Impact of the new Common Agricultural Policy of the EU on the runoff production and soil moisture content in a Mediterranean agricultural system

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Abstract

Soil moisture variability and the depth of water stored in the arable layer of the soil are important topics in agricultural research and rangeland management. In this study we use the Distributed Rainfall-Runoff (DR2) model to perform a detailed mapping of topsoil moisture status (*SMS*) in a mountain Mediterranean catchment. This model, previously tested in the same study area against the Palmer *Z*-index, is run at monthly scale for the current scenario of land uses and under three scenarios that combine the land abandonment and the application of the new Common Agricultural Policy (CAP) of the European Union. Under the current conditions, runoff yield is scarce and presents a high spatial variability when monthly rainfall intensity and depth are low, and infiltration processes mainly lead to water storage in the soil. When rainfall intensity is high, runoff accumulation along the hillslopes controls the depth of available water in the soil, and *SMS* is more homogeneous. On average, scrublands and pasture have the wettest values, crops of winter cereal and abandoned fields have intermediate conditions, and areas of bare soil and forest have the driest conditions all the year around. The abandonment and no revegetation of the low productive fields located in steep areas and the

collapse of their landscape linear elements (LLEs) produces both an increase of 2.3% of the overall *SMS* in the catchment in comparison with the current scenario but also an increment of the effective runoff that cross the cultivated areas of the lowlands and the runoff depth that reach the wetlands, increasing the soil erosion risk and compromising the conservation of the lakes. When the new green areas of the CAP are installed in the upper part of the fields of the lowlands and around the lakes, the runoff depth and thus siltation risk clearly decreases but also *SMS* decreases 1.7 and 1.1% considering the current land uses and adding revegetation practices in the abandoned fields, respectively. Hence, a management scenario where: i) abandoned fields are covered with a dense cover of shrubs, ii) the LLEs are preserved, iii) the green areas of the PAC are created, and iv) runoff harvesting practices are applied to partially compensate the water deficit, will help to preserve the humidity of the soil and will be of interest to keep the agricultural land use around the protected lakes of the study area.

Keywords: Topsoil moisture; DR2 model; winter cereal; Estaña Lakes; Mediterranean agro-system; new Common Agricultural Policy

1 Introduction

Soil moisture monitoring and the study of its temporal and spatial variations are ongoing trends in agricultural water research and rangeland management and restoration (e.g. Gao and Shao, 2012; Gala and Melesse, 2012). In the last decade, the number of water balance models, devices for the assessment of soil water content and drought indices has increased in all scientific disciplines (e.g. Frot and van Wesemael, 2009; Vicente-Serrano et al., 2011a; Mittelbach et al., 2012). Drought is one of the major natural hazards that trigger serious economic and environmental damages. A direct and well documented correlation exists between the available water storage in the entire soil profile and the crop yield in rain-fed agricultural systems (Tao et al., 2003). This correlation is even more significant than that between crop yield and rainfall depth or temperature. In the Iberian Peninsula, the mean duration of drought episodes has increased in the last 3 decades by approximately 1 month due to increases of the potential evapotranspiration rates (Vicente-Serrano et al., 2011b).

Large scale conversion of natural ecosystems to agricultural land has taken place in the last three centuries exacerbating the problems of soil degradation (García-Ruiz, 2010). New irrigated areas with an upward trend in water requirement are appearing as a consequence of increasing world population (Neumann et al., 2011). The current global scenario of agricultural expansion and climate change causes great stress on soil and water resources and stress the need for research on sustainable agriculture (Yang et al., 2012). This concern has promoted the creation of specific laws, such as the European Union Water Framework Directive (DIRECTIVE 2000/60/EC) and the Thematic Strategy for Soil Protection (COM, 2006). The sustainable use of land resources is significant to keep economic development and environmental protection in fragile agro-ecosystems where changes of land use and land management are the main driving forces that modify the natural dynamic and rates of runoff, soil moisture and sediment yield (Zhao et al., 2013). Recently the European Commission presented a set of regulations that constitutes the draft of the new Common Agricultural Policy (CAP) that will come into force in January 2014. The proposals of the new CAP (http://ec.europa.eu/agriculture/cap-post-2013/legal-proposals/index_en.htm) set the rules for a greener policy that will boost the efficiency of food production through better resource management and farm innovation.

Accurate and realistic estimations of soil moisture and runoff require the use of many input variables due to the spatial and temporal variability and complexity of the processes of runoff generation and accumulation. Soil moisture maps can be drawn with data obtained from satellite images, such as the information provided by SMOS (the European Space Agency's Soil Moisture and Ocean Salinity mission; Piles et al., 2010) or by RADARSAT-1 SAR (Synthetic Aperture Radar; Gala and Melesse, 2012) though the spatial resolution is usually coarse for agricultural research. The collection of hydrological models include the empirical ones, such as the "curve number model" (Soil Conservation Service, 1985), dynamic models like LISEM (Sheikh et al., 2010) or KINEROS (Nedkov and Burkhard, 2012), regional scale models such as the Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005), and event based runoff models from agricultural fields and hillslopes (e.g. STREAM, Frot and van Wesemael, 2009). However, some of the available rainfall-runoff models do not characterize the humidity status of the soil, such as the CASC2D (Downer et al., 2002) and the TOPMODEL (Huang et al., 2012), or they are too complex and require many input parameters, like the GSSHA (Gridded Surface/Subsurface Hydrologic Analysis; Downer and Ogden, 2003) model. In this study, we run the water balance DR2 model (López-Vicente and Navas, 2012) to perform a detailed mapping of topsoil moisture, cumulative runoff and water deficit at monthly scale and under four different scenarios of land uses that includes the strategies of the new CAP. In a previous study, the DR2 model was tested in the same study area and for the current conditions against soil moisture values of the Palmer *Z*-index, showing that the spatial predictions with the DR2 model identify the different sub-categories of soil wetness for each soil type in greater detail than the Palmer *Z*-index (details in López-Vicente and Navas, 2012). This study provides valuable information that will be of interest for developing a sustainable soil and water resource management in both agricultural systems and rangelands. This target is achieved in a medium size catchment located in the Spanish Pre-Pyrenees where rain-fed cultivated areas are intersected with forest, scrublands and grass.

2 Materials and methods

2.1 Study area

The Estaña Lakes catchment is a medium-size watershed (246 ha) located in the External Ranges of the Spanish Pre-Pyrenees and within the Ebro Basin (Fig. 1a). This study site includes three fresh-water lakes with a maximum flooding area of 17.3 ha. The three lakes and their surrounding vegetation cover 22.7 ha and are under regional protection since 1997. The protected area is included in both the Inventory of Singular Wetlands of Aragón (BOA, 2010) and in the European NATURA 2000 network as Site of Community Importance (SCI). Elevation ranges between 676 and 896 m a.s.l. and the mean slope steepness is 19.5%. Steep slopes (slope steepness higher than 22.5%) occupy 20% of the study area whereas gentle slopes (slope steepness lower than 8%) cover 33%. The parent material of the soils corresponds to Mesozoic gypsiferous marls, dolomites, limestones, and sparse saline deposits and karstic processes partially dominate the evolution of this landscape (López-Vicente et al., 2009a). Twenty-one types of soils are distinguished using the FAO classification (Machín et al., 2008) that can be grouped into six main types: Calcisols (covering 32% of the total surface), Leptosols (32%), Regosols (23%), Gleysols (4%), Gypsisols (5%) and Vertisols (3%). Calcisols and Leptosols are associated to limestones, and Gypsisols, Regosols and Vertisols to clayish materials. Texture is mainly silty loam and in some parts silty clay loam. Gleysols are developed on clay materials where the water table is seasonally near the soil surface and appear around the lakes. The different soil types present a complex spatial distribution as a consequence of the intricate geology and topography (Fig. 1b).

