter was the driest season with a 10% of the total rain. The period studied only 1% of the rain have an intensity higher than 2 mm/h, only 9 episodes of rain possess values higher than 10 mm/h. An normal rain does not surpass 27 mm/h to rainfall event (observed data). These data are in agreement with Orozco (2006) who studied the precipitation during a different period in the same area, which ensures the representativity of the studied period.

5.3.2 Analysis of runoff

The total runoff amounts in the different plots, during the studied period (each point represents the total of a rain time period) are shown in table 5.1. Fig 5.2 shows the simulated and observed runoff values of every rain event in the different plots.

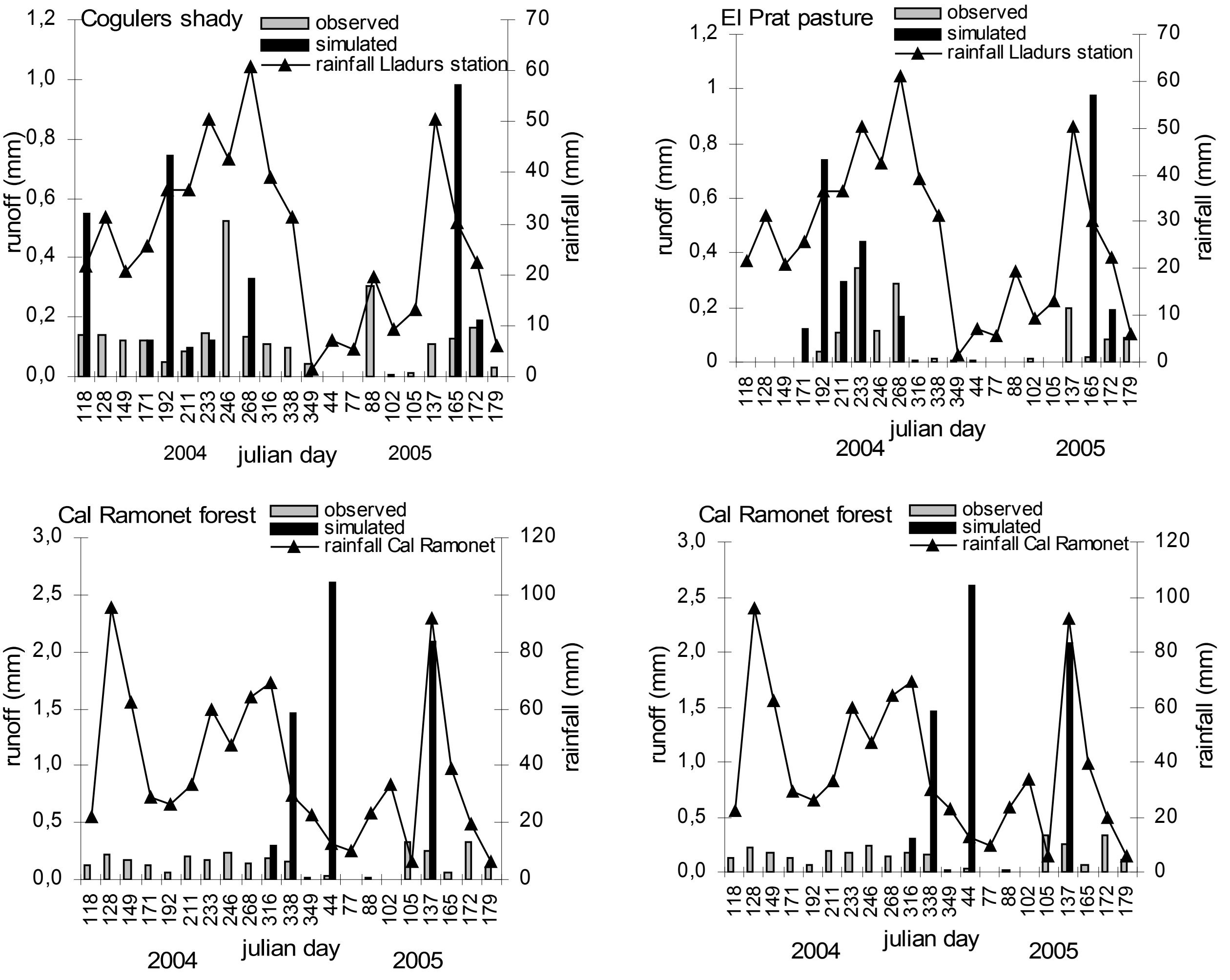


Fig 5.2 Runoff observed, simulated and rainfall to different soil uses during the period 21/04/2004 - 28/06/2005

The surface runoff in the Ribera Salada basin, of the studied period fluctuates between 0.24 and 1.21 % of the total rainfall. These low values are coincident with reports of other authors who measured the following maxim runoff values in the same basin: 0.70% in pastures, 0.59% in tillage zones and 0.28% in forest (Rodríguez, 2004). The runoff coefficients according to Sanz (2005) in the same basin are 0.86% in tillage zones and 0.61% under forest cover. The runoff values do not reach 1% under forest and 4% under pasture in Canalda according to Verdú et al., 2000. These values do not indicate any influence of cover type on runoff formation, except those of Orozco (2005) who reports higher runoff values (2.25%) for pastures than in forest (0.22%). Underneath holm oak forest in Mediterranean zones, Àvila (1987) reported runoff values of 1.3% of the total rainfall. Under *Q. pyrenaica* moist Mediterranean forest, runoff values were 0.2 - 0.6% of the total rainfall (Gallardo & Moreno, 1999).

