EFFECTS OF AFFORESTATION ON RUNOFF AND SEDIMENT LOAD IN AN UPLAND MEDITERRANEAN CATCHMENT

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Abstract

We assess annual and seasonal trends in runoff and sediment load resulting from climate and afforestation in an upland Mediterranean basin, the Ribera Salada (NE Pre-Pyrenees). We implemented a hydrological and sediment 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 reconstruct the hydrosedimentary response of the basin for the period 1971-2014 using historical climate and land use data. Reconstructed 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, while decreasing (although non-significant) trends were found for precipitation. Annual runoff showed downward trends, as well as sediment yield, although results for the latter showed lower levels of significance. When afforestation was not considered in the model, reductions in runoff were less intense, while trends in sediment yield were reversed. Last, results also suggested that an increase in the river's torrential behaviour may have occurred throughout the studied period, with low and high flow events gaining importance to the annual contribution but its magnitude being reduced over time.

Keywords: afforestation, climate change, Mediterranean, sediment yield, runoff, Ribera Salada.

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 Weingarter, 2004). Their role as source of freshwater is due to a 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-Ruiz, 1996). This vegetation growth, along with management strategies thought to improve environmental forest services (e.g. MIMAM, 2000; Marey-Pérez and Rodríguez-Vicente, 2008), have favoured the shift from crop fields and meadows towards 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. Beguería et al., 2006; López-Moreno et al., 2008; Morán-Tejada et al., 2010). Decreasing trends in river flow have been detected in most of the streams of the southern Pyrenees (Beguería et al., 2006; Delgado et al., 2010). For example, the mean annual flow of the river Ebro has decreased c.a. 40% in 50 years due to increased irrigation, climate shift and forest expansion. Each cause was estimated to contribute at a similar proportion (c.a. 33%) to the streamflow decrease (Gallart and Llorens, 2003, 2004). 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 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. López-Tarazón et al., 2009, Bussi et al., 2014). The major problem when assessing the relative magnitude of the impact of land-use change and climate variability on river runoff and sediment load is exacerbated by the scarcity of 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-Ruiz 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.

Given the lack of long-term sediment transport data in river basins, modelling tools are a useful instrument for assessing the effects of land-use changes on the hydrological response and sediment transport. In this study, we combined continuous flow 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 Spanish Pre-Pyrenes). This work follows previous modelling efforts undertaken in the basin (i.e. Müeller et al., 2009). However, the modelling approach presented here 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, Frances 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. Our specific objectives are: (i) Reconstruct 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) Determine changes in the frequency distribution and magnitude of low and high flow events; and (iv) Assess the relative effect of forest expansion and climate variability on annual runoff and sediment yield.

2. MATERIALS AND METHODS

2.1. Study Area

The hydrosedimentary response to increased forest cover was examined for the Ribera Salada at Canalda (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 Segre River (in turn one of the main tributaries of the Ebro River) at the Rialb Reservoir (Figure 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^{0}C, with minimum temperatures reaching values below -10^{0}C in winter (e.g. -21ºC registered at the summits) and temperatures above 30^{0}C in the summer (e.g. 38ºC 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 1200mm during the autumn months).

Soils in Canalda are shallow (soil depth varies between 30 and 70cm) calcareous and stony (Estruch, 2001; Poch et al., 2002). Typic and Lithic Ustorthents and Udorthents 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 is 40%, with nearly a 53% of the total basin area showing a slope value above 35% (Estruch, 2001). Woodland occupies the major part of the basin (c.a. 70%) and consists mainly of pine (*Pinus sylvestris* and *Pinus uncinata*) and deciduous oak forest. Agricultural areas occupy less than a 4% of the basin, and are mainly located in the middle part. 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 the lower-most parts of the Canalda basin and hence the establishment of agricultural fields in this part. Pastures and grassland occupies c.a. 20% of the area and are mainly located in the upper-most part, above 1600 m a.s.l. The rest of the basin area (c.a. 8%) consists of bare soil and rocky outcrops.

Ubalde et al., (1999) studied land-use changes between 1957 and 1993 for the Canalda basin and reported a reduction in agriculture accompanied by land abandonment and subsequent afforestation. Here, we assess the relative effects that these and subsequent changes in the territory, have exerted on the basin's runoff and sediment load.

2.2. Field measurements: Discharge and suspended sediment transport data

Water discharge was continuously measured at the Canalda section for the period January 2009-December 2013. Water depth was measured by means of a pressure transmitter (Druck® 1730-PDCR) at 5 minute intervals and subsequently converted to a discharge ratio using a rating curve (h/Q relation). In May 2012 an Ultrasonic Doppler Instrument (Starflow® 6526, range 21 mm/s to 4500 mm/s) was installed and was used for measuring continuous flow and velocity. The discharge ratio associated with the different water stages was modelled using HEC-RAS® V.4.1. (USACE, 2010). The results have been validated with data from starflow meter and periodic manual gaugings using an electromagnetic flow metre (Valeport 801) during base and flood flows.