The study area has a relatively long history (since the 10th century) of human occupation like the San Esteban romance hermitage from the 11th century, agricultural practices and water management (Morellón et al., 2008), with increasing population along the 19th century and a continuous depopulation trend since then (Morellón et al., 2011). Nowadays, there are only 8 citizens in the Estaña village and most farmers live in other next villages like Benabarre and Estopiñán del Castillo. The landscape is representative of the typical former rain-fed Mediterranean agro-ecosystem where small patches of natural and anthropogenic areas are heterogeneously distributed (Fig. 1c). Cropland of winter barley, pasture and orchards cover 31% of the study area, whereas forest and scrubland occupy 67%. The remaining 2% of the soil surface is covered with rock pavements and screes. These percentages are related to the soil surface without considering the lakes. Active soil erosion by water affects large parts of this study site such as it appears described in the literature (e.g. López-Vicente and Navas, 2010; Gaspar et al., 2013; Navas et al., 2013) with high rates of soil loss mainly affecting the crops (ranging from almost zero to 108 Mg / ha yr) and areas with low vegetation cover and also high rates of sedimentation are threating the lakes (ca. 3.41 mm / yr) (Morellón et al., 2011). These studies highlight that siltation processes seriously threaten the wetlands of the Estaña Lakes and thus mitigation and conservation practices are urgently needed.

The study area is located between the semi-arid areas of the Ebro valley to the south and the humid areas of the Pyrenees to the north. Climate is continental Mediterranean with two humid periods, one in spring (April and May) and a second in autumn (September and October) and a dry summer with rainfall events of high intensity. The average maximum rainfall intensity in 30 min, I_{30max}, is higher than 15 mm h^{-1} between May and October, attaining the highest values, from 22 to 26 mm h^{-1} in July, August and September, and below 10 mm h^{-1} between December and March (López-Vicente et al., 2008) (Fig. 1d). Average annual precipitation at the weather station of Canelles (8 km to the southeast of the study area) was 520 mm for the reference period 1961-1990 considered by the World Meteorological Organization, whereas the average precipitation during the last teen years (2002-2011) was 15% lower (442 mm) (Fig. 1e). Annual precipitation has a strong inter-annual oscillation of 378% for the period 1941–2011. The average annual potential evapotranspiration is 1227 mm at the Barbastro weather station (33 km to the west of the study area) (Fig. 1f). Low summer precipitation can cause summer droughts and long periods of low rainfall depth can cause severe damage in natural vegetation and crops, and reduce the volume of available water in the lakes. From an average number of 83 annual rainfall events in the Canelles station, only 11 had precipitation above 12.7 mm and can be considered as erosive events (Fig. 1d) following the definition proposed by Renard et al. (1997). Weather, topography, land uses and tillage practices in the study area are representative of rain-fed areas in Mediterranean mountainous agro-ecosystems.

2.2 The DR2 model

The water balance Distributed Rainfall-Runoff (DR2) model estimates for each month of the year the soil moisture status (*SMS*) of the arable layer of the soil at hillslope and catchment scale. This model, developed by López-Vicente and Navas (2012) and enhanced by López-Vicente et al. (2013a), was applied in the same study area to obtain a detailed analysis of the different role played by the topographic, climatic and infiltration parameters on the soil moisture status. These authors successfully validated the predictions of the DR2 model against values of the widely used Palmer moisture anomaly index (*Z*-index; Palmer, 1965). Even though, the predictions of the DR2 model describe with more detail the spatial and temporal changes of *SMS* than the Palmer *Z*-index. In this study, the DR2 model is applied with an extended database of climatic parameters and a more detailed map of the different soil types and their infiltration values to assess the *SMS* changes under different land use scenarios. The DR2 model computes the *SMS* as the ratio between the depth of actual available water (W_{aa}, mm) and potential reference evapotranspiration (ET_0, mm):

$$SMS = \frac{W_{aa}}{ET_0}. \quad (1)$$

where W_{aa} is defined as the total depth of water that is stored and infiltrated in the soil profile during an average storm event for each month. Water inputs are assumed to be the sum of the direct rainfall depth and of the upslope contributing runoff, and moisture demand is computed as equal to potential evapotranspiration. The depth of W_{aa} at each pixel of the study area is computed with GIS techniques following a sequence of calculations in three steps such as it appears in Fig. 2. In the first step the unsaturated and saturated pixels by direct rainfall (no runoff contribution) are distinguished. In the second step unsaturated pixels with and without upslope contribution of runoff are discriminated. Finally, the upslope contributing runoff is calculated for the unsaturated and saturated pixels as a function of the effective depth of cumulative runoff. Following this step-by-step approach five different situations of water inflow in the soil are distinguished (Fig. 2).

2.2.1 Initial runoff generated at raster cell

Soil only becomes saturated during a storm event or when the water table reaches the soil surface. Time to ponding (*Tp*, s) is the time until the surface of the soil is saturated under a rainfall intensity greater than the saturated hydraulic conductivity (K_{fs}, cm s^{-1}) (Esteves et al., 2005). Before *Tp* all the water infiltrates, beyond *Tp* only a fraction goes into the soil profile and the other part becomes runoff. Time to ponding depends on soil infiltration properties, rainfall intensity and the antecedent soil moisture content and can be calculated as a function of saturated hydraulic conductivity (K_{fs}, cm s^{-1}) and soil sorptivity (S_p, cm s$^{-0.5}$). Hogarth et al. (1991) proposed that time to ponding (*Tp*, s) has a minimum and a maximum time and state that the average value can be calculated as:

$$\frac{1}{2}\frac{S_p^{\,2}}{K_{fs}}\ln\left(\frac{I}{I-K_{fs}}\right) \le Tp \le \frac{1}{2}\frac{S_p^{\,2}}{I-K_{fs}}, \qquad (2)$$

$$S_p = \sqrt{2(\Delta\theta)\phi}, \qquad (3)$$

$$\Delta\theta = \theta_S - \theta_0. \qquad (4)$$

where I (cm s^{-1}) is the rainfall intensity, ϕ is the matrix flux potential (cm^2 s^{-1}) of each soil type and θ_S (% vol.) and θ_0 (% vol.) are the saturated and initial volumetric water content, respectively. The saturated volumetric water content is the maximum amount of water that can be stored within the soil and the initial water content is the volume directly measured in the field (antecedent topsoil moisture).

Time to ponding is calculated in each point of topsoil moisture measurement for a characteristic rainfall event for a month (i.e. average maximum intensity). Then, the potential overland flow per raster cell for each month *m* (Q_{0m}, mm) is estimated as a function of the depths of monthly effective rainfall (ER_m, mm) and rainfall to ponding (Rp_m, mm):

$$Q_{0m} = ER_m - (Rp_m\, e_m) = ER_m - (Tp_m\, I_m\, e_m) \ge 0, \qquad (5)$$

$$ER_m = R_m(1 - A_m)\cos S. \qquad (6)$$

where Tp_m is the monthly time to ponding (s), I_m is the monthly rainfall intensity (cm s^{-1}) and e_m is the monthly number of rainfall events. Values of *ER* are estimated after considering the depth of precipitation intercepted by the canopy of the crops and natural vegetation, *A* (0–1), from the total rainfall depth, *R* (mm), and using the improvement presented by Morgan and

Duzant (2008) to consider the effect of slope angle, S (radians), on the quantity of rain received per unit area. The DR2 model runs on a monthly time step and intends to assess the average wetness status of the soil and not to calculate the humidity of the soil after each rainfall event.

2.2.2 Effective runoff (CQ_{eff}) and actual available water (W_{aa})

Once time to ponding and initial runoff are calculated at each sampling point, the corresponding maps for the whole catchment are created with the Kriging interpolation method (ordinary type with constant trend removal) that gets the minimum standard error. In the second step of the DR2 model, initial runoff is routed into the digital elevation model (*DEM*) of the catchment using the multiple flow accumulation algorithm with a coefficient of concentration of 0.9 and the potential cumulative runoff, CQ_0 (mm), is obtained. In this step the effect of the man-made linear landscape elements (*LLEs*) is added as effective players modifying the natural runoff connectivity along the hillslopes and fields. This concept is based on the index of connectivity (*IC*) presented by Borselli et al. (2008) and successfully used by these authors and by others (e.g. López-Vicente et al., 2013b; Cavalli et al., 2013) in medium-size agricultural and mountainous catchments in Italy and Spain to identify areas with net soil loss and deposition. The digital elevation model of the study area is very accurate allowing the precise spatially distributed simulation of the runoff processes. Maps of CQ_{0m} draw narrow overland flow pathways within the gullies and channels and wide pathways near the divides, in the interrill areas and in the gentle areas of the catchment.

$$CQ_{0m} = f\left(Q_{0im}, \mathrm{Acc.Algorithm}_{\mathrm{MD}}^{c=0.9}, LLEs, \mathrm{DEM}_{\mathrm{resol}}\right). \quad (7)$$