Verdú et al. (2000) attribute the formation of runoff for short saturation periods of the soil profile. Several authors attach more importance to soil cover and land use than to soil type in the runoff generation, but in this case (stony and porous soil) the soil characteristics are more important than the cover type. Gallart et al. (2005) showed in the Vallcebre basin that the dominant runoff generation mechanism changes along the year, as a result of both varying antecedent wetness conditions in the catchment and changing rainfall events (intensity and volume).

Summer and spring are the seasons with the highest runoff volume. The Runoff values are low due to high infiltration. When the soil is slightly saturated, the model response by increasing runoff, by minimum 1m area. In real conditions this runoff increase occurs punctually (Verdú et al., 2000). This difference leads eventually to an overestimation of the simulated values, the real soil moisture being slightly lower.

5.3.3 Analysis of infiltration

The total infiltrated water, in the different plots, during the studied period, can be observed in table 5.1. Fig 5.3 shows water infiltration for different soils uses in the Ribera Salada Catchment during the period 2004 - 2005.

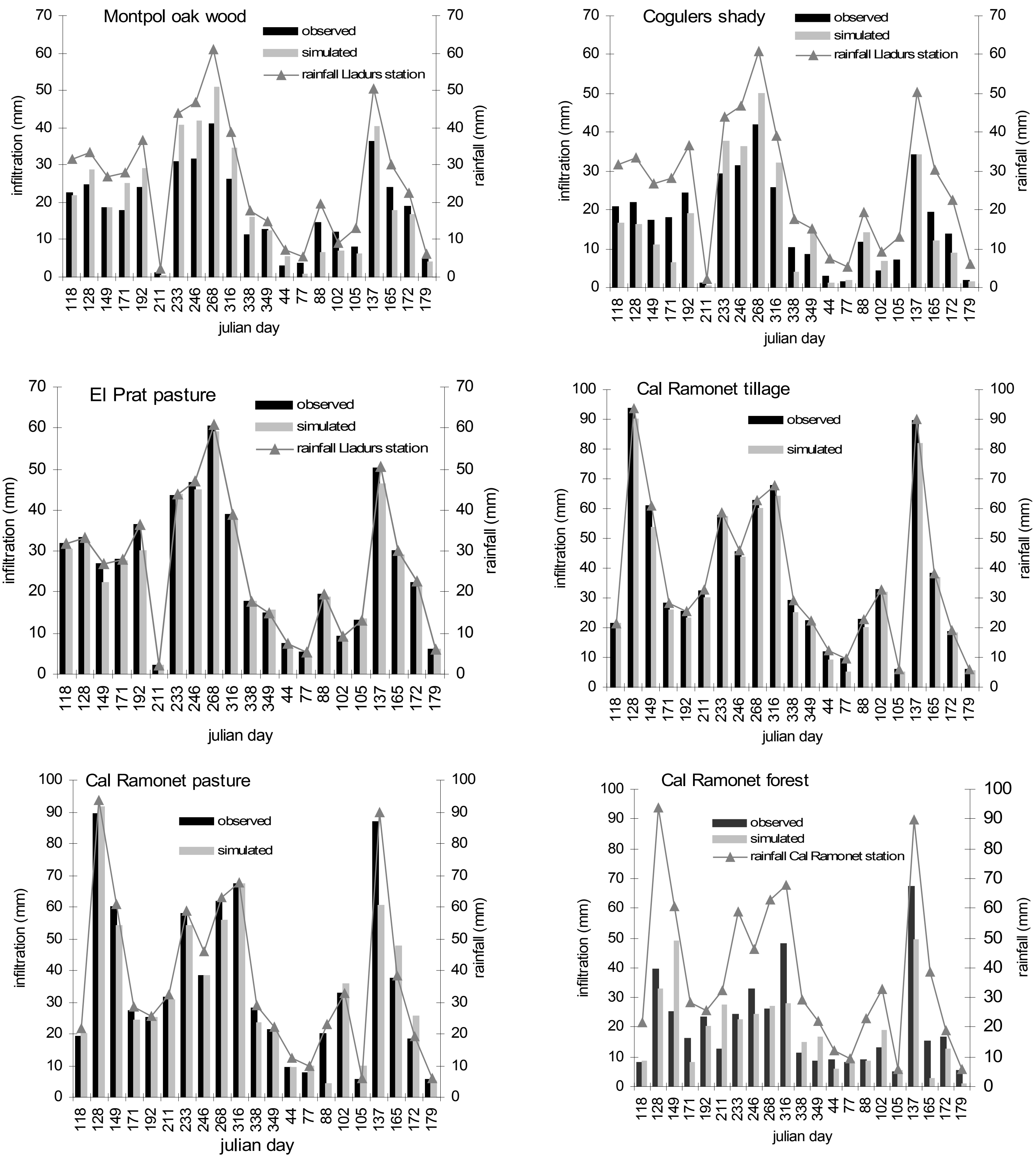


Fig 5.3 Soil infiltration observed, simulated and rainfall to different soil uses during the period 21/04/2004 - 28/06/2005

Fig 5.3 show, the observed and simulated infiltration(each point represents the total for a rain time period), both graphs are quite similar, therefore it can be said that the calibrated model works well in the studied basin. The simulation model represents accurately low infiltration values under moderate or low rainfall, without overestimating the infiltration values. Under a forest cover, the soil moisture percentages are lower along the year, but the infiltration values tend to be higher than those of the other soil uses.

