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Patterns of runoff and sediment production in response to land-use changes in an ungauged Mediterranean catchment

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SUMMARY

Modelling hydrology and sediment yield and its scale dependency has been limited by the quantity and quality of instrumental data. This paper aims to apply alternative methods to estimate runoff and sediment production rates at the event-scale and to characterize the hydro-sedimentary response of a highly torrential Mediterranean catchment to historical changes in land use and vegetation. A selection of well-dated and spatially-distributed check dams within the catchment were used to calibrate and validate a hydro-sedimentary distributed model (TETIS). Sediment volumes deposited by individual runoff events and trapped in check dams were estimated on the bases of detailed stratigraphic descriptions and subsequent GPS/TLS surveys. The model results showed a good agreement with the observed water flows and sediment volumes deposited behind several check dams. Management and land uses proved to be a decisive factor in the hydrological behaviour of the catchment, especially affecting erosion and sediment yield. It was observed that while the hydrological response of the catchment was sensitive to the percentage of each land use type, the sedimentary response was more dependent on the spatial distribution of land use. These differences between hydrology and sedimentary behaviour imply that the optimal soil use distribution for soil conservation may differ from the optimal soil use scenario oriented to attenuate flood peaks. This study suggest that soil use policies and erosion mitigation strategies should consider a holistic hydro-sedimentary approach, in order to become an adaptive option to reduce and mitigate the effects of erosion and flood peaks under global change.

1. Introduction

In Mediterranean regions, soil erosion and desertification studies have been mainly focused on the hill slope or small catchment (<5 km^2) scales (García-Ruiz and López-Bermúdez, 2009; Nadal-Romero et al., 2011). However, watershed and land management practices demand reliable assessment of runoff and sediment yield at the catchment and regional scales. The extrapolation of on-site erosion rates to catchment sediment yield requires attention to high level properties of the catchment and the up-scaling of the surface processes to the scale of interest (de Vente et al., 2007; Wasson, 2002). Moreover, the sediment budget at any point in a catchment is the net result of all processes occurring upstream and conveys spatial and time scale problems related to the sediment connectivity, erosion sources and depositional sinks (Walling, 1983). For instance, in SE Spain the annual sediment yield recorded in a variety of plots and catchment sizes range from 0.02 to 90.68 Mg ha^{-1} yr^{-1} (Romero-Díaz et al., 2007). This reflects an inherent difficulty to characterize sediment production across different spatial and temporal scales. Over the last decades, major research efforts have focused on the development and application of catchment scale modelling as a mean to assess sediment production rates and to analyse the sensitivity of soil erosion to environmental changes (land use/land cover under similar meteorology; de Vente and Poesen (2005). Understanding the hydro-sedimentary response of a catchment to diverse land use configurations requires the implementation of conceptual or physically based models to simulate soil erosion and sediment

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transport processes across varying spatial and temporal scales. The state-of-art generation of spatially distributed catchment models have provided promising insights concerning the simulation of sediment dynamics from slope erosion to sediment routing along stream channels at event scale over long-term simulations (Aksoy and Kavvas, 2005). One of these physically based distributed models is TETIS, which was used in this study due to its good performance in simulating Mediterranean catchments. TETIS is a distributed rainfall-runoff model that includes a sediment yield sub-model capable to simulate catchment hydrology and sediment transport budgets at event scale over long term simulations (Bussi et al., 2013) as well as for future climate scenarios (Bussi et al., 2014a).

Regardless of the hydro-sedimentary model chosen, a major methodological problem to face for its implementation is the lack of reliable benchmark data to support the calibration and validation process. To cope with this limitation, reservoir sediment volumes have been considered in the literature as an alternative indirect method to obtain sediment production rates (Avendaño et al., 1997; Boix-Fayos et al., 2008; Romero-Díaz et al., 2007). This approach provides total sediment yield over time intervals between surveys, but does not supply information of the partial contribution of individual runoff events (Bussi et al., 2013). In Mediterranean regions, large intense rainfall events, as defined by González-Hidalgo et al. (2007) and González-Hidalgo et al. (2012), are contributing a high percentage of the total sediment yield. Therefore it is important to characterize their individual hydro-sedimentary contribution (Benito et al., 2015; Lewin et al., 1995; Machado et al., 2011). In a recent study, Bussi et al. (2013) presented a new methodology for model calibration and validation based on stratigraphic records from sediments stored in a check dam following sedimentary criteria normally used in paleohydrology studies (Baker et al., 1983; Benito et al., 2010, 2003; Corella et al., 2014; Machado et al., 2011). This approach introduces additional aspects to be considered, such as the representativeness of the retained volume of sediment in one check dam compared to the total sedimentary yield from the catchment, as well as the connectivity of sediment delivered by different inhomogeneous sub-catchments. Hence, it is necessary to test this calibration method on larger and more complex catchments where sediment contribution may vary among sub-catchments in relation to the lithology and land-use/land cover conditions. In order to assess the spatial patterns of soil erosion and sediment transport, in this study we propose the use of detailed infill stratigraphy from several check dams distributed all over the catchment area. This allows quantifying with high accuracy the sediment yield of different sub-catchments, which can then be related to land-use variations in space and time.