As there are many types of cumulative algorithms, and each type generates a different map with different values, a water balance correction factor (α) is added to achieve that the volume of balanced potential cumulative runoff (CQ_{0B}) equals the initial volume of available water to be accumulated along the catchment. The "α" factor allows other users of the DR2 model to choose whatever type of cumulative algorithm and improves the parameterization of the model. Then, the effective cumulative runoff ($CQ_{eff\text{-}m}$, mm) is calculated after considering the saturated hydraulic conductivity (K_{fs}, mm s^{-1}) and the average duration of a storm after the soil becomes saturated till the end of the rainfall event for each month m (Tq_m, s):

$$CQ_{0Bm} = \alpha \cdot CQ_{0m} = \frac{\sum_{i=1}^{i=k} ER_{im} - \sum_{i=1}^{i=k} Rp_{im}\, e_m}{\sum_{i=1}^{i=k} CQ_{0m}} \cdot CQ_{0m}, \tag{8}$$

$$CQ_{eff-m} = \left(CQ_{0Bm} - K_{fs}\, Tq_m\, ee_m - SS_{\max-m}\, ee_m\right) \sin S, \tag{9}$$

$$Tq_m = (TER_m - Tp_m) + Tq_{AftER} = (TER_m - Tp_m) + \left(FlL / FlV\right), \tag{10}$$

and the maximum amount of water retained on the soil surface (SS_{max-m}, mm) according to Driessen (1986):

$$SS_{\max-m} = 0.5\, RG_m \frac{\sin^2(SIG - S)}{\sin(SIG)} \frac{\cot(SIG + S) + \cot(SIG - S)}{2\cos(SIG)\cos(S)}. \tag{11}$$

and the slope steepness (S, radians). Where TER_m (s) is the total duration of an average storm event considering an average value of rainfall intensity for each month m, FlL (m) is the flow length and FlV (m/s) is the flow velocity. RG_m (mm) is the surface roughness, i.e. the maximum depth of the soil micro-relief, and SIG (radians) is the surface furrow and ridge angle determined by tillage marks and micro-topography. A SIG value of 30º is used in the study area according to the value used in the previous application of the *DR2* model. Finally, values of actual available water (W_{aa}) and soil moisture status (*SMS*) are estimated for each month following the comprehensive approach described in Fig. 2 and Eq. (1). Values of *SMS* are scaled so that they fit into seven categories (see Table 1).

2.3 Land use scenarios and simulation of the new CAP of the EU

The DR2 model has been run under four different scenarios of land uses (Fig. 3). The first one mirrors the current conditions of land uses and landscape management, whereas the other scenarios represent three different possibilities of land uses and landscape management under the imminent application of the new CAP of the EU and the trend of land use changes observed in the last decades in Spanish Mediterranean agricultural systems. European Commission plans to require farmers to set aside green areas under the next phase of the EU's agriculture support programme. Farmers who get EU support would have to set aside 7% of their land as wooded areas or habitats as part of the EU executive's draft proposals for a greener Common Agricultural Policy (CAP) that will be considered over 2013.

Nowadays, fields of winter barley cover 28.6% of the study area, whereas pastures and orchards only represent 2.2% and 0.5% of the total surface. The 28 recently abandoned fields, less than 25 years ago, appear in the hillslopes and summarizes 4.0% of the total surface of the study area. The 32 old abandoned fields, more than 50 years ago, occupy 10.5 ha (4.6% of the total surface). Cultivated fields are on average only 0.62 ha and often trails adopt irregular shapes. The current landscape linear elements have a total length of 19,800 meters and include agricultural and step agricultural terraces, buffer strips, ditches, pond walls, small settlements, scarps and screes.

In the first simulated scenario (SimSc1), crops located in steep areas are abandoned without adding any support or conservation plan, and the landscape linear elements (LLEs) associated to these fields (mainly stone-walls) are ruined. In the simulated scenario 2 (SimSc2) and the simulated scenario 3 (SimSc3) the green areas of the CAP are added as new LLEs. These elements are located in two places: i) around the lakes in those areas where the direct supply of sediments from the hillslopes to the wetlands have the highest rates, and ii) in the upper part of the fields located on the lowlands of the catchment where runoff from the gullies can trigger high values of soil loss. The 16 new LLEs protecting the lakes (P. lakes) occupy 0.98 ha and the 17 new LLEs protecting the crops (P. crops) cover 0.73 ha. The new green areas seek to reduce the siltation rates to the wetlands and to preserve the arable layer of the soil against soil erosion processes. In the SimSc2 all fields are cultivated such as it happens in the current scenario whereas in the SimSc3 we have considered the abandonment of the low productive fields located on the hillslopes like in SimSc1 but preserving the LLEs of the fields (Table 2). The land use associated with the green areas corresponds to a dense coverage of shrubs that is the most successful type of vegetation used in revegetation of banks and slopes against soil erosion under Mediterranean climate conditions (Bochet et al., 2010).

2.4 Acquisition of inputs data

The monthly rainfall depth (*R*), rainfall intensity (*I*) and number of effective rainy days (*e*), were obtained from the records of the Canelles weather station registered every 15 minutes during the period 1997-2011. Values of potential evapotranspiration (ET_0) were acquired from the records of the Barbastro weather station. Soil sorptivity (S_p) was estimated with previously calculated values of saturated water content (θ_S) and antecedent soil moisture (θ_0) in 236 measurement points in the same study area (details in López-Vicente and Navas, 2012) and those of precipitation intercepted by the canopy of the crops and natural vegetation (*A*) from the previous study of characterization of the vegetation by López-Vicente et al., 2008. López-Vicente et al. (2009b) measured the highest values of θ_0 in autumn (53.2% vol.) and the lowest in summer (32.1% vol.) showing a positive correlation with seasonal precipitation and an inverse relationship with seasonal solar radiation. Steep northern slopes presented the highest values of θ_0 in spring, summer and winter and topsoil moisture progressively decreases from steep northern slopes to gentle slopes and from gentle slopes to steep southern slopes, defining a topographical trend. Any topographical trend was observed in autumn when values of θ_0 were very high within the whole catchment. In this study we used a high spatial resolution map of soil types where 21 different units were distinguished, according to the FAO classification. In each of these units three measurements of matrix flux potential (ϕ) and saturated hydraulic conductivity (K_{fs}) were performed, and a realistic map of the infiltration processes was obtained. These maps improve significantly the accuracy of the DR2 model to estimate the monthly values of time to ponding in comparison with the previous application of the model in the same study area. In this work the roughness value, RG_m of Eq. (11), for forest areas (random roughness, RG = 20.3 mm) was taken from Renard et al. (1997). Tillage tools produce random and orientated roughness. For the tillage direction perpendicular to the contours, RG is the roughness immediately after tillage and before rainfall, and it is 32 mm for the plough, 23 mm for the heavy cultivator and 18 mm for the disk-harrow (Gilley and Finkner, 1991). For the tillage direction parallel to the contours, RG is the orientated surface roughness, which can be considered to be equal to the initial tillage depth immediately after tillage and before rainfall (250 mm for the plough, 150 mm for the heavy cultivator and 80 mm for the disk-harrow). All input values, the interpolation and mathematical operations and the output maps were done with the *ArcView© GIS 3.2* and *ArcMap™ 10.0* applications at a spatial resolution of 5 x 5 m of cell size.

3 Results and discussion

3.1 Current scenario

On a monthly basis and on average for the whole catchment, predominant wet conditions occurred during the period October–January and in a minor way in April, whereas a dry situation appeared in the soils in June, July and August. Drying-up conditions were identified in February and May and wetting-up conditions occurred in March and September (Fig. 4).

These temporal patterns were previously described by López-Vicente and Navas (2012) in the same study area and also agreed with those described by Latron and Gallart (2008) in the small Can Vila catchment (NE Spain), where climate and topographic conditions are comparable to those in the Estaña Lakes catchment. In this study, the spatial prediction of actual available water has been refined and the new maps of *SMS* draw with more detail the spatial changes of soil moisture. As it was studied by Rojas et al. (2008) in soil erosion models and by Xu et al. (2007) in a rainfall-runoff model, the spatial resolution of the input maps affects the ability of predicting models to produce accurate and realistic maps. Therefore, the enhanced maps of W_{aa} and *SMS* obtained in this study let us refine the analysis of the soil moisture variations for the different land uses and also to obtain an accurate prediction of the effect of the three simulated scenarios on *SMS* changes.