Water turbidity measurements started later, in June 2011, when a turbitidy meter (ANALITE® NEP9350; range: 0-3000 NTU) was set up at the monitoring station. In addition, an automatic water sampler (ISCO-3700) was installed close to the turbidity meter. Automatic water samples were collected during flood events, while periodic manual samples were collected during low flow conditions. A total of 308 water samples (0.5l) were collected during the study period. Water samples were used to convert turbidity data (NTU) to suspended sediment concentration (SSC, mg l^{-1}) by means of lineal relation between NTU and SSC.

2.3. Modelling approach

2.3.1. TETIS model description

The TETIS hydrological and sediment distributed model (Francés et al., 2007; Bussi et al., 2013) was used to evaluate the effect of climate variability and land-use change on runoff and sediment yield at the Canalda basin. This model was chosen because it has been largely used in the Iberian Peninsula (e.g. Andrés-Domenech et al., 2010; Cowpertwait et al., 2013; Salazar et al., 2013). In addition, previous applications were developed for a catchment located in Eastern Pyrenean area (Riverv Ésera, Bussi et al., 2014), proving the applicability of the model for the region of study. TETIS model is a spatially-distributed model, and thus allows the reproduction of land-use variability in space. The split-structure of its parameters (Francés et al., 2007) allows its calibration without altering the spatial structure of the parameter maps, including the land cover.

The hydrological sub-model is based on a tank structure, where each of the tanks represents a relevant process in the hydrological cycle, such as snow melt, canopy interception, soil static storage, soil gravitational storage and aquifer storage. The total flow to the drainage network is calculated by summing direct runoff, interflow and base flow, and then routed downstream using the geomorphological kinematic wave methodology. The model calibration can be carried out by adjusting up to twelve correction factors. The sediment sub-model is based on the concept of balance between sediment transport capacity of the flow and sediment availability. The sediment transport capacity of overland flow is computed by means of the modified Kilinc-Richardson equation (Julien, 2010) and the total stream network transport capacity is computed through the Engelund and Hansen (1967) equation. The transported material is divided into three textural classes (sand, silt and clay). The sediment sub-model is calibrated through adjustment of up to three correction factors, which multiply the sediment transport capacity for overland flow, gully flow and river channel flow respectively.

2.3.2. Model parameterisation and implementation

a. Model parameterisation

Data from a total of five meteorological stations located near-by the Canalda basin were used in this study (Figure 1). Three of these meteorological stations belong to public institutions (Ebro Water Authorities and the Meteorological Service of Catalonia) and measure precipitation, temperature and evapotranspiration at 15-min intervals. This meteorological network is complemented by two rain-gauges set up in the basin by the Forest Sciences Center of Catalonia, where only precipitation measures are recorded. All meteorological data was aggregated to daily values for modeling purposes.

The TETIS model parameters at Canalda were estimated based on a 100×100m mesh. The Digital Elevation Model (DEM) and the subsequent DEM-derived parameters were obtained from the 1:5000 topographic map available at the Cartographic and Geological Institute of Catalonia (ICGC). Soil parameters were obtained from previous studies on soil hydrology undertaken in the basin (Estruch, 2001; Poch et al., 2002; Loaiza, 2007) and the soil types map elaborated by Orozco (2003). Vegetation cover in the basin was represented by four different land-use maps, which reproduced the historical forest expansion occurred in the basin since 1957. Maps from 1957 were obtained from Ubalde et al. (1999), who used aerial photographs from the American flight of 56 (made by the Photogrammetric Service of the American army between 1956 and 1957). Recent land-use maps (from 1993, 2005 and 2009) were derived from the Land Cover Maps of Catalonia, elaborated by the Centre for Ecological Research and Forestry Applications (CREAF). Map legends were homogenized to a simplified legend with four cover classes: woodland, farmland, grassland and others (i.e. bare soil, scarce vegetation and rocky outcrops).

b. Model implementation and validation

Given the different time periods available for discharge and sediment transport data, hydrological and sediment sub-model were validated using different time intervals. First, the hydrological submodel was calibrated using data from January 2013 to December 2013. The validation period covered the interval from January 2009- December 2012. Second, the sediment sub-model was calibrated with data from January 2013 to December 2013 and validated using the period from June 2011 to December 2012. The sediment sub-model validation period falls within the validation time windows of the hydrological sub-model.