The infiltration fluctuates in accordance with the cover type, from 40 % to 99 % of the total rainfall. For storms with a rainfall of lower than 27 mm, infiltration is higher, ranging between 54 - 99 % of the total rain. When coping with individual rain events, especially when the rain is lower than 1 mm, infiltration is null, while rain episodes between 10 - 27 mm show a very efficient infiltration (observed data).

Under *Quercus ilex* forest in moist Mediterranean climates, the infiltration values consisted 46% of the total rain. Under *Q. pyrenaica*, infiltration reached 27 - 66% of the total rain, and under this type of forest, the annual rainfall that surpasses 500 mm is converted into drainage water (Gallardo & Moreno, 1999). Quite the opposite, under a deciduous forest in Serra de Prades, the infiltration values were much lower, between 3 - 15% of the total rainfall (Lledó & Piñol, 1989; Àvila, 1987). The same author affirms that under the driest Mediterranean conditions, the infiltration values only reach 8% of the total rain. Orozco (2003) found that in the Cogulers catchment, under pastures, the infiltration value was 98% of the total rain.

Our results show that the simulated values are similar to the field observations, even in the infiltrations peaks. The highest infiltration values are registered in spring and autumn, having low infiltration during the rest of the seasons. In fig 5.3 we can see how infiltration increases after long events of rainfall. The model predicts well the infiltration under to all rainfall intensities, without overestimating the infiltration taxes. Under a pasture and tillage cover, the infiltration percentage tends to be higher than underneath forest. In case of existent lateral water contributions, the observed date show a infiltration that is slightly higher than the precipitation.

Figure 5.4 represents the relationships between infiltration, drainage and rainfall in the different study plots.