Under the current scenario (year 2013), from November to June (8 months) areas with no runoff production appear due to the low values of rainfall intensity and the spatial variability of Q_0 values is high. These conditions appear in an area of ca. 9% of the total soil surface from November to March, of 3% in April and below 1% in May and June. The spatial location of the areas with no runoff production is positively correlated with the presence of soils with high infiltration rates (e.g. above 153 mm day^{-1} for the prevalent conditions of rainfall intensity in December) and their extension decreases throughout these 8 months as rainfall intensity increases. Moreover, from October to April (7 months) relatively large areas of dry conditions, ca. 22% of the total soil surface, appear along the divides of the different sub-catchments despite the overall wet conditions (average *SMS* > 1.1) described for the whole catchment. This fact is explained by the low production of effective runoff (CQ_{eff}) during this period as a consequence of the concurrence of low rainfall intensity and relatively high infiltration rates that present an average and maximum values of 153 and 434 mm day^{-1} for the different soil types. According to Eq. (9) the infiltration rates and the number and duration of the erosive events play a critical role in the estimation of the effective cumulative runoff. Thus we consider that further research may include a detailed study of the combined effect of soil types and land uses in the runoff production at hillslope and plot scales. Similar spatial variations in runoff yields were described by Needelman et al. (2004) after analysis of runoff depth in different types of soil with different infiltration rates. When rainfall intensity (I) is high (July, August, September and October), Q_0 is predicted along the whole surface of the catchment and when high values of I are combined with high values of rainfall depth (from May to September), the variability of *SMS* is very low and produces homogeneous patterns of the soil moisture status.

The soil moisture status varies for the main land uses of the Estaña Lakes catchment and these variations also change during the twelve months of the year (Fig. 5). On average, scrublands present the wettest values (annual value of *SMS* = 1.7) although pasture has the moistest conditions in January, March and December (annual value of 1.6). Crops of winter cereal and abandoned fields have similar conditions, with average values of 1.4 and 1.3, respectively, whereas areas of bare soil (annual value of 1.2) and forest (annual value of 1.1) have the driest conditions during all the year. The Fisher's least significant difference procedure denotes that the differences are not statistically significant due to the low range of variation in the values of *SMS*. A deeper and further analysis of the *SMS* as a function of the different land uses may include the values of actual evapotranspiration instead of the currently used values of potential reference evapotranspiration that offer and homogeneous map for each month. The low values of *SMS* in the forestry soils are explained by the spatial location of the forests, mainly placed on the divides of the catchment and along the divides of the different sub-catchments, where runoff production is lower than the runoff depth generated on the hillslopes and at the bottom of the catchment. Although the lowest standard deviations of *SMS* for each land use appear from May to September, during the period from April to October, the differences between the driest and wettest mean conditions among the different land uses are the highest: forest soils are 41% drier than the scrubland soils during this period and 33% drier from November to March in comparison with the scrubland and pasture soils. The spatial variability of *SMS* obtained in this study as a function of the land use agree with other studies performed in Mediterranean areas, such as in Greece (Kargas et al., 2012) where plowed soils and land uses with high values of soil roughness store more water within the soil profile. In a comparison study of the hydrologic response between two Spanish Pyrenean catchments, one used for agriculture in the past, and the other covered by dense natural forest, Lana-Renault et al. (2011) obtained similar spatial and temporal variations of soil moisture, showing a marked seasonal pattern, with higher values of runoff in the agricultural catchment under dry conditions, and usually higher values in the forested catchment under wet conditions. We can summarize that the more water is available for the whole catchment, the less difference appears between the different land uses though the variability of the *SMS* within each land use increases.

3.2 Simulated scenarios

The abandonment of the low productive fields located in the steep slopes (1 year cultivated – 1 year fallow rotation) and the creation of new green areas significantly modifies the values and spatial patterns of the effective cumulative runoff (CQ_{eff}). On an average monthly scale, these changes can be observed in detail in Fig. 6. As can be seen in this figure, the collapse of the stone-walls in SimSc1 trigger higher connectivity between the runoff pathways that cross the abandoned fields, reducing the number of areas where runoff is blocked (Fig. 6, graphs a.2, a.3 and a.4). Under this scenario, there is an increase of 30% of the depth of available runoff that can be redistributed along the hillslope triggering the saturation of a larger area than the area saturated in the current scenario (Fig. 6, graphs a.1 and a.5). However, when the same fields are abandoned in SimSc3 and the LLEs are preserved, no significant change is observed in the spatial patterns either the runoff depth or the CQ_{eff} on the hillslope and on the set-aside fields. The conversion of small parts of the fields (0.84 ha, 1.1% of the original cultivated area) and forest (0.87 ha, 0.6% of the original forestry area) into "green areas" in SimSc2 and SimSc3 clearly modify the current spatial patterns and depth of cumulative runoff along these new LLEs. This effect is observed both in the green areas bordering the fields at the bottom of the catchment (Fig. 6, graphs b.1 and b.2) and in the green areas that surround the lakes (Fig. 6, graphs c.1 and c.2). The new spatial patterns of CQ_{eff} shown in the maps describe the existence of new areas where runoff is stopped preventing the continuity of the overland flow pathways that currently reach the wetlands. The runoff-blocking-effect of the new "green areas" will reduce the sediment yield into the lakes as there is a clear and well-known relationship between the runoff depth and the amount of suspended sediments delivered on (e.g. Onderka et al., 2012) and thus it will be of interest to preserve the wetlands of the Estaña Lakes catchment.

On a monthly average basis and in comparison with the current conditions of humidity, the soil moisture status changes 2.3% to wetter conditions in the SimSc1 for the whole catchment, whereas drier conditions are predicted in SimSc2 (1.7% drier) and SimSc3 (1.1% drier) (Fig. 7). These changes are not constant during the whole year and significant variations are observed for the different months. As can be seen in Fig. 8 between December and March the humidity status of the soil changes to significant wetter conditions in SimSc1 (3.4% wetter) and changes to drier conditions, 2.0 and 1.6%, in SimSc2 and SimSc3, respectively. However, during the summer months these changes vary notably for SimSc1 and SimSc3 and opposite conditions of humidity are found in comparison with the current scenario. From July to September, drier conditions (0.2% on average) are obtained for the whole catchment in SimSc1 and the general trend of drier conditions described for SimSc2 are only 0.5% on average drier during these three months. From May to October wetter conditions of 0.5% on average and by 0.9% in July and August are predicted for SimSc3, which disagree with the yearly average change to drier conditions. This change of trend turned out to be of benefit for the vegetation as the soil remains more humid than under the current scenario during the six months period when temperatures and evapotranspiration are higher, and thus a lower water stress of the vegetation can be expected. These variations are explained by the spatial location of the landscape linear elements along the hillslopes and by the different processes of soil saturation and runoff generation that take place during the different months with different values of rainfall depth and intensity: saturation-excess overland flow during the winter months and infiltration-excess overland flow in summer and autumn and partially in spring. From July to October the whole soil surface of the Estaña Lakes catchment becomes saturated for an average storm event (Q_0 of Eq. (5) is higher than zero) due to the high values of rainfall intensity and thus the spatial pattern of generated runoff differ from those patterns and values found during the rest of the year. In the current scenario the average runoff depth generated per raster cell, Q_0, equals 16, 23, 52 and 65 mm in July, August, September and October, respectively, with minimum values of 14, 21, 50 and 59 mm. However, the high values of ET_0 registered in summer explain the dry conditions of the soils showed in Fig. 4. The evaluation of these results against the intra-annual wet and dry periods described above for the current scenario (standard deviation of the average monthly values of *SMS* equals 1.21) suggests that the temporal changes that take place for SimSc2 (sd = 1.18) and SimSc3 (sd = 1.19) are minor. Additionally, in the SimSc3 it takes place a lower increase of the soil humidity during the wet period but also a lower decrease of the actual available water during the so-called “extended summer period”, from May to October.

