Science of the Total Environment 540 (2016) 144–157

Contents lists available at ScienceDirect

Science of the Total Environment

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

Effects of afforestation on runoff and sediment load in an upland Mediterranean catchment

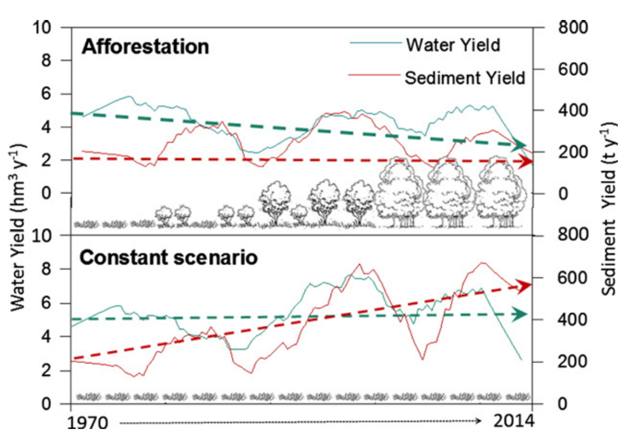
C. Buendia [a,b,*], G. Bussi [c], J. Tuset [b,d], D. Vericat [b,d], S. Sabater [a,e], A. Palau [b,f], R.J. Batalla [a,b,d]

[a] Catalan Institute for Water Research — ICRA, Scientific and Technological Park of the University of Girona, Emili Grahit 101, 17003 Girona, Catalonia, Spain
[b] Fluvial Dynamics Research Group — RIUS, University of Lleida, Alcalde Rovira Roure 191, 25198 Lleida, Catalonia, Spain
[c] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom
[d] Forest Sciences Centre of Catalonia, Crta. Sant Llorenç de Morunys km 2, 25280 Solsona, Catalonia, Spain
[e] Institute of Aquatic Ecology, University of Girona, Campus Montilivi s/n, 17003 Girona, Catalonia, Spain
[f] Department of Environment and Climate Change of Spain and Portugal, ENDESA SA, Crta. Tarragona km 89, 25191 Lleida, Catalonia, Spain

HIGHLIGHTS

- We applied a distributed hydrological model to reconstruct runoff and sediment yield.
- Decreasing trends were detected for both variables at the annual and seasonal time scales.
- Afforestation seemed to be the main factor driving the trends observed.
- An increase in the torrential behaviour and reduction of peak flows was detected.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 1 July 2015
Accepted 1 July 2015
Available online 15 July 2015

Keywords:
Afforestation
Climate change
Mediterranean
Sediment yield
Runoff
TETIS
Ribera Salada

ABSTRACT

This paper assesses annual and seasonal trends in runoff and sediment load resulting from climate variability and afforestation in an upland Mediterranean basin, the Ribera Salada (NE Iberian Peninsula). We implemented a hydrological and sediment transport distributed model (TETIS) with a daily time-step, using continuous discharge and sediment transport data collected at a monitoring station during the period 2009–2013. Once calibrated and validated, the model was used to simulate the hydrosedimentary response of the basin for the period 1971–2014 using historical climate and land use data. Simulated series were further used to (i) detect sediment transport and hydrologic trends at different temporal scales (annual, seasonal); (ii) assess changes in the contribution of extreme events (i.e. low and high flows) and (ii) assess the relative effect of forest expansion and climate variability on trends observed by applying a scenario of constant land use. The non-parametric Mann–Kendall test indicated upward trends for temperature and decreasing trends (although non-significant) for precipitation. Downward trends occurred for annual runoff, and less significantly for sediment yield. Reductions in runoff were less intense when afforestation was not considered in the model, while trends in sediment yield were reversed. Results also indicated that an increase in the river's torrential behaviour may have occurred throughout

* Corresponding author at: Catalan Institute for Water Research — ICRA, Scientific and Technological Park of the University of Girona, Emili Grahit 101, 17003 Girona, Catalonia, Spain.
E-mail address: cbuendia@icra.cat (C. Buendia).

http://dx.doi.org/10.1016/j.scitotenv.2015.07.005

TETIS,
Ribera Salada

the studied period, with low and high flow events gaining importance with respect to the annual contribution, although its magnitude was reduced over time.

1. Introduction

Mountain areas are of major importance since water availability in downstream regions largely depends on runoff generation in high-altitude areas (Viviroli and Weingartner, 2004). Their role as source of freshwater is related to their higher specific runoff as a result of higher precipitation coupled with lower evapotranspiration rates (Vanham and Rauch, 2009). These areas are considered particularly vulnerable to temperature and precipitation changes, notably in arid and semi-arid regions, where there is already a great dependence on water from mountains (López-Moreno et al., 2008).

Climate change and population growth are expected to intensify the water scarcity and seasonal variability characteristic of the Mediterranean area (IPCC, 2013). However, along with varying temperatures and precipitation patterns, other factors should be taken into account when assessing observed hydrological and sediment transport trends. Particularly, land use has been largely reported to affect the hydrosedimentary response of basins due to the alteration of overland runoff (Zhang et al., 2001) and the balance between evaporation, groundwater recharge and stream discharge (Chase et al., 2000; Benyon et al., 2006; Piao et al., 2007). However, the relationship between land use and hydrology is complex, with linkages at a variety of spatial and temporal scales which largely depend on the direction of the land-use change: conversion to irrigated land, deforestation, afforestation, and urban development (Calder, 1993; Gessesse et al., 2014).