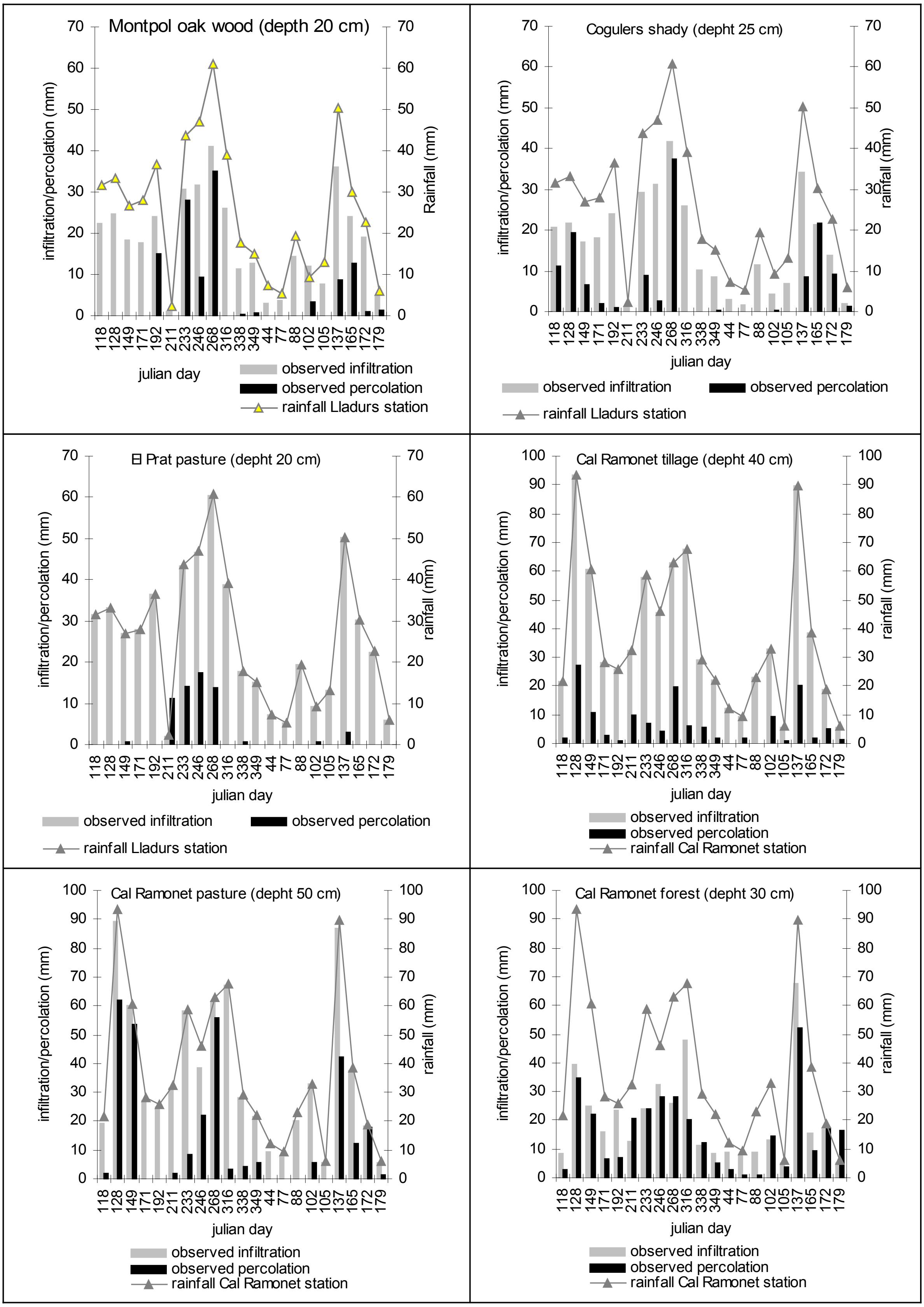


Figure 5.4 Infiltration, drainage and rainfall observed

The drainage water constitutes 11 - 77 % of the total infiltration water, and 11 - 41% of the total rainfall. In the Cogulers catchment, Orozco (2003) found 43 - 40% (of the total rainfall) of water drainage under pasture and forest. In Cal Ramonet the forest drainage water results to be 25 % and 75 % more than in tillage and pasture respectively. In the other parts of the catchment the drainage water of the pasture is 47 - 59 % less than that of the forest. The high drainage values are probably due to the low soil water retention.

The low runoff values are explained by the high infiltration capacity of the soil, even under crops or pastures. These conditions are optimal for saturation flow formation after long rainy periods. The unexisting relation between rainfall intensity and runoff suggests that hortonian flow is rare. Under these conditions the model performance is good and predicts accurately the soil infiltrations dynamics.

5.3.4 Analysis of interception

In the Ribera Salada, the basin interception (which was calculated according to the regression data obtained by Solsona (2005)) fluctuates according to the cover type. The maximum and minimum simulated interception values for a rain event during the studied period are: *Quercus ilex* 26.4% - 43.8 %, *Pinus nigra* 6.5% - 60.5%, *Pinus sylvestris* 31.2% - 72.3 % and brook forest 17.8% - 72.3 % of rain.

The total of intercepted water is shown in table 5.1 (each point represents the total for a certain rain time period) and also in figure 5.5. Most of the events are long, with low rainfall intensities and wet atmospheric conditions.