On annual basis, in the set-aside fields, the soil moisture status lightly changes to wetter conditions (the average *SMS* decreases 0.1%) for SimSc1 and clearly changes to wetter conditions (the average *SMS* decreases 9.5%) for SimSc3. The latest increase of humidity is directly related to the higher values of soil roughness, *RG* in Eq. (11), of the coverage of dense scrubland (*RG* = 20.3 mm) than the value of *RG* ascribed to the cultivated areas (average *RG* = 17.8 mm). The first value agrees with the overall trend observed for the whole catchment, whereas the value estimated for SimSc3 differs with the general trend observed for the rest of the catchment and clearly supports the human-induced reforestation of the set-aside fields as a clear increase of water storage is predicted. On the other hand, the set of green areas protecting the fields located on the lowlands satisfactorily reduce the depth of water that might cross through the new *LLEs* and reach the crops and thus a decrease in the intensity of soil erosion could be expected. However, the clear decrease of 38% of the humidity status predicted in the first row of pixels downwards the new green areas compromises the growth and maintenance of the rain-fed crops. In order to supply fresh water to the field and thus to compensate for the water deficit, we consider that runoff harvesting practices could be applied in the new green areas protecting the crops. This technique has been successfully used in other Mediterranean areas to address the scarcity of surface water, such as in Israel for crop irrigation (Tal, 2006) and in California as a part of the water balance system of highly anthropized areas (Strecker and Poresky, 2010). The green areas located around the three wetlands of the study site show a decrease of 11.5% in the soil moisture status as a consequence of the "runoff-blocking-effect" of these new LLEs. As the water table is near the soil surface around the lakes, we do not expect water stress in the reed grass bordering the lakes and thus the protecting effect of the new LLEs in the lakes would not compromise the development of the natural vegetation.

4 Conclusions

Under the current conditions, runoff yield is scarce and presents a high spatial variability when monthly rainfall intensity and depth are low, and infiltration processes lead to storage of water in the soil. However, when rainfall intensity and/or depth is high, runoff accumulation processes control the depth of water available in the soil, and the soil moisture status is more homogeneous across the catchment. As the DR2 model calculates the *SMS* for each month without considering the humidity status of the soil during the previous month or months, some errors can happen and thus in further research a "memory factor" should be added to the model of at least one month prior to refine the estimation of the classes of humidity.

As the application of the new CAP of the European Commission will be mandatory since January 2014, and if the abandonment of the low productive fields would happen in few years, we conclude that the SimSc3 summarizes the most-probably scenario of land uses and management practices that might occur in the Estaña Lakes catchment. Although a low decrease in the soil moisture status is predicted for the whole catchment in this scenario, a clear increase of the humidity status of the soil is predicted for the set-aside fields revegetated with a dense coverage of shrubs. In addition, the new green areas would create a runoff-blocking-effect that will protect the fields located on the lowlands against the processes of soil loss by water and will reduce the sediment yield to the wetlands. Therefore, the application of the new CAP will be of interest to preserve the Estaña Lakes. As the new landscape linear elements will reduce the runoff depth that reach the fields and thus the *SMS* would decrease in a small section of the crops, we propose for future research the study and application of runoff harvesting techniques along hillslopes in order to supply additional fresh water to the crops. In order to spread the use of the DR2 model we are currently developing a module for the open-source and free *SAGA* GIS software that is called *DR2-2013*© *SAGA v1.0*. This module is built using C++ code and contains all scientific methods and equations, and is presented in a user-friendly interface that will be of interest for the scientific and academic community as well as for the European Authorities. The new module will offer 15 different options to model runoff accumulation by using 8 different flow accumulation algorithms and will be available in the web site of our research center (www.eead.csic.es) and also in the repository of the Spanish Council for Scientific Research (https://digital.csic.es/) in autumn 2013.

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Figure 1 Geographic situation of the Estaña catchment in NE Spain (a); map of soil types (b); picture of the study area showing the "*Estanque de Arriba*" lake and the crops located in the hillside and the lowlands of the catchment (c); monthly average (period 1997-2011) values of maximum rainfall intensity (I_{30}) and number of erosive rainfall events (d); annual values of precipitation recorded at the Canelles weather station for the period 1941-2011 (e); and monthly average (period 1997-2011) rainfall (Canelles weather station), potential reference evapotranspiration and minimum and maximum temperature (Barbastro weather station) (f).

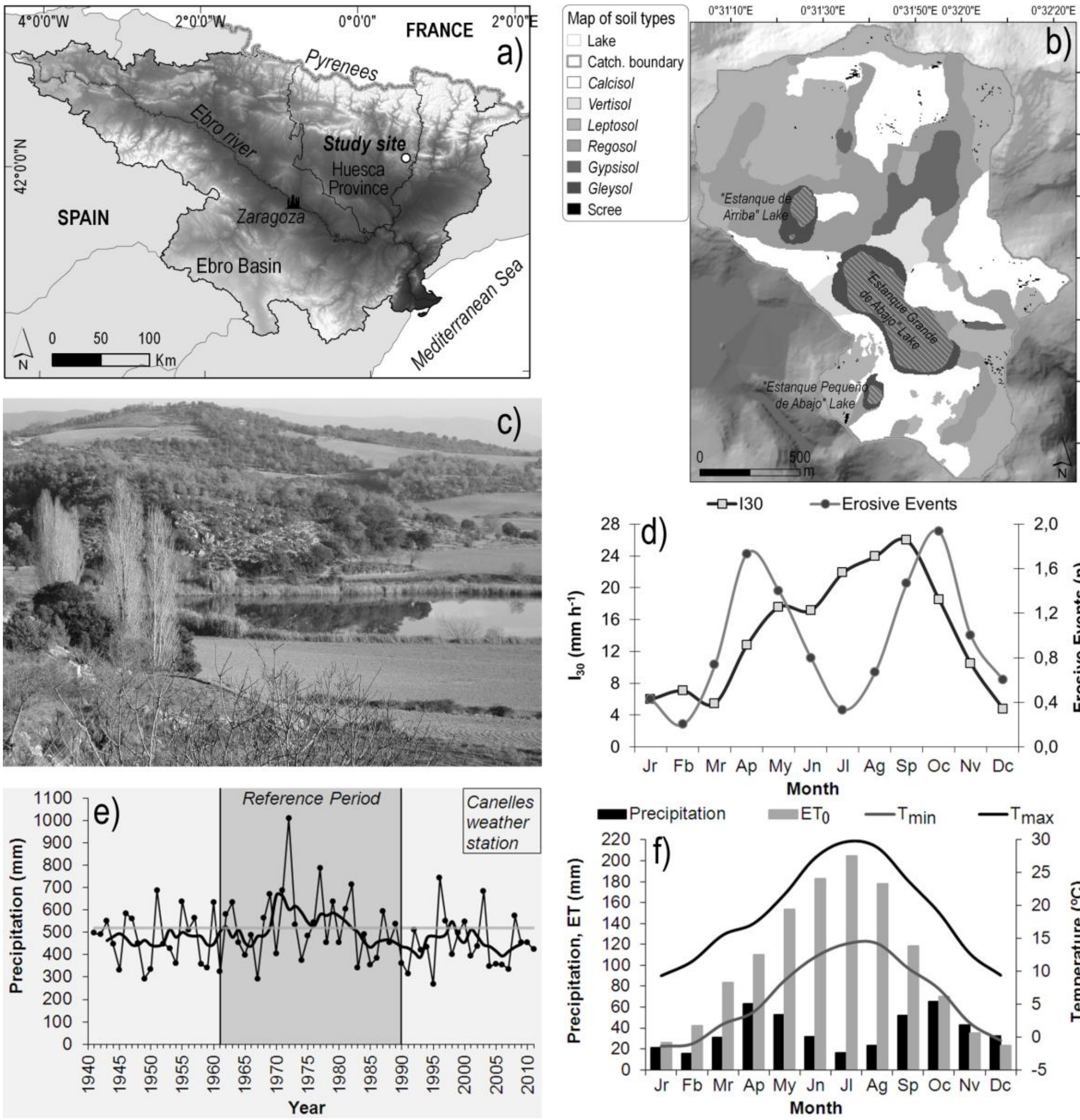
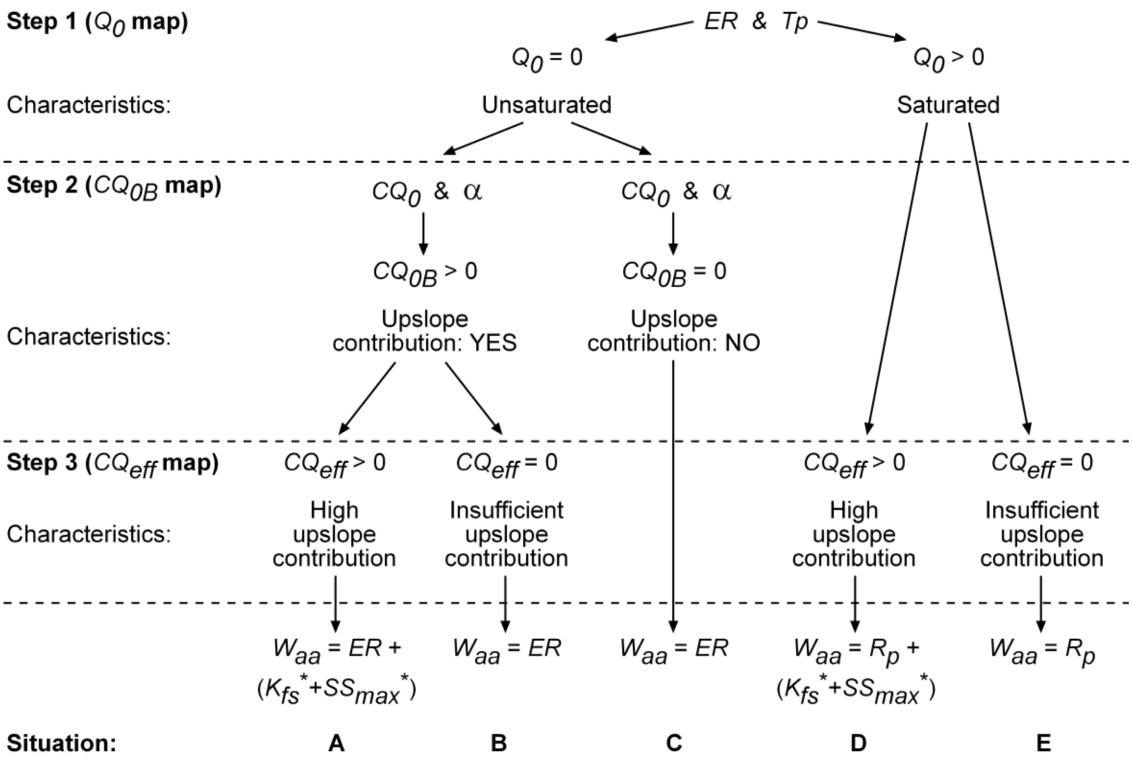


