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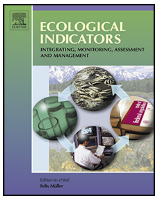

Natural vegetation covers as indicators of the soil water content in a semiarid mountainous watershed

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ABSTRACT

This paper investigates the use of the vegetative state of natural covers as an indicator of soil moisture conditions at the end of the dry season in order to evaluate the cumulative effect of the hydrological regime. To achieve this, the three major vegetation covers in a mountainous semiarid environment in southern Spain were selected. Temporal and spatial trends of NDVI from Landsat-TM images were computed and related to the different hydrological patterns of variables in the study site, which were obtained with the hydrological WiMMed model. The heterogeneity in the hydrological behavior during the study period (914.5 mm of annual rainfall in the wettest year (2009–2010) and 284.4 mm in the driest year (2004–2005)) was reflected in the annual differences in NDVI values with steady mean NDVI values in coniferous vegetation (0.5–0.6) and more variable values in scrub cover. Both Correlation Analysis and Principal Component Analysis showed correlations among the different states of the vegetation cover, the variables involved in the soil water balance and those related to the snow dynamics of the antecedent year. Exponential fits were obtained between the mean annual soil water content and NDVI values with Pearson r^2 coefficients of over 0.7 in scrub cover. In certain years, the best fits were also found in scrub cover with r^2 values of up to 0.9. These results demonstrate the relationship between soil water content, the vigor of the natural vegetation and the hydrological characteristics of the antecedent year. The expressions obtained may serve to adjust the soil water content at the beginning of a hydrological year and to use the scrub cover as an indicator of the soil water balance in the area for a given year.

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1. Introduction

Distributed hydrological models at the watershed scale require the calibration of the parameters involved in the computation of hydrological processes (Refsgaard, 1997). The number of parameters depends on the complexity of the model in terms of the spatial and temporal discretization applied by the model to solve the hydrological cycle. The calibration process is always carried out with water flow data registered at certain control stations in the watershed (Chaponnière et al., 2008; Moussa et al., 2007). However, other intermediate variables calculated by the models (e.g. infiltration, soil moisture, runoff, etc.) could be used in the calibration process, especially under situations with scarce water flow data. This is crucial in semiarid areas where the absence of hydrological response at the outlet of the watershed, for most of the time, makes it impossible to evaluate the internal status of the watershed (Maneta et al., 2008). However, a combination of both the technical difficulties in measuring intermediate variables at the watershed scale on a regular basis and financial issues mean that hydrographs are more commonly used instead.

Soil moisture constitutes the main state variable in the soil vadose zone, since it determines the partition of rainfall into infiltration and runoff in a storm event, and the loss of moisture between storm events. In Mediterranean areas, runoff events are often caused by high-intensity storms of a short duration (Moussa et al., 2007) and reduced to a limited number of runoff events per year. They are largely determined by antecedent soil moisture conditions (Castillo et al., 2003) and thus, their calibration in continuous hydrological modeling constitutes a major problem in semiarid areas.

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Even though soil surface moisture estimates can be derived from certain remote sensing data, the availability of data at the required spatial and temporal scales is often the main constraint (Brocca et al., 2010). Thus, the use of derived variables which are easy to measure from commonly available data sources, and at the same time closely related to soil moisture (e.g. rainfall, vegetation vigor, temperature, etc.), could aid the calibration of the different processes of the hydrological cycle. This could also allow us to assess the performance of hydrological models accurately simulating intermediate processes, as already suggested by some authors (Chaponnière et al., 2008; Wooldridge et al., 2003).

Meteorological variables such as rainfall and temperature are obviously closely related to soil moisture, since they are the most relevant forcing agents in the hydrological cycle. In addition, these variables are usually available in many areas with convenient spatial and temporal resolutions. Another relevant variable which is often measured is solar radiation, which in semi-arid areas, is the driving force behind soil drying processes because of the characteristics of these climates with mild temperatures and long and dry summers. Here, high radiation values exert a significant acceleration of the evaporation processes (Aguilar et al., 2010).