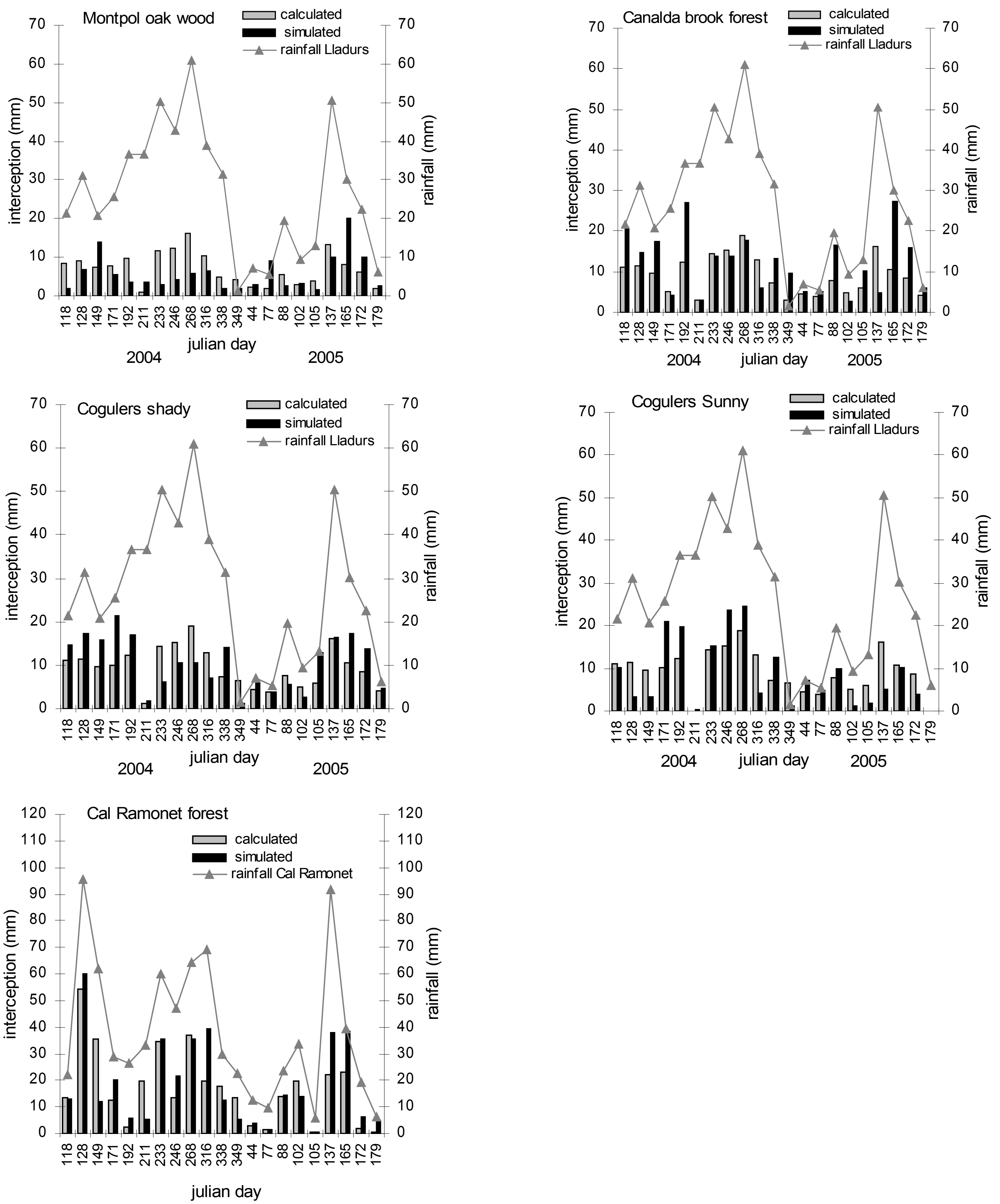


Fig 5.5 Interception calculed, simulated and rainfall under different soil uses during the period 21/04/2004 - 28/06/2005

Under *Pinus nigra* in the Cogulers basin, Rosanes (2000) found interception values close to 18% of the total rain (0.5 to 76%). Analyzing rainfall in the same site, working with an extended data set, Jiménez (2002) reported interception values of between 0 - 31% of incident rain, with 21 % as the average value. Measured interception in the Ribera Salada basin is for *Quercus ilex* 25% , for *Pinus nigra* 30% and for *Pinus sylvestris* 55% of the total rain (Solsona, 2005). In Vallcebre under *Pinus sylvestris*, Llorens et al. (2003) report interception values of 24% of the total rain. Under *Q. ilex* in Mediterranean zones the interception is less, around 12.9% (Bellot & Escarré, 1998). Under *Q.pyrenaica* Mediterranen moist forest, the interception values are between 11 - 19% of the total rain (Gallardo & Moreno, 1999).

The differences between the observed and simulated interception are comparable to or smaller than those obtained in the literature for tree species in Mediterranean conditions according to Llorens (1997) and Llorens et al. (1997). The parameters obtained in the 21 events were used to check the model interception losses for the period April 2004 - June 2005. Fig 5.5 shows the rainfall interception values using the calibration data and Solsona (2005) equations, Table 5.1 and 5.2 reflect how, during the studied period, the model underestimated interception under *Quercus ilex* and sunny *Pinus nigra*. In other plots the model overestimated the interception.

According to Llorens et al. (1997) *Pinus sylvestris* interception values in the Pyrenees increase when the rainfall volume is high and has a low intensity. Interception vs rainfall follows a decreasing curve with a positive slope, tending to a steady value. This curve is not followed under high intensity rainfall events.

The use of the equations found by Solsona (2005) for events higher than 10 mm, in combination with the TOPLATS model gives correct results. Under low rainfall conditions or high rain intensities it is difficult to calculate the intercepted rainfall volume. Interception is difficult to calculate due to high variations in the rainfall duration, intensity and volume, which make it complicate to predict interception.

Table 5.1 shows the observed and simulated interception losses for the whole period. Our results suggest that the calibrated TOPLATS model is sufficiently robust to be applicable in Mediterranean mountain conditions to obtain the total precipitation losses.

The percentages of prediction are similar to those obtained in the Vallcebre interception simulation by Llorens (1997), who made use of the Gash interception model.