Figure 2 Step-by-step procedures to estimate the actual available water (W_{aa}) at pixel scale (for more details, see López-Vicente and Navas, 2012 and López-Vicente et al., 2013).



ER: Effective rainfall; *Tp*: Time to ponding; Q_0: potential runoff per raster cell; CQ_0: potential cumulative runoff; α: water balance factor; CQ_{0B}: balanced potential cumulative runoff; CQ_{eff}: effective cumulative runoff; K_{fs}^*: saturated hydraulic conductivity ($K_{fs}\ Tq_m\ e_m$, see Eq. (9)); SS_{max}^*: maximum surface storage capacity ($SS_{max\text{-}m}\ e_m$, see Eq. (9)); R_p: rainfall to ponding.

Figure 3 Maps of the different land use scenarios simulated in this study (see Material and Methods section for more details).

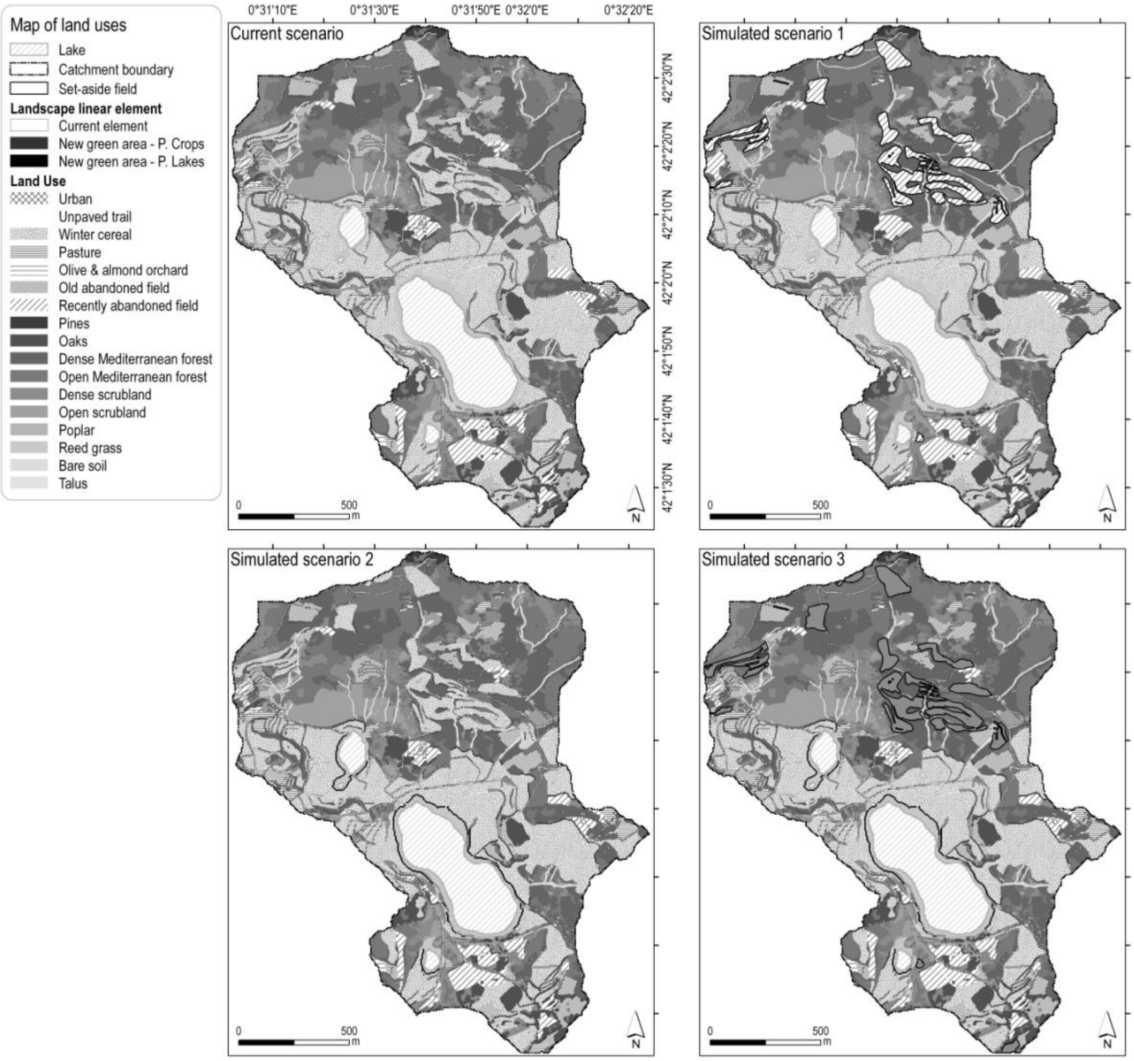


Figure 4 Monthly maps of Soil Moisture Status in the Estaña catchment calculated for the current scenario of land uses.

