Journal of Hydrology (2008) **356**, 245–260

available at www.sciencedirect.com

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journal homepage: www.elsevier.com/locate/jhydrol

Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees

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Received 8 October 2007; received in revised form 3 April 2008; accepted 13 April 2008

KEYWORDS
Mountainous mediterranean catchments;
Runoff generation;
Soil erosion;
Sediment transport;
Land-use changes;
Spanish Pyrenees

Summary Three small catchments (<2.5 km^2 in size) were monitored in the Central Spanish Pyrenees to analyse the hydrological and geomorphological consequences of different land covers under the same climate scenario: (i) the San Salvador catchment represents a dense, undisturbed forest environment; (ii) the Arnás catchment corresponds to an old, abandoned cultivated area subjected to colonisation by plants; and (iii) the Araguás catchment consists in part of active badlands. The obtained results demonstrate that plant cover is a key factor, influencing (i) the seasonality and intensity of floods, (ii) the annual volume of discharge, and (iii) the suspended sediment concentration, total sediment yield and proportions of different types of sediment. The forested catchment tends to generate floods in late winter and spring, when the water table is close to the surface, and flood hydrographs are generally gentle, with solutes largely prevailing over suspended sediment. The old agricultural catchment produces in average twice the number of floods as that recorded in the forested catchment, with the highest floods recorded in autumn and spring; this catchment behaves as a complex mosaic, with a large spatial and temporal variability in terms of both sediment- and runoff-contributing areas; in addition, suspended sediment is equal to solutes, and bedload reaches a relatively high importance. Finally, the badland catchment reacts to all rainstorm events throughout the year, with a high suspended-sediment load. Sediment outputs from the Araguás catchment are two orders of magnitude higher than in the Arnás and San Salvador catchments. Suspended

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2008.04.013

sediment concentrations exceed 300 g l^{-1} in the Araguás catchment, whereas they rarely exceed 20 g l^{-1} in the Arnás and rarely 1.5 g l^{-1} in the San Salvador catchment.

Introduction

Hydrological studies rely upon the analysis of processes at different spatial scales (from small experimental plots to large basins) and temporal scales (with resolutions ranging minutes or hours to several decades). In this regard, small experimental catchments (tens or hundreds of hectares in size) possess the following advantages in conducting hydrology-based studies: (i) they tend to be relatively homogeneous in terms of topography and lithology, and can therefore be considered as representative of a certain land use or plant cover; (ii) the installation and maintenance of different measurement devices is relatively controllable, and can be achieved in a simple way; (iii) the obtained results can be used to validate hydrological and sediment-transport models, as well as to predict hydrological functioning under different environmental scenarios.

For the above reasons, the number of experimental catchments has increased markedly in recent years (Walling, 1991), particularly in Spain, where they are found in contrasting environments ranging from areas with a semi-arid Mediterranean climate (Castillo et al., 2000; Cantón et al., 2004), to high Pyrenean mountains (Alvera and García-Ruiz, 2000), mid-altitude mountains (Gallart et al., 1997, 2002; Llorens et al., 1997; Arnáez et al., 1999; García-Ruiz et al., 2000, 2005; Lana-Renault et al., 2007; Serrano-Muela et al., 2008), and dehesa environments (Ceballos and Schnabel, 1998).

The Department of Geo-environmental Processes and Global Change (Instituto Pirenaico de Ecología, CSIC, Spain) has monitored three experimental catchments in the Central Spanish Pyrenees, each separated from the others by 10 km, and each with a different history of land use. These catchments enable the study of the hydrological response to rainstorms, the temporal variability of sediment transport and the hydrological roles of different factors, such as variability in the water table and the partitioning of precipitation between interception, infiltration, and runoff due to plant cover (Foley et al., 2005). It is a critical problem that the evolution of plant cover, related to marked changes in land use, directly influences the evolution of the quantity and quality of water resources, as well as soil erosion and conservation (Beguería et al., 2003; Nogués-Bravo et al., 2007).

Mediterranean mountains are particularly sensitive to these changes due to (i) the abandonment of south-facing slopes after centuries of cultivation and consequent re-colonization by shrubs and forests, and (ii) new scenarios of climate change, that have pronounced effects in southern Europe (Beniston, 2003; López-Moreno et al., 2008). In addition, the scarcity and irregularity of precipitation in the Mediterranean region imparts a special importance to mountain areas, which are the main runoff-generation areas and the origin of most of the important rivers in the region (Viviroli and Weingartner, 2004); in contrast, most of the population and the main agricultural and industrial centres are located in lowland areas.

Given the above, detailed studies undertaken in catchments with different land uses are of paramount importance in comparing hydrological responses at different temporal scales (from daily events to long-term average discharge and sediment transport). This information is fundamental in validating hydrological models and forecasting the trend of water resources under different environmental scenarios.

This paper is a synthesis of the most relevant results obtained from three experimental catchments in the Central Spanish Pyrenees. The aim of the study is to answer the important question of how land cover influences runoff and flood generation, the timing of discharge, response to a rainstorm event and spatial and temporal variability in sediment transport. For this reason, different environments are studied, ranging from badland areas in the sub-Mediterranean climate sector of the Pyrenees to dense forests and abandoned areas of previously intensively cultivated farmland; together, these represent the most important environments in a mid-altitude Mediterranean mountain environment.

Study area: the catchments

The three catchments are located in the upper Aragón Valley, Central Spanish Pyrenees (Fig. 1). Table 1 is a summary of their relevant characteristics.

The Araguás catchment (0.45 km^2) is a north—south oriented tributary of the Lubierre River. The altitude of the catchment ranges between 780 and 1105 m (all elevations are provided relative to sea level), and in its middle and lower sectors is mainly characterised by the presence of a dense network of badlands, where ravines incise into Eocene marls of the Inner Pyrenean Depression, on a pediment that connects with the fluvial terrace of +60 m (Photo 1). Small landslides and mudflows dominate the steepest slopes of the badlands, along with gullying, rilling and sheet wash erosion. The badland area occupies 25% of the catchment, showing a slightly asymmetric distribution on slopes of different exposures associated with differences in the thermal and hydrological regime (Nadal-Romero et al., 2007). The headwater of the catchment, developed upon flysch bedrock, was artificially reforested in the 1960's with *Pinus nigra* and *Pinus sylvestris*, upon abandoned terraced fields. The average annual precipitation is about 800 mm, with annual rainfall varying between 500 and 1000 mm.

The Arnás catchment (2.84 km^2) is a west—east oriented tributary of the Lubierre River. The substratum is intensively folded and faulted Eocene flysch, composed of thin, alternating layers of sandstones and marls. The beds generally dip to the north, giving rise to a dissymmetry between the north- and south-facing slopes (*cuesta* relief), the former having smoother gradients than the latter. The north-facing slope is characterised by the old scars and tongues