ARTICLE IN PRESS
STOTEN-18103; No of Pages 19
Science of the Total Environment xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Science of the Total Environment
journal homepage: www.elsevier.com/locate/scitotenv

Rainfall, runoff and sediment transport in a Mediterranean mountainous catchment

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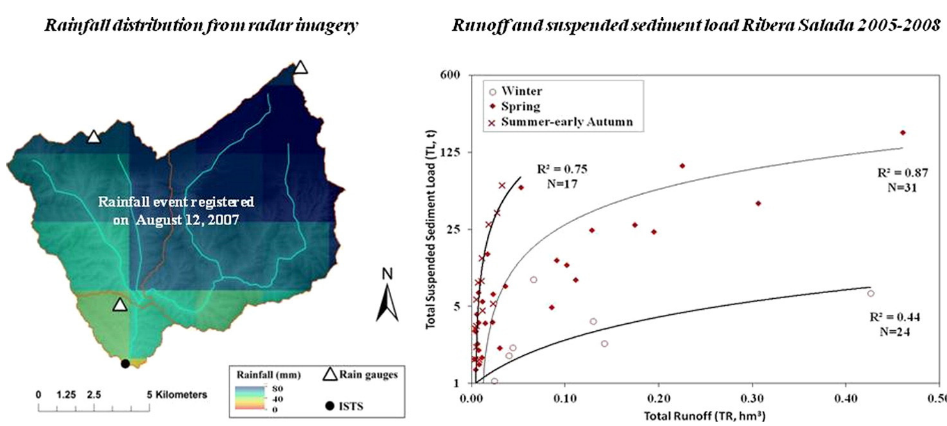
HIGHLIGHTS

- Total suspended load is predicted from rainfall and runoff variables.
- Suspended sediment concentrations are largely correlated with flood magnitude.
- Sediment load is highly dependent on direct runoff.
- Sediment load is not uniform through time but mostly concentrated in spring.
- Rainfall distribution from radar images are used and compared to field data.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 14 July 2015
Accepted 15 July 2015
Available online xxxx

Editor: D. Barceló

Keywords:
Rainfall
Runoff
Sediment transport
Radar
Meso-scale catchment
Ribera Salada
Ebro basin

ABSTRACT

The relation between rainfall, runoff, erosion and sediment transport is highly variable in Mediterranean catchments. Their relation can be modified by land use changes and climate oscillations that, ultimately, will control water and sediment yields. This paper analyses rainfall, runoff and sediment transport relations in a meso-scale Mediterranean mountain catchment, the Ribera Salada (NE Iberian Peninsula). A total of 73 floods recorded between November 2005 and November 2008 at the Inglabaga Sediment Transport Station (114.5 km^2) have been analysed. Suspended sediment transport and flow discharge were measured continuously. Rainfall data was obtained by means of direct rain gauges and daily rainfall reconstructions from radar information. Results indicate that the annual sediment yield (2.3 t km^{-1} y^{-1} on average) and the flood-based runoff coefficients (4.1% on average) are low. The Ribera Salada presents a low geomorphological and hydrological activity compared with other Mediterranean mountain catchments. Pearson correlations between rainfall, runoff and sediment transport variables were obtained. The hydrological response of the catchment is controlled by the base flows. The magnitude of suspended sediment concentrations is largely correlated with flood magnitude, while sediment load is correlated with the amount of direct runoff. Multivariate analysis shows that total suspended load can be predicted by integrating rainfall and runoff variables. The total direct runoff is the variable with more weight in the equation. Finally, three main hydro-sedimentary phases within the hydrological year are defined in this catchment: (a) Winter, where the catchment produces only water and very little sediment; (b) Spring, where the majority of water and

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http://dx.doi.org/10.1016/j.scitotenv.2015.07.075

Please cite this article as: Tuset, J., et al., Rainfall, runoff and sediment transport in a Mediterranean mountainous catchment, Sci Total Environ (2015), http://dx.doi.org/10.1016/j.scitotenv.2015.07.075

sediment is produced; and (c) Summer–Autumn, when little runoff is produced but significant amount of sediments is exported out of the catchment. Results show as land use and climate change may have an important role in modifying the cycles of water and sediment yields in Mediterranean mountain catchments.

1. Introduction

Rivers are dynamic and complex natural systems that transfer water and sediments from sources to sinks (Schumm, 1977). In order to understand their complexity and dynamism it is necessary to study the interaction between physical processes at multiple spatial and temporal scales. The amount of rainfall and its intensity and variability control, on the one hand, the generation of runoff and, on the other, the erosional processes operating at different scales. These interactions can be greatly variable in Mediterranean catchments with marked hydrological fluctuations. Long dry periods are contrasted with intense rainfall events. Additionally, intra-event variability can be also important. These catchments are characterised by high reliefs and local microclimates with rain shadows. Rainfall in these environments often presents an altitudinal gradient (e.g. Verdú et al., 2006; Frota et al., 2008). These particularities will influence the production of sediment in the headwaters and, consequently the transfer of sediment downstream through channel networks. Moreover, land uses in the majority of the headwaters of Mediterranean mountain catchments have been changed since the middle of the twentieth century (Gallart and Llorens, 2001, 2004; Améztegui et al., 2010); a fact that will control the hydrological regime (García-Ruiz et al., 1997; Beguería et al., 2003; Buendia et al., 2015a and 2015b) and the sediment delivery at different temporal and spatial scales (e.g. García-Ruiz et al., 1996, 1997; Gallart et al., 2002; García-Ruiz et al., 2008; Lana-Renault et al., 2014; Buendia et al., 2015b).