Increasing urban and industrial development during the second half of the 20th century led to a depopulation of Mediterranean mountain areas such as the Spanish Pyrenees. The abandonment of agricultural fields constituted the main cause of change in vegetation cover in the headwaters of most Pyrenean basins (Lasanta and García-Ruíz, 1996). This vegetation growth, along with management strategies thought to improve environmental forest services (e.g. MIMAM, 2000; Marey-Pérez and Rodríguez-Vicente, 2008), favoured the shift from crop fields and meadows to shrub and forested covers. Percentages of forest increase during this period can reach values above 40%. For example, Arnáez et al. (2008) found an increase of 44% in the Cameros area (west of the Iberian Peninsula) for a period of 45 years (1956–2001) and Gallart and Llorens (2004) estimated an increase of 17% in 21 years (1970–1991) in the headwaters of the Ebro basin (NE of Spain).

Forest expansion has been acknowledged to be an important driver of the runoff reductions observed in the Iberian Peninsula (e.g. López-Moreno et al., 2008; Morán-Tejeda et al., 2010). Decreasing trends in river flow have been detected in most of the streams of the southern Pyrenees (Delgado et al., 2010). For example, the mean annual flow of the river Ebro has decreased ca. 40% in 50 years due to increased irrigation, climate shift and forest expansion. Each cause was estimated to contribute at a similar proportion (ca. 33%) to the streamflow decrease (Gallart and Llorens, 2003). Similarly, Buendia et al. (2015) recently reported that afforestation explained up to 37% of the flow decrease observed in the Noguera Pallaresa, one of the River Ebro's main sub-catchments.

The interest in the assessment of the relative contribution of climate and forest growth mainly stems from the vulnerability of water resources in the Mediterranean and its dependence on impounded water bodies, whose life span has been severely reduced due to siltation problems (e.g. Navas et al., 2004, 2009, 2011; Palazón and Navas, 2014). The major concern when assessing the relative magnitude of the impact of land-use change and climate variability on river runoff and sediment load is enhanced by the few long-term records of flow and sediment transport in river basins. Therefore, most of the studies are undertaken in experimental plots or at the hillslope scale and few studies are done at the meso- and macro-scales. Results from these studies provide evidence of the sensitivity of erosion to land use and human activity (e.g. García-Ruíz et al., 2008). However, their results need to be interpreted with caution since they are only comparable within other data from the same experimental stations.

Such lack of long-term sediment transport data in river basins requires modelling tools to assess the effects of land-use changes on the hydrological response and sediment transport. In this study, we combined continuous flow measurements and sediment transport data with a modelling approach with the aim of understanding the effects of increased forested area and climate variability on the hydro-sedimentary response of a meso-scale Mediterranean basin (the Ribera Salada, NE Iberian Peninsula). This work follows previous modelling efforts undertaken in the basin (i.e. Müeller et al., 2009). However, the modelling approach here presented is based on a larger and more detailed dataset consisting of a daily register of flow and suspended sediment concentration, which was used to calibrate and validate the model used in this study (TETIS, Francés et al., 2007; Bussi et al., 2013). Furthermore, land-use change and climatic variations were analysed jointly in an effort to quantify the impact of global change on the water and sediment yields. The specific objectives were: (i) Simulate water discharge and sediment transport data for the period 1971–2014; (ii) detect temporal trends in runoff and sediment yield at the annual and seasonal time scales; (iii) assess the relative effect of forest expansion and climate variability on annual runoff and sediment yield and (iv) determine changes in the frequency, distribution and magnitude of low and high flow events.

2. Materials and methods

2.1. Study area

The hydrosedimentary response to increased forest cover was examined for the Ribera Salada at the Canalda sub-basin (65 km^2 basin area). The Ribera Salada is a typical Pre-Pyrenean mountainous basin located in the NE of the Iberian Peninsula, which flows into the River Segre (in turn one of the main tributaries of the River Ebro) at the Rialb Reservoir (Fig. 1). The altitude in the basin ranges from 420 m a.s.l in the southwest to 2385 m a.s.l. in the northeast. The mean annual temperature is 11 °C, with minimum temperatures reaching values below −10 °C in winter (e.g. −21 °C registered at the summits) and temperatures above 30 °C in the summer (e.g. 38 °C in the lowlands). Mean annual precipitation is 620 mm, with minimum values observed in winter (i.e. a total of 160 mm for the whole season) and maximum values registered in the summits during the spring and autumn seasons (i.e. up to 1200 mm).

Soils in Canalda are shallow (soil depth varies between 30 and 70 cm) calcareous and stony (Estruch, 2001; Poch et al., 2002). Typic eutrodept and Lithic Ustorthents prevail throughout the basin (SSS, 1993, 2006; Ubalde et al., 1999) and are characterised by a low water retention capacity and moderately high infiltration rates (Poch et al., 2002). Mean basin slope in Canalda is 40%, with nearly a 53% of the total basin area showing a slope value above 35% (Estruch, 2001). Forest areas occupy the major part of the basin (ca. 70%) and consist mainly of pine (*Pinus sylvestris* and *Pinus uncinata*) and deciduous oak forest. Agricultural areas occupy less than 4% and are mainly located in the middle part of the basin. According to Ubalde et al. (1999), the steep relief, together with the torrential character of the river and the deeply incised river network, hinders the development of an alluvial plain in