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Land use sediment production response under different climatic conditions in an alpine–prealpine catchment

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ABSTRACT

Loss of soil and subsequent export of sediments to streamflows by water erosion constitute significant environmental threats because of the areal extent typically involved and the agricultural activities that they support. Climate change is expected to impact on the availability of water and therefore on soil resources. In this context, hydrological and soil erosion models allow for the mapping and quantifying of soil redistribution and sediment productions for different land uses and climatic scenarios that can be used for valuable projections for catchment management. A simulation experiment was achieved by using the Soil and Water Assessment Tool (SWAT) model in the mountainous catchment of the Barasona reservoir (1509 km^2, Central Spanish Pyrenees), which is characterized by a heterogeneous climate and topography, that brings it a varied mosaic of soil types and land uses. In order to investigate differences in sediment productions from the land uses under different climatic conditions the sediment produced from the land uses was assessed for two years. 2003 and 2005 were selected to represent contrasted precipitations and wet and dry conditions, respectively. Moreover, the distribution of land uses and climate in the catchment enabled the division of the catchment into two parts which allowed the assessment of the sediment productions in the northern alpine and the southern Mediterranean parts of the catchment. The specific sediment yield varied largely in relation with precipitation, seasons, land use types and catchment parts, from 0 to 243 t ha^{-1} year^{-1}. Furthermore, according to the prediction of the IPCC and climatic studies for the region an increase of 2 °C was simulated to assess the impact on sediment yield. Different responses to the temperature increment were observed between wetter (2003 and northern part) and drier (2005 and southern part) conditions and also for the land use types. Great decreases in sediment production were observed for the 2 °C increase scenario in wetter conditions, whereas low decreases with some increments occurred in the drier conditions. The proposed model proved useful for the assessment of the behaviour in sediment production from the land uses under different climatic conditions in large alpine–prealpine catchments at a regional level.

1. Introduction

The loss of productive soil by water erosion does not only reduce soil quality, but also has important effects on the soil functions such as decreasing their net primary productivity of the agricultural lands and the natural ecosystems (Pimentel, 2006; Stavi and Lal, 2011). Estimates indicate that one-sixth of the global land area is affected by water erosion (Schröter et al., 2005), constituting an important economic, social and environmental problems. In temperate climate mountain areas water induced hillslope erosion is one of the more common forms of erosion (Navas et al., 2005). However, surface runoff, soil detachment and sediment delivery are non-linear processes that depend on many soil, climatic, topographic, vegetation and land use parameters and, furthermore, their effects change when considering different temporal and spatial scales (Cerdà et al., 2013). To develop environmental and land use management plans, policy makers require quantification of erosion rates at regional and global scales, identification of sediment sources and estimates of the relative contribution from the different land uses. Thus, these measurements allow erosion prevention efforts to be concentrated in places that will benefit most (de Vente et al., 2008; Ramos and Martínez-Casasnovas, 2014).

Changes in precipitation, temperature, and vegetation cover alter the water balance and the partitioning of precipitation between evapotranspiration, surface runoff, and groundwater flow (Foley et al., 2005). Variations in a precipitation regime directly affect the quantity of water that reaches the soil, the runoff generation mechanisms, and the magnitude of river discharge. More scattered and intense rainstorms could potentially cause changes in the vegetation cover (Kundzewicz et al., 2007; Nunes and Nearing, 2011). The rise in temperature, together with changes in other parameters (solar radiation, wind speed, and humidity), could decrease the quantity of precipitation falling as snow,

Abbreviations: SWAT, Soil and Water Assessment Tool; HRUs, Hydrological Response Units; TLAPS, temperature lapse rate in SWAT; PLAPS, precipitation lapse rate in SWAT; SSY_{LU}, specific sediment yield from the land uses; 2°S, scenario with the temperature increase; OS, scenario with the observed data; PD, percentage difference.

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accelerating the melting process and consequently reducing the snow duration. It could also increase the transpiration processes in plants as well as evaporation from the soil and water bodies (García-Ruiz et al., 2011). All these changes result in water balance disturbances that may alter both the quantity of water in the soils and its temporal distribution, which are highly related to the land uses existing in the contributing areas thus affecting soil erosion and the supply of sediments. Therefore, global climate change has the potential to modify sediment productions and soil erosion depending on the possible changes in climate and the physiographic (e.g. vegetation cover, soil, geology, hydrology and geomorphology) characteristics of the region.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGI AR5 2013) summarized that the total increase between the average global surface temperature of the 1850–1900 period and the 2003–2012 period was 0.78 (0.72 to 0.85) °C, based on the single longest dataset available. For most of the simulated climatic change scenarios, the global surface temperature change for the end of the 21st century is likely to exceed 1.5 °C in relation to the 1850–1900 period. In the Central Spanish Pyrenees, the scenarios generated by several climate studies point to a clear increase trend in temperature of about 1.5–3 °C but the precipitation trend is not clear (e.g. López-Moreno et al., 2008; Ribalaygua et al., 2013).

Due to a variety of land covers, climatic heterogeneity and altitudinal gradients, a great diversity of processes relating to soil erosion and sediment yield occur in the Central Spanish Pyrenees. Furthermore, human activity during the last 4000 years has contributed to the disturbance of the original landscape by changing land uses and therefore its hydro-morphological dynamics (Navas et al., 1997; García-Ruiz and Valero-Garcés, 1998; Navas et al., 2008). In addition, many rivers on the Spanish side of the Pyrenees have been dammed in the last century to provide water for the Mediterranean lowland areas (e.g. Yesa and Barasona reservoirs). Hydrologic characteristics of the Spanish Pyrenean and changes in land use over the last few decades have changed the supply of sediment loads (Navas et al., 2011; Morellón et al., 2011), triggering soil erosion and, consequently, the derived off-site environmental problems such as the siltation of reservoirs (Valero-Garcés et al., 1999; Navas et al., 2009).