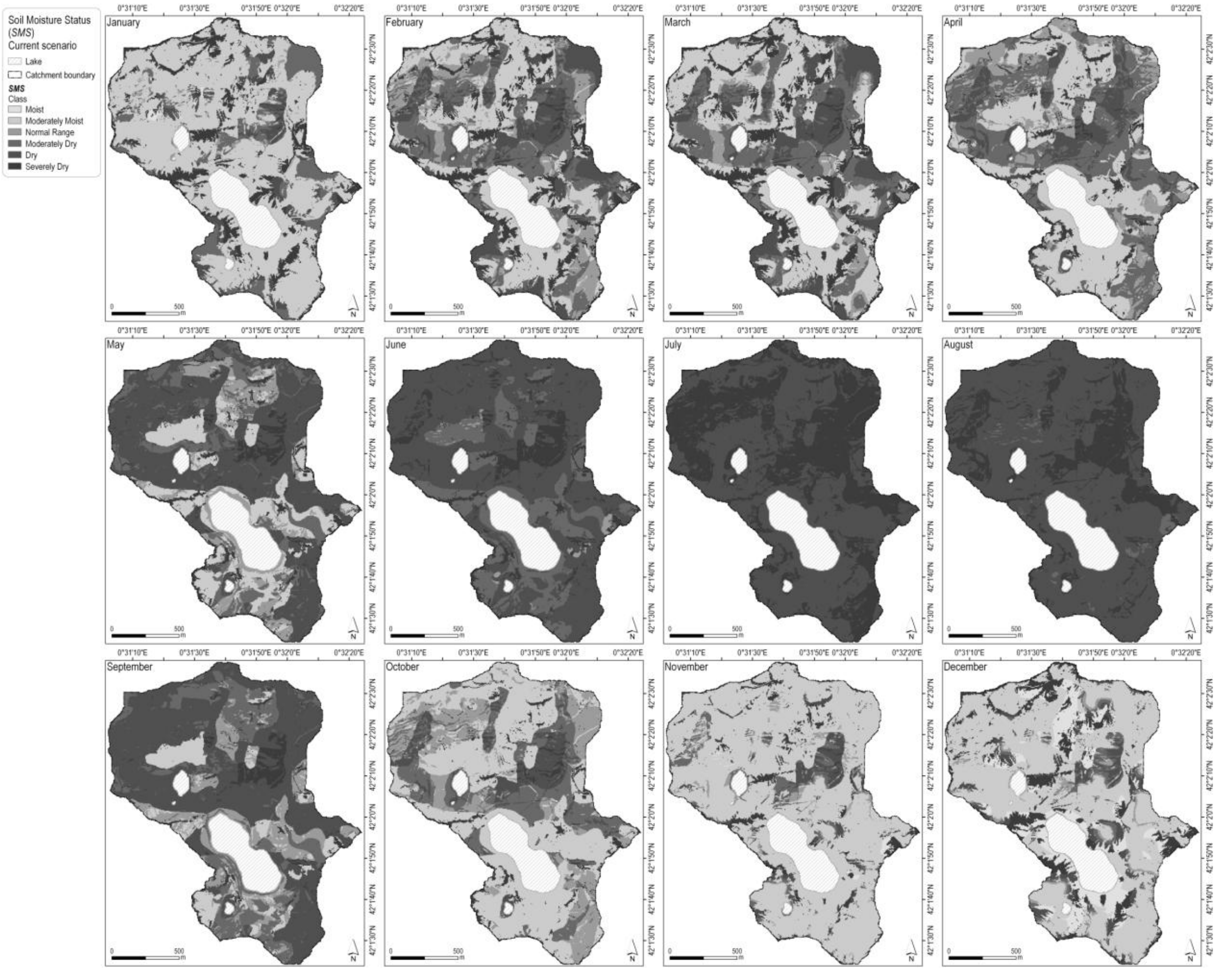


Figure 5 Monthly values of Soil Moisture Status in the Estaña Lakes Catchment calculated for the main land uses under the current scenario.

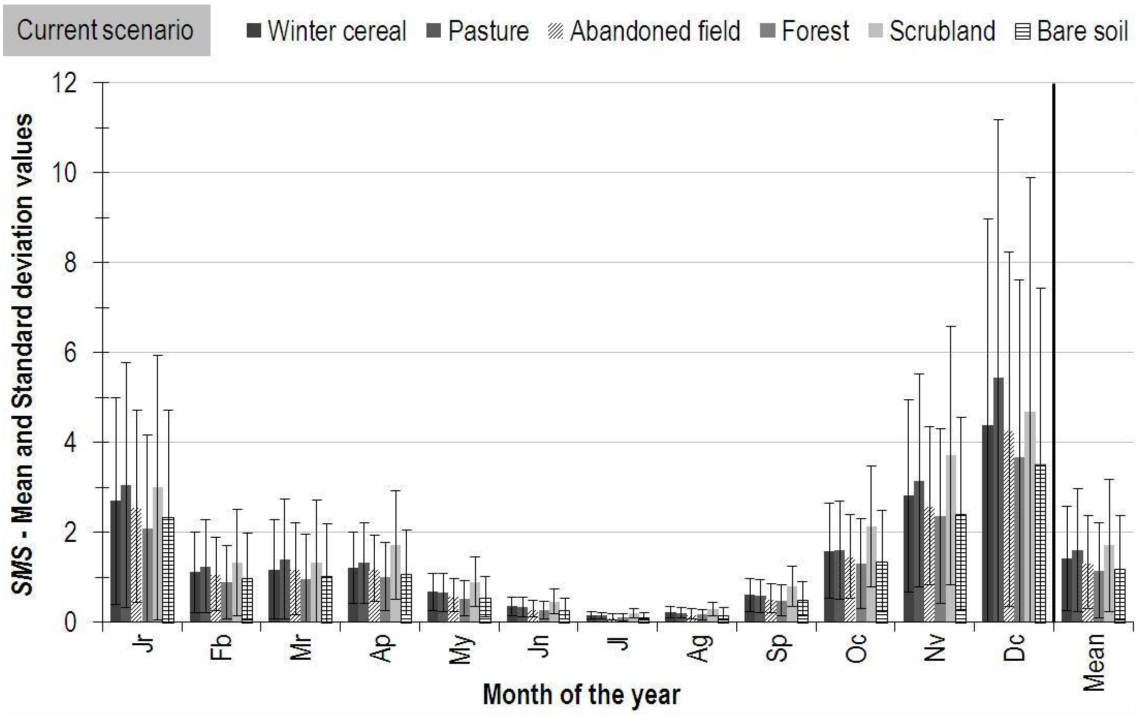
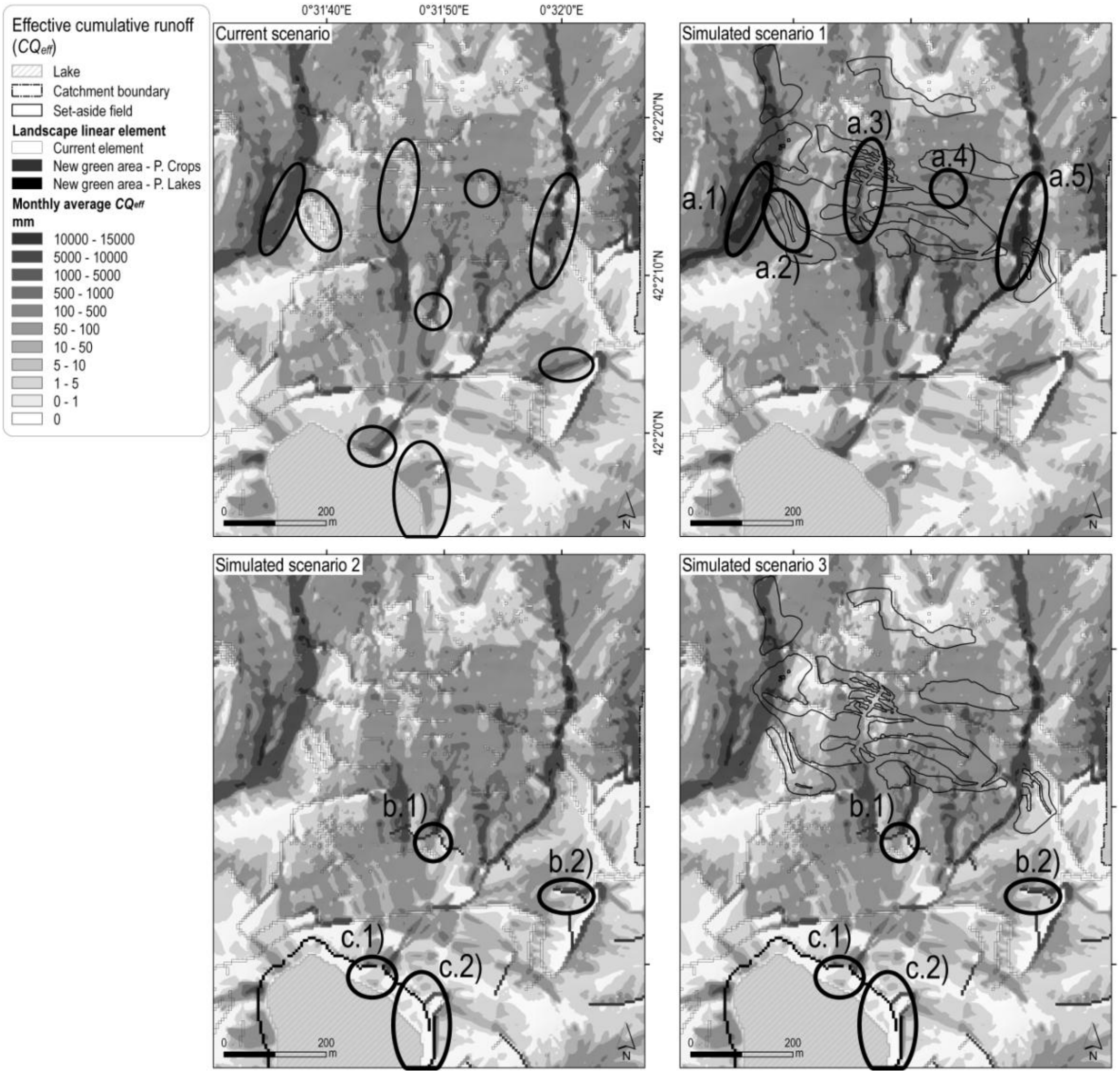
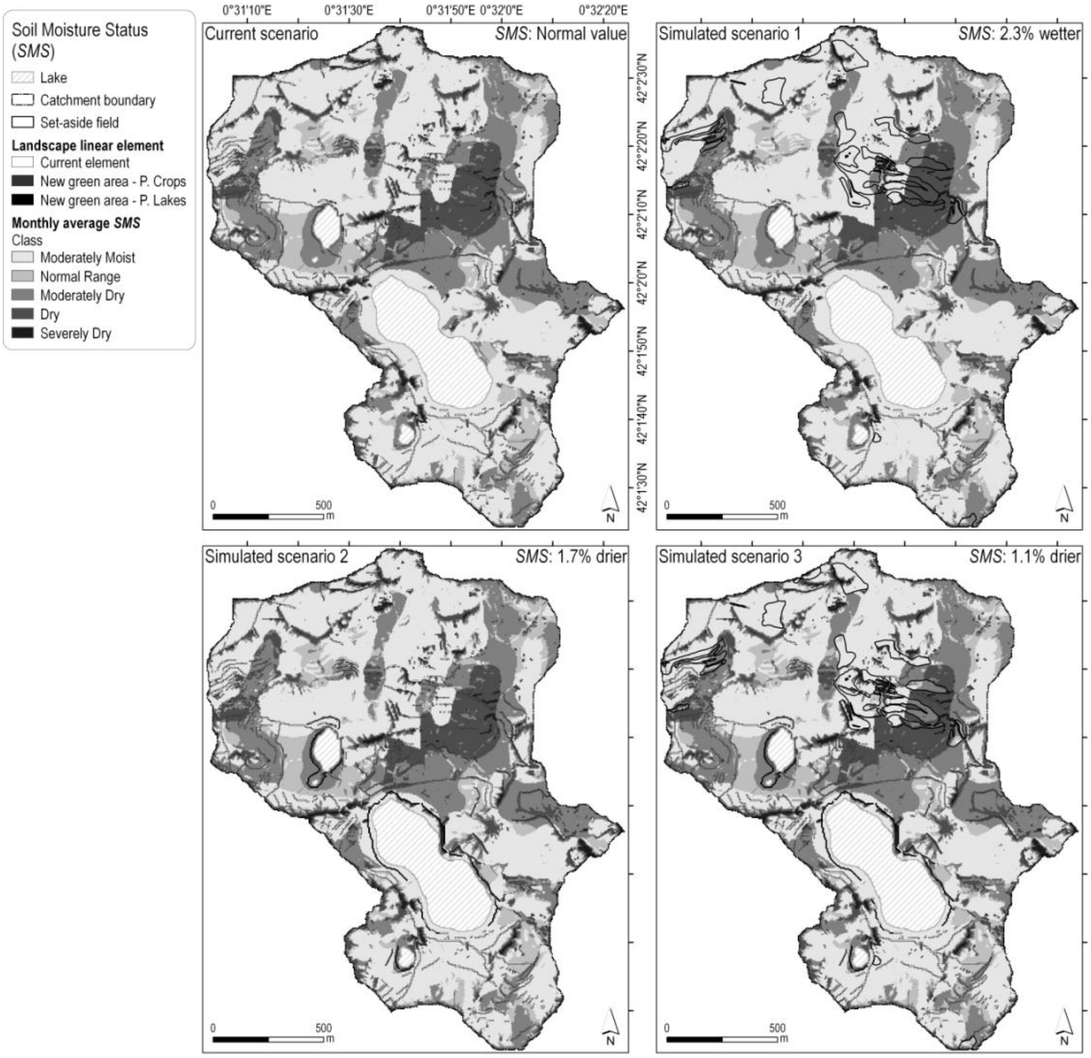