As a result of the scarcity of data and the complexity of the processes, the hydrological response and the sediment transport in arid and semi-arid Mediterranean areas are challenging to assess. We propose to use jointly check dam infill volumes, check dam stratigraphy and a distributed sediment and hydrological model to gain insights of the hydrological and sedimentary response of a highly complex and flashy semi-arid catchment. The characteristics of the study area can be considered representative of many other Mediterranean catchments in terms of data availability and hydro-sedimentary response. The complexity of the case study requires the use of a distributed model along with indirect data estimation techniques to determine the hydro-sedimentary response of this catchment.

Thus, the purposes of this paper are: (a) to present a multidisciplinary methodological approach for implementation of a distributed hydro-sedimentary model calibrated and validated with sedimentary records from check dams infill deposits in an ungauged Mediterranean catchment, (b) to test the performance of this model to quantify the hydro-sedimentary response to different configurations and historical changes in land use and vegetation cover at the catchment scale and on the long term, and (c) to provide environmental lessons learned from past land-use/land-cover changes implemented during the 20th for water and sediment conservation practices.

2. Materials and methods

2.1. Study area

The study area is the upper Guadalentín River catchment (SE Spain), with a drainage area of 429 km^2 and elevations ranging between 2045 and 687 m a.s.l. (Fig. 1A). The study catchment comprises two main sub-catchments (Fig. 1B): the northern sector is drained by Rambla Mayor and the southern part by the Alcaide River. The Caramel River results from the junction of both streams upstream of the Valdeinfierno reservoir. The climate is Mediterranean (mean annual temperature ~13 °C) with semi-arid characteristics on the lower part of the catchment, and mountainous features in the high elevation reliefs. The mean annual precipitation ranges from 460 mm at the Sierra de Maria to 320 mm at the Valdeinfierno reservoir. Extreme rainfall (>30 mm h^{-1}) is generally characterized by short events (from a few hours to a day) and takes place mainly in spring and autumn. Summers are characterized by dry weather. Soils within the study area show a poor development in agreement with its semi-arid Mediterranean characteristics. In the northern part of the catchment, soils are highly degraded with dominant occurrence of Calcaric Regosols, Cambisols and Calcisols. In the southern part Leptosols are concentrated on the uplands and Regosols on the lowlands (the latter especially in the eastern part, where the majority of agricultural land is located). The soil organic matter content is usually moderately high, in general between 2% and 10%, with maximum values at 17%. The soils are thicker in the lowlands (depth: 50–100 cm) and thinner in the uplands (20–30 cm). The soil texture is mostly clay loam, loam and silt loam, with some sandier patches located in the central part.

The study area is representative of semi-arid Mediterranean regions with an environmental history characterized by dry land agriculture, mainly cereals with rotations of unseeded fallow, and grazing even on steep slopes. Since early 20th century, the studied catchment was the focus of extensive afforestation activities by the Spanish Water Authority to fight against soil erosion and reservoir siltation, which is already a major problem in the study area (>70% of the Valdeinfierno reservoir silted; CEDEX, 1995). The extensive afforestation led to the declaration of the Natural Park of Sierra de Maria-Los Velez as an area of high environmental and cultural value in 1987. The current land management based on forest in the mountain reliefs and agricultural lands in the valley bottoms is representative of other Mediterranean regions (MME, 1998).

2.2. TETIS model and input information description

The TETIS distributed hydrological and sediment model (Frances et al., 2007; Bussi et al., 2013; Bussi et al., 2014a, 2014b) was used to reproduce the hydro-sedimentary response of the Guadalentín River catchment up to the Valdeinfierno reservoir. This model was chosen because it has been largely used in similar catchments and it has also been previously employed for land-use change analysis (e.g. Velez et al., 2009; Salazar et al., 2013; Bussi et al., 2014a; Buendia et al., 2015).

TETIS is composed by two main sub-models: the hydrological and the sediment transport sub-models. The hydrological sub-model is based on a tank structure, where each tank represents a