The Pyrenees are a very sensitive area in terms of impacts of climate change on hydrological dynamics and related processes, as water erosion. Hence, information on processes related to soil erosion and sediment export in mountainous catchments are essential to support the implementation of management practises to preserve soils, to promote rational uses of the land and to prevent erosion (Molino et al., 2007). Catchment models offered an effective way of studying land–surface dynamics in mountain environments and obtaining information on water-induced erosion processes linked to hydrological systems. Moreover, catchment models, like SWAT, make it possible to evaluate the impacts of natural or management induced environmental changes in a way that cannot be done through field experiments and direct observation and as such, constitute as chief tools in developing environmental management plans at a regional scale (e.g. Dessu and Melesse, 2012, 2013). Therefore, it could serve as a decision-making tool for performing risk analysis in the implementation of measures to prevent the on-site and off-site effects of soil erosion, and to assess the possible impacts resulting from land use or climate changes.

The SWAT model has been extensively applied throughout the world (e.g. Zhang et al., 2008; Luo et al., 2012; Dessu et al., 2014) to deal with a wide range of scales and issues (Gassman et al., 2007). Although SWAT was primarily built for plain agricultural areas, it has been widely implemented to perform hydrological simulations to estimate streamflow timing and volumes and sediment yield from mountainous catchments worldwide (e.g. Rostamian et al., 2008; Flynn and Van Liew, 2011; Morán-Tejeda et al., 2015). However, there are not as many studies assessing the sediment production from different land uses under different climatic scenarios (e.g. Nunes et al., 2008) and none are in the alpine–prealpine catchments in the Pyrenean region.

A previous satisfactory application (calibration and validation) of SWAT for hydrology and sediment supplies to the Barasona reservoir (Palazón and Navas, 2014) proved to be useful for identifying area where significant erosion processes take place in large alpine–prealpine catchments and also for assessing the sediment yields which reach the reservoir. Results from that application encouraged the exploration of the model's performance on sediment yields from the different land uses existing in the catchment for different precipitations, seasons and areas. In this research, two different years with contrasted precipitation amounts (2003 and 2005) were selected to obtain information related to different sediment productions from the land use. Moreover, an increase of 2 °C was simulated with SWAT to assess how this change of temperature could affect soil erosion and sediment production under different land uses. It was considered that modelling a large mountain catchment such as the Barasona catchment under different climatic scenarios/conditions would be of interest to assess the sediment production and changes in relation to the land uses.

2. Material and methods

2.1. Study area

The Barasona reservoir research catchment (1509 km^2) is located in the central part of the Spanish Pyrenees, in the basin of the upper Cinca River, the second largest tributary of the Ebro River (Fig. 1a). The Barasona reservoir was built in 1932 for irrigation purposes and power generation. It also supplies water to the Aragón and Cataluña canal, which provides irrigation to more than 100,000 ha. Over the past 65 years there has been a considerable loss of storage capacity in the reservoir and siltation management problems (e.g. Navas et al., 1998, 2004; Valero-Garcés et al., 1999).

The climate is defined as mountain type, wet and cold with both Atlantic and Mediterranean influences. Temperature and precipitation gradients are observed for both north–south and west–east regions according to the relief, along with the influences of the Atlantic Ocean and Mediterranean Sea. The average annual precipitation and temperature range from more than 2000 mm and 4 °C in the headwaters, to less than 500 mm and 12 °C at the Barasona reservoir.

The hydrologic regime of the study area is transitional nival–pluvial characterized by two maxima; the spring period (April–June), due to snowmelt and the late autumn (October–November) due to precipitation (García-Ruiz et al., 2001). Snow covers the catchment above 1700 m a.s.l. from mid November to May. High slopes and the presence of deep and narrow gorges favour rapid runoff and large floods. The catchment is drained by the Ésera River and its main tributary, the Isábena River. Part of the Ésera headwater (28.9 km^2) was discounted as an effective drainage area because it drains through a subterranean route through the Jueu Karst System to the Garona River, on the Atlantic northern side of the Pyrenees. This represents an average discharge loss of about 3 $m^3\ s^{-1}$ from the Ésera River (López-Moreno et al., 2002). Small headwater reservoirs (such as the Linsoles and Paso Nuevo reservoirs which are both of 3 hm^3), canals and dams for hydropower purposes regulate the Ésera River, whereas the Isábena River is non-regulated.

The area is characterized by heterogeneous relief, vegetation and soils. The catchment altitudes comprise from 424 m a.s.l. at the catchment outlet (Barasona reservoir) to 3404 m a.s.l. (Aneto Peak) in the northern headwater of the catchment. The distribution of the altitudes and slope ranges decreases in value from the north to the south of the catchment.

In general, the soils are stony and alkaline, overlying fractured bedrock with textures from loam to sandy loam. Soils are mostly shallow (< 0.6 m) and well drained with limited average water content and moderate to low structural stability. The predominant soil types (FAO, 2007; based on the Soil Map of Aragón, Machín, unpublished data, 2000) are Kastanozems (33%) with substantial accumulations of organic matter and other poorly developed mineral soils with low organic