5.3.6 Analysis of soil moisture

Fig 4.2 shows the observed soil moisture and the TOPLATS soil moisture predictions for the soil uses in the Ribera Salada catchment. Soil moisture change is used as a reference parameter in water balance components for different plots. The soil moisture behaviour values in the different plots of the studied period are shown in section 4.3.2.

5.3.5 Analysis of evapotranspiration

Fig 4.6 shows evapotranspiration in of the Lladurs station (Meteorological reference station) and the TOPLATS predictions. Evapotranspiration values are used as reference parameters, for a detailed study of evapotranspiration and energy flux it is necessary to implement tools to measure the energy flux in the field.

5.3.7 Analysis of water balance components

The different contents of the water balance components in the studied plots during the period April 2004 - June 2005 are analyzed, and the results are shown in table 5.1 .

Table 5.1. Measured water balance components values by plot

Plot	Rainfall	Runoff	Infiltration	Interception	ΔSW
			(mm)		
Montpol oak wood	545	6.6	387	149	- 0.3
Canalda brook forest	545	-	-	191	0.6
Cogulers shady	545	1.9	346	197	- 23.4
Cogulers sunny	545	-	-	193	- 7.5
El Prat pasture	545	1.3	544	-	-15.4
Cal Ramonet					
Tillage	785	2.5	783	-	- 43
Pasture	785	2.2	751	-	- 17.8
Forest	785	2.9	424	358	- 9.7

ΔSW: water storage variation.

Table 5.2. Simulated values of water balance components using TOPLATS

Plot	Rainfall	Runoff	Infiltration	Interception	ΔSW
	(mm)				
Montpol oak wood	545.3	0	424	121	7.6
Canalda brook forest	545.3	-	-	255	-2.2
Cogulers shady	545.3	3.2	322	220	-34.7
Cogulers sunny	545.3	-	-	184	-12.5
El Prat pasture	545.3	2.9	517	-	-7.8
Cal Ramonet					
Tillage	785	0	730	-	-17.5
Pasture	785	4	712	-	-35.7
Forest	785	6.5	391	387	-11.3

ΔSW: water storage variation.

It is remarkable that under these Mediterranean conditions, the net soil water storage (ΔSW) was negative or close to 1% of the total rain. This is due to high evapotranspiration, which results in a gradual decline of the soil water content during the dry season. Both solar energy and available water are necessary to cause evapotranspiration. Of the total amount of water taken up by plant roots, about 95% is transpired through the stomata, a process that is not controlled solely by physical conditions, because plants regulate the rate at which water is released in transpiration in a manner that varies by plant type. The forestation increases the amount of transpiration and interception (and consequently evaporation from interception store); and this results in a decrease of soil moisture and runoff (Hornberger et al., 1998).

The soil water content was almost constant and nearly reached the wilting point along the year. Soils tended to have intermediate moisture conditions, and rarely reached too moist values. The soils have low moisture retention, which explains the low variation in soil moisture content and high water drainage. Usually, replenishment of water in the soil occurs in spring and autumn. The AWC is sufficiently replenished, but it is very low and the soil water is not sufficiently supplied in summer given the transpiration and interception demands. In zones under a forest cover, due to rain characteristics (Llorens, 1997), a high percentage of rainfall is lost through interception. In Mediterranean environments runoff has little importance compared to other water balance components. Lledó & Piñol (1989), Arauzo et al. (2003) and Gallart et al. (2005) argued that most part of the rainfall is used as evapotranspiration and infiltration, but this observation is strongly affected by the high interannual variability in Mediterranean environments.

5.3.8. Water flow at subcatchment scale

The downscaling of the model at subcatchment scale was done for the Canalda and Cogulers subbasins. The water flow maxima, minima and averages values (m^3/s), both simulated and observed, are found in table 5.3.

Table 5.3 Water flow values in Canalda and Cogulers subcatchments

		Water flow (m^3/s)			
Catchment		Min	Max	Average	RMSE
Canalda	Observed	0.00278	2.2476	0.1375	0.0238
	Simulated	0.0953	0.1044	0.1091	
Cogulers	Observed	0	0.3676	0.0042	0.00048
	Simulated	0.0015	0.0028	0.0019	

It can be seen that the simulated water flow values are much lower than the actual ones, due to the fact that the model only considers water flow contributions by run-off. Figure 5.7 show the daily average water flow in the Canalda and Cogulers subcatchments.

The real discharge values register abrupt changes, while the simulated values are mostly constant along time. This is because the simulated water flow is generated by runoff. As we have seen, actual runoff is very low (section 5.3.2.), whereas infiltration values are high (section 5.3.3.). Due to the low ACW of the soil, little water is retained in the soil and the circulates as drainage water to a subterranean aquifer or to the river course along the slopes.