Figure 6 Detailed maps of the effective cumulative runoff in the area surrounding the main overland flow path line generated in the four scenarios simulated in this study and in the area surrounding the northern part of the "*Estanque Grande de Abajo*" Lake.



Legend: P. Crops: "green area" protecting the crops; P. Lakes: "green area" protecting the lakes.

Figure 7 Maps of average monthly Soil Moisture Status (*SMS*) for the current scenario and the three simulated land use scenarios in the Estaña Lakes catchment.



Legend: P. Crops: "green area" protecting the crops; P. Lakes: "green area" protecting the lakes.

Figure 8 Percentage of variation of the monthly average values of Soil Moisture Status (*SMS*) in the Estaña Lake's Catchment for the three simulated scenarios in relation to the current scenario.

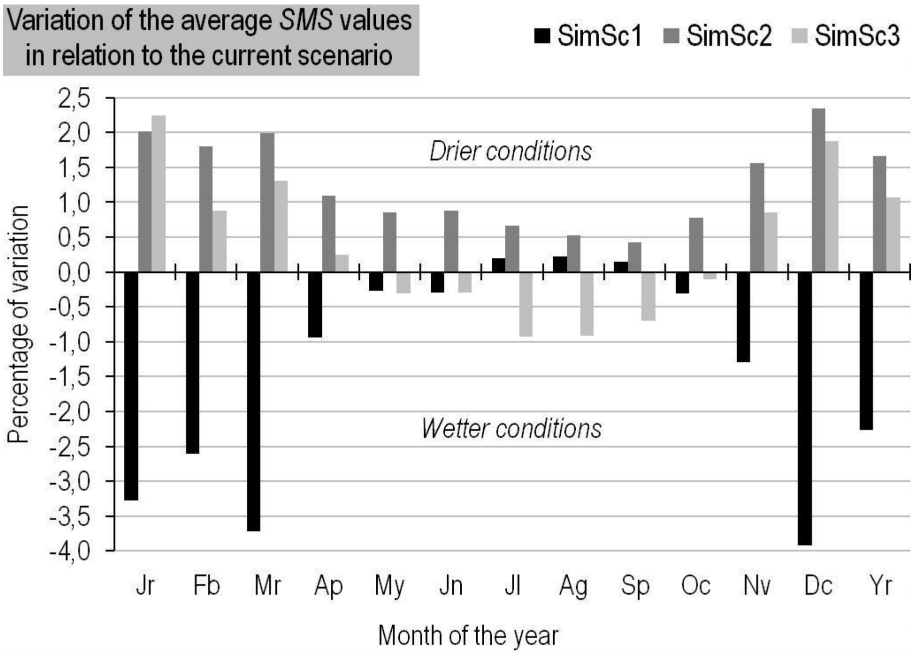


Table 1 Classes for wet and dry conditions for the soil moisture status (*SMS*) of the DR2 model.

SMS value	Wetness-Drought index categories
≥ 100	Severely moist
10 to 100	Moist
1.1 to 10	Moderately moist
0.9 to 1.1	Normal range
0.5 to 0.9	Moderately dry
0.1 to 0.5	Dry
0 to 0.1	Severely dry

Table 2 Landscape characteristics of the current and simulated scenarios in the Estaña Lake's Catchment. The "Simulated scenario 1" represents the worse-case-scenario and the "Simulated scenario 2" and "Simulated scenario 3" includes the creation of "green areas" in accordance with the new Common Agricultural Policy of the European Union (draft of the proposal presented in Brussels in October 2011; http://ec.europa.eu/agriculture/cap-post-2013/legal-proposals/index_en.htm).

Landscape characteristics	Current scenario	Simulated scenario 1	Simulated scenario 2	Simulated scenario 3
New set-aside fields	No	Yes	No	Yes
Landscape linear elements associated with the set-aside fields	No change	Dismantled	No change	Preserved
SUPPORT PRACTICES				
- Revegetation of the set-aside fields with shrubs	No	No	No	Yes
- New "green areas" protecting the fields located in gentle areas	No	No	Yes	Yes
- New "green areas" protecting the lakes	No	No	Yes	Yes