At a larger temporal scale, another soil moisture-related variable is the state of the woodland cover. In Mediterranean ecosystems, the water balance is the most important factor in the woodland vegetative state (Martínez-Vilalta et al., 2002). Canopy water stress at the end of the dry season can be assumed to reflect the hydrological conditions of the antecedent hydrological year. Besides, the use of variables related to canopy water stress as indicators of soil moisture content has the advantage of describing a larger soil depth, that of the root zone, unlike direct measurements through remote sensing techniques whose data are only representative of the first few centimeters of the soil profile (Ellis et al., 2009). The Normalized Difference Vegetation Index (NDVI) is often used to evaluate vegetation vigor as well as temporal changes in the vegetation cover (Aguilar et al., 2012). NDVI is based on differences in reflectance in the red region of the spectrum (due to pigment absorption) and maximum reflectance in the near infrared (caused by cell structure). NDVI has proven to be extremely useful in assessing vegetation phenology, and estimating net primary production in a variety of land cover situations over large areas (Adegoke and Carleton, 2002). NDVI saturates easily and is not considered to be a good estimator of high leaf area index (LAI) (Asner et al., 2000; Brantley et al., 2011); however, NDVI still retains ecological relevance as an indicator of green biomass change (Wang et al., 2003). NDVI can be a useful tool for combining climate, vegetation distribution and performance at large spatial and temporal scales (Pettorelli et al., 2005). Since vegetation vigor and productivity are related to hydrological variables (rainfall, evapotranspiration, etc.), NDVI serves as a surrogate measurement of these factors at the landscape scale (Groeneveld and Baugh, 2007; Wang et al., 2003). The use of remote sensing for deriving NDVI and relationships with hydrological variables can allow for rapid, large-scale estimation of the soil water content when no other sources of soil moisture data are available.

The objective of this paper is to assess the relevance of the state of the natural vegetation covers as an indicator of soil moisture conditions at the end of the dry season. For this, the three major vegetation covers in a mountainous semiarid environment in southern Spain were selected. The temporal and spatial trends of their NDVI were calculated and related to the different hydrological variables patterns in the study site. The analysis was performed at the end of the hydrological year in order to evaluate the cumulative effect of the hydrological regime.

2. Methodology

2.1. Study site and data sources

The study area is located in the Guadalfeo river watershed (Andalusia, Spain) (Fig. 1). It has an area of 1300 km^2, with an approximate length of 50 km from East to West and 44 km North–South. The region is characterized by the strong contrasts in the physical environment (climate, hydrology, etc.) due to the severe altitudinal gradient, falling from 3482 m in height to sea level over a distance of only 40 km. Therefore, the climate is the combination of both semiarid Mediterranean (South area of the watershed) and alpine (summits and North area). The hydrological behavior of the watershed is determined by the occurrence of episodic flood events in response to particular rainfall events (storms or local convective storms) and several snowmelt events during the year.

The classification of the different types of land covers was obtained from a study previously performed in the area by Polo et al. (2011), who applied a supervised multispectral classification method (Jensen, 2005) on the superposition of the five scenes in the area. Training sub-areas were selected from aerial photographs and field data, by the identification of homogeneous surfaces representative of each class. A comparison between the multispectral information and that obtained from the training sub-areas was made and later validated by stochastic sampling of each class. Thus, 11 types of classes of interest were indentified, four of which belonged to natural vegetation: conifers (*Pinus sylvestris*, *Pinus nigra*, *Pinus halepensis* and *Pinus pinaster*), scrub (great variety of species, highlighting *Retama sphaerocarpa, Pistacia lentiscus, Ulex spp* and *Cystus ladanifer*), Holm oak (*Quercus ilex*) with undergrowth of scrub, and pasture (seasonally high mountain pastures). Following this classification, the three types of natural cover most representative in terms of the area covered in the watershed were analyzed in this study: coniferous (7.04%), scrub (26.12%) and Holm oak with undergrowth of scrub (2.82%) (Fig. 1). Note that the fourth natural cover present in the area, pasture (15.82%), was excluded from the study due to its seasonal nature and lack of vigor during the summer period.

Topographic data were obtained from a digital elevation model (DEM) with a horizontal resolution of $10 \times 10\,\text{m}^2$ and a vertical accuracy of 1 m. This DEM spatial resolution of 10 m was re-sampled to 30 m to fit with the resolution of the satellite images used in the characterization of the vegetation cover. Furthermore, due to the wide extent of the study area, a cell size of 30 m was assumed to be an ideal balance between the runtime of the tools applied and the level of detail required for the study (Egüen et al., 2012). Thus, the DEM was re-sampled using the average of the values of the three nearest cells in the original raster.

Soil distributed data of surface and subsurface saturated hydraulic conductivity, soil thickness, matrix potential (wet and dry), residual and saturation soil moisture, the value of Van Genuchten's *n* and surface and subsurface roughness for the flow speed were obtained from the raster maps available for the study area with a spatial resolution of 250 m (Rodriguez-Alvarez, 2009). Once again, re-sampling was applied and 30 m cell-size raster maps of the following soil properties were derived: hydraulic conductivity (mm h^{-1}), saturation and residual moisture values (mm mm^{-1}) and soil thickness (mm).

Finally, meteorological data were collected from different weather networks available in the area. Hourly and daily rainfall (mm), temperature (°C), solar radiation (MJ m^{-2}), vapor pressure (kPa) and mean daily wind speed (m s^{-1}) data from the Spanish Meteorology Agency (AEMET), the Agroclimatic Information Network (RIA) and the Automatic Weather Station and Remote Network (EARM) were used in this study. The choice of the stations was

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