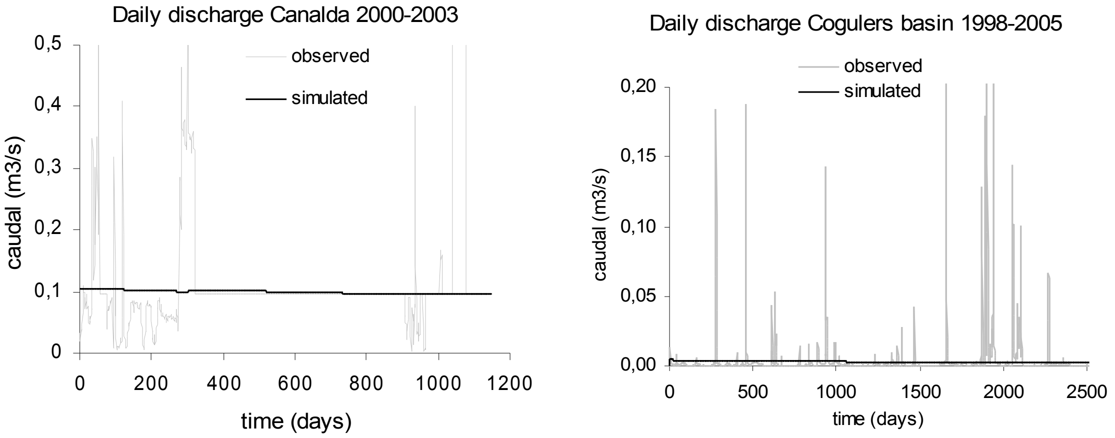


Fig 5.7 Predicted and observed daily water flow to Canalda and Cogulers subcatchments

For between 400 - 800 time days in the Canalda graph, the real and simulated values are similar. This is a period with low soil moisture conditions under low intensity rain events, when all rainfall water would recharge the soil profile. In this period, runoff form the main contribution to the water flow. In very dry conditions the water flow is directly recharged from the aquifer.

Therefore, the lack of adjustment of the actual and simulated values indicates the high contribution of aquifers and subsuperficial flow to the river's daily discharges base flow. It is interesting to know the runoff contribution of higher slope and bare rock zones in the catchment.

5.4 Conclusions

This chapter demonstrates the feasibility of combining measured parameters with model generated parameters, to estimate the behavior of the water balance components in a small to medium catchment, where calculated canopy interception has been modeled with generated equations by means of interception plot measurements and evapotranspiration to meteorological reference station. Runoff, infiltration and soil moisture were calculated with good adjustments with those measured in situ.

The registered runoff corresponds to punctual saturations of the soil profile or to the rain drops they are effect (speed and size). The lisimeter results show that in the basin, there is a subsuperficial flux. Considering the water contributions to the aquifers, the forests can provide more water than the tillages and pastures can (between 25 and 75 %), due to the forests high drainage.

The results simulate correctly the high infiltration tax into the basin, which is related with high soil porosity. In events lower than 1 mm/h, the infiltration is inexistent. In events higher than 2 mm/h it starts to register a rain infiltration from 40 to 99%. The infiltration taxes can difficulty be surpassed by common rain intensities.

The water drainage amount is quite important (11-41 % of the total rain), being destined to the aquifer recharge and the other part of the rain is destined to water flow as subsuperficial runoff. The drainage and infiltration conditions differ with the low moisture that these soils contain. These conditions, in combination with the soil profile boundary, a high amount stones and porosity, and a variable roots distribution, make it difficult to calculate ETo, based on field data.

Our results show that the largest part of the inputs go to infiltration, evapotranspiration, interception and drainage (in order of importance). The runoff values are very low and therefore their influence in the water balance is not significant. Regarding soil moisture, we conclude that this is an important reference parameter, having in most of the cases values closer to -1500 kPa in the medium part of the basin, and in the highest part these values increase until intermediate moisture conditions (-33 kPa>x>-1500 kPa).

This study also proves that the net change in soil water (ΔSW) is negative or low during most part of the year, reaching critical values in the dry months. Soil moisture recharge occurs only partially during the wet season. This is especially important in Mediterranean mountain zones, where slight changes in rainfall or temperature can provoke changes in the soil water balance and increase the annual soil water deficit. Correct calibrations in soil moisture permit a right prediction of the water balance parameters.

To conclude, the TOPLATS model can be used to predict the hydric balance components under Mediterranean conditions, if there is a preliminary field follow-up and the soil and vegetation components have been characterized at field. These recommendations allow us to realize a preliminary model calibration.

Chapter 6

GENERAL CONCLUSIONS

The use of hydrological models allows us to understand the impact of soil use changes in watershed hydrology, as well as to infer the possible effects derived from different climatic conditions. The calibrated models help us to perform complete hydrological balances, enabling us to know the contribution of each of its components. In that follows, the most relevant conclusions of the research are summarized:

Chapter 2

In the Ribera Salada watershed the ustic moisture regime (SSS 2006) is predominant and the soil temperature regime forms a transition between mesic-thermic. In the driest years xeric regimes are reached, mostly in forest with shallow soils and in high mountain pastures.