The study of the rainfall distribution at the catchment scale has been of wide interest for geomorphologists in order to understand the interaction between precipitation, runoff generation and sediment transport. Catchment-scale maps of rainfall variability have been traditionally obtained from spot rainfall records by applying different interpolation methods (e.g. Syed et al., 2003; López-Tarazón et al., 2010; Ly et al., 2013; Szcześniak and Piniewski, 2015). Remote sensing data have improved the spatial and temporal coverage of rainfall. For instance, information from radar (e.g. Quirmbach and Schultz, 2002; Fiener and Auerswald, 2009; Navratil et al., 2012; Borga et al., 2014; Hasan et al., 2014; Marra et al., 2014) provides new opportunities in terms of not just the spatial but also on the temporal resolution of catchment rainfall data. Although such approaches require calibration and validation, technological advances are improving the quality of these estimates.

The volume of runoff during a flood can be influenced by the antecedent rainfall conditions including soil saturation and moisture (e.g. López-Tarazón et al., 2010; Yuan et al., 2001), the precipitation during the event (e.g. Taylor and Pearce, 1982; Nu-Fang et al., 2011), and other factors like rainfall intensity (e.g. Nu-Fang et al., 2011) and the evapotranspiration and air temperature (e.g. Hibbert, 1967; Swank et al., 2001; Serrano-Muela et al., 2008). The importance of some of these factors can be highly variable. For instance, temperature is a key factor since it modifies the generation of surface runoff during periods of snowmelt or in systems with frozen soils (Ollesch et al., 2005). Additionally to these factors, land cover and land uses have a significant influence on the hydrological response of a catchment, directly or indirectly by interfering to the above indicated factors. The infiltration capacity of the soils is an example with a direct effect on the generation of runoff. High infiltration capacities in temperate forests (Mulungu et al., 2005) generate a slower or delayed hydrological response when compared to other environments (e.g. González-Hidalgo and Echeverría, 1990).

The amount and intensity of rainfall together with land cover, soil properties and landscape morphometric characteristics control the main processes of hydric erosion. Rainfall erosivity varies depending on the kinetic energy and the intensity of the precipitation. To quantify the erosivity, several studies have linked the characteristics of the rain with soil losses induced by the precipitation. Nwosu et al. (1995) established that the intensity of the rain was the variable best correlated to soil erosion and runoff. Yin et al. (2007) concludes that the maximum intensity in 60 min ($Imax_{60}$) is the factor most correlated with erosion. Although soil erosion may increase linearly with rainfall intensity in Mediterranean regions (e.g. vineyards in Arnaez et al., 2007), this correlation is not always found in channel networks. For instance, López-Tarazón et al. (2010) did not find any correlation between rainfall intensity and suspended sediment transport in the River Isabena, a Mediterranean mountainous meso-scale catchment.

Only a fraction of the sediment produced in the headwaters of the catchment is exported at their outlets. This proportion will depend on the temporal scale. The Sediment Delivery Ratio (SDR) represents the proportion of the sediment that is delivered in a given point of a catchment in relation to the production of sediment upstream (Williams, 1977; Walling, 1983). The SDR can be heavily variable across the channel network and temporally. For instance, in large systems, sediment export at annual scales may represent less than 10% (Roehl, 1962; Williams and Berndt, 1972; Walling and Webb, 1983; Porto et al., 2011) of the primary production. This variability is influenced by multiple factors such as the location of the source of sediments (distance), the connectivity between slopes and river networks, the frequency and magnitude of flood events, the duration of competent flows, and the size of the catchment, between others (e.g. Walling, 1983; Verstraeten et al., 2002; López-Tarazón et al., 2012; Buendia et al., 2014). These processes can be in turn modified by human impacts such as dams (e.g. Vericat and Batalla, 2006), gravel mining (e.g. Rovira et al., 2005), forest or wild fires (e.g. Cerdà and Lasanta, 2005; Cerdà and Doerr, 2008) and changes on land uses (e.g. Alatorre et al., 2012). Once sediments reach the river network their residence time will be determined by the cycles of mobilization, in-channel sedimentation and remobilization (e.g. Charlton, 2007; López-Tarazón et al., 2011; Piqué et al., 2014). Inter-annual variability of the SDR is often considerable but can be also highly variable between catchments influenced by contrast sediment production processes (i.e. erosion) and sediment loads (e.g. Vanmaercke et al., 2012a).

As discussed previously, erosion rates are variable and these cannot be directly used to estimate the sediment load at a given point. Consequently, as for instance was pointed out by Vanmaercke et al. (2012b), it is necessary to study the dominant erosion processes in each catchment according to the principal factors controlling these. Rodríguez-Blanco et al. (2010) explained that a majority part of the suspended sediment load during an event can be explained by the maximum discharge and the runoff. The relationships between rainfall, runoff and sediment transport have been widely investigated. Several studies have found as the relationship between suspended sediment transport and runoff, although might be significant in some episodes, presents high variability (e.g. Rodríguez-Blanco et al., 2010). In those cases suspended sediment transport cannot be predicted by runoff intensity and the development of rating curves to assess annual sediment loads (as per Walling, 1983) will not be fully appropriate. Estrany et al. (2009) found that rainfall was the most important factor in controlling the magnitude of suspended sediment concentrations in a small (1 km^2) Mediterranean catchment. However, Onderka et al. (2012) found, in a small (2.7 km^2) pluvio-oceanic catchment, that the mean suspended sediment concentrations (SSCs) are better correlated to runoff.

Within this context, the main objectives of this study are: (a) to characterise rainfall, runoff and sediment transport dynamics in a meso-scale Mediterranean mountain catchment during three consecutive hydrologically contrasted years; (b) to analyse the relationship between key variables of rainfall, runoff and sediment transport; and (c) to develop a multivariate statistical analysis between sediment

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