The spatial and temporal variability of the water content in the Ribera Salada depends on the soil characteristics and cover type. In the intermediate part of the basin, under moderately deep soils, pastures tend to be slightly drier than soils under forest, root depth being in this case another limiting factor.

The driest periods are winter and summer. In the highest part of the basin the driest soil moisture values occur in winter, because the rain falls in the shape of consequently snow, and the plants can not use this water. In the medium part of the basin, summer is the driest season, due to an increase of evapotranspiration demand. In general, autumn is the season in which the highest moisture content is recorded, but due to the low recharge, the capacity of the soil water content decreases quickly.

The change in soil use to forests tends to diminish soil moisture because it increases evapotranspiration in order to increase the canopy interception and a high rooting depth and the drainage water. Soils under pastures extract most water from shallow layers, while in forests the water is extracted from deeper layers which influence the evapotranspiration volume and consequently diminish the soil moisture content. The presence of forest helps aquifers to recharge and water to flow (to subsuperficial flow).

Regarding the studied soil moisture regime models, JSM (Jarauta) comes closest to the real soil water behaviour. In all cases the models have limitations under extreme moisture conditions, like drought periods or soil saturation conditions. JSM works well under intermediate soil moisture conditions, whereas NSM (Newhall) tends to overestimate the soil moisture content. The process of soil use change to a forest use, leads to an increase of the area with a ustic regime. During the driest years it evolves to a xeric regime, mostly in shallow soils.

The preliminary modelling of the soil temperature regime with the Lladurs station data using both models (NSM and JSM) gives results in agreement with the field measurements, mostly a Mesic-Thermic regime. This regime varies to thermic regime conditions in the hottest years.

Chapter 3

The application of the TOPLATS model to the watershed, once calibrated, presents a correct simulation of the soil moisture behaviour and of other hydrological components like infiltration and run-off. The obtained graphs of these parameters show an adjusted behaviour in soil moisture, infiltration and run-off, when compared to the measured values. In the case of run-off, both the simulated and real values are very low.

Chapter 4

The TOPLATS model simulates correctly the soil moisture behaviour under different soil and land uses. It works better during periods of constant soil moisture than in periods with short time changes of the soil moisture content. Despite of that, in the worst cases the differences between the simulated and real values do not reach 5%.

The differences between the measured and simulated infiltration fluctuate between 4 % and 15%. Summer and spring, the seasons with the highest infiltration, are the periods with the best fits.

TOPLATS gives a good estimation of evapotranspiration and soil temperature behaviour of the reference meteorological station, which suggests the high model sensibility of energy flux parameters.

Chapter 5

The results of the hydric balance show that most of the water losses are due to evapotranspiration, interception and infiltration (in order of importance). The runoff values are very low and therefore their influence in water balance is not significant. Net changes in soil water values (ΔSW) are negative or low during most part of the year, reaching critical values in the dry months. Soil moisture recovery occurs partially during the rest of the year.

The lysimeters show the importance of subsurface flow in the catchment in order to recharge the aquifers and ensure a base flow. They are favoured by the presence of soil lythological discontinuities and lithic contacts. The change of soil use to forest helps to increase water supply to aquifers recharge and river base flow. Soils under forest use are drier than soils under tillage or pastures, due to rainfall interception and high drainage.

The obtained results show the model flexibility and applicability. The TOPLATS calibration with real values for the different hydric balance components (run-off, infiltration, soil water content, evapotranspiration and canopy interception) allows its use with a high precision level in the water flux estimation in Mediterranean mountain zones or under other climate conditions or watersheds.

Certainly, the results of this research can be implemented as a tool for better understandment of hydrologic paths and processes in the basin, allowing a sustainable use of hydric resources. Furthermore, they can be used to study the hydrologic dynamics in other Mediterranean basins. At the same time they can be implemented under different climatic scenarios and soil use. Finally, this research can be applied as a tool for basin management.

Further research:

The use of the Jarauta model for the determination of soil moisture regimes in mountain zones, could be improved of the topographic characteristics and soil profile thickness were taken into account. These characteristics are difficult to map under the studied scale in this research.

The TOPLATS calibrated model allows us to know the contribution of run-off to the water flow along the slopes after a rainfall event. This makes it possible to calculate approximately the water amount from subsurface run-off in rainfall periods or those coming from subterranean aquifers in dry seasons.

The used methodology can be applied to other Mediterranean mountain basins, but it is recommended to compare the obtained results by means of the simulation models with acquired field information.

It would be interesting to use calibrated models in the Ribera Salada to predict the soil water behaviour, moisture and temperature regimes under meteorological changes and vegetation variation.

The information collected by the field equipments can be used to manage the water resources of the basin for multiple uses: agricultural and forestry production, prevention of fires and managing water reservoirs. Soil moisture information can be used for water use planning by the catchment users.

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