The implementation of the TETIS model at the Canalda basin intends to simulate runoff and sediment transport trends resulting from historical land-use changes. However, meteorological records at the selected stations started between 1996 and 2003, which provides a relatively short time window to assess historical trends. Given this limitation, the dataset Spain02 v4 developed by the Santander Meteorology Group (Herrera et al., 2012, 2014) was employed to reproduce past meteorological conditions. This dataset is a series of high-resolution daily precipitation and temperature data on a 12 km resolution mesh containing meteorological data from 1971 to 2008. Unfortunately, the Spain02 dataset ends in 2008, while the water discharge records begin in 2009. For this reason, the model calibration and validation was carried out using point data from the meteorological stations showed in Figure 1 as input, while the historical analysis was carried out using Spain02 as model input.

In order to implement Spain02 in the developed TETIS model, a linear q-q plot bias correction (Déqué, 2007) was applied to the Spain02 precipitation and temperature series. The linear bias correction was determined by comparing precipitation and temperature data from the meteorological stations showed in Figure 1 and from the spatially distributed Spain02 dataset from 2005 to 2008, and then applied to the whole series of Spain02 precipitation and temperature data. The corrected temperature series were used to compute reference evapotranspiration by means of the Allen et al. (1998) equation.

Once the corresponding corrections were applied to the Spain02 dataset, we applied TETIS for the whole 1971-2014 period to obtain the historical hydrological and sediment transport record, using the bias-corrected Spain02 series as model input from January 1971 to March 2008 and the point data from the meteorological stations from April 2008 to September 2014. In order to account for the changes in the territory, we divided the 43-year period into four sub-periods and applied the TETIS model in each using its corresponding land-use map. Therefore, the land-use map from 1957 was used for modelling the period 1971-1985; for the period from 1986-2000 we used the 1993 map; for the period 2001-2008 the map from 2005; and last, the map from 2009 for the period from 2009 to 2013. Note that for the first period (1971-1985) the meteorological record started later than the first land-use map available (1957). Therefore we assumed this map to be the starting point of our data series given the lack of prior meteorological data. However, the most important changes in the Pyrenees started during the 60's and 70's (Garcia-Ruiz and Lana-Renault, 2011) and hence agriculture and forest area probably remained the same (or forest growth was still limited) during the 1957-1971 period.

In order to gain an insight on the relative effects of afforestation and climate change on annual runoff and sediment yield, we used the TETIS model to simulate the hydrological and sediment cycle, using climate data for the 1971-2014 period as input, but keeping the land use constant over time, and equal to the 1957 map. In this way, we analysed a hypothetical scenario in which the land use did not change, with the aim of isolating the effects of climate changes. The modelled data obtained using the sequence of different land-use maps (i.e. obtained changing the land use over time) is referred to as "*actual*" dataset, while the hypothetical data is referred to as "*scenario*" dataset.

2.4. Data analysis

2.4.1. Trend analysis

The non-parametric Mann-Kendall trend test was used to identify the statistical significance of climate (temperature and precipitation), runoff and sediment yield trends. This test detects monotonic increases or decreasing trends in a dataset by comparing differences between successive values (Mann, 1945; Kendall, 1975). The Mann-Kendall's tau statistic (τ_{MK}) indicates the strength and direction of the trend detected. It has been widely used to investigate trends in hydro-climatological signals to assess randomness against linear trend since it is less sensitive to outliers than parametric statistics such as Pearson's correlation coefficients (Douglas et al., 2000; Kahya and Kalaci, 2004; Tao et al., 2011; Burn et al., 2012; Wang et al., 2013). The Man-Kendall test was applied to climate data (total annual precipitation and mean temperature) as well as total annual runoff (hm^3 y^{-1}) and sediment yields (ton y^{-1}). All statistical analysis were performed within the R environment (R Development Core Team, 2014).

2.4.2. Effects of climate and land use on annual runoff and sediment yield

Reconstructing runoff and sediment yield data driven exclusively by observed climate variability permits the assessment of the dissimilarity between the observed and the reconstructed data series. Such differences can be then used as a surrogate of the changes occurred in the basin, and hence allow the evaluation of the streamflow and sediment yield trends caused by both climatic and non-climatic effects for the period 1971-2014. First, a Mann-Kendall trend test was applied to the *scenario* dataset to determine the presence and direction of the hypothetical trends if afforestation had not occurred (i.e. resulting from climate variability alone). A linear regression was then applied to annual runoff and sediment yield for the *actual* and *scenario* datasets. Analysis of Covariance (ANCOVA) was used to test whether the slopes of linear regressions fitted on both datasets (*actual* and *scenario*) for runoff and sediment yield differed. Then, in order to determine the changes driven exclusively by land use, trends in the residual values (differences between the *actual* and *scenario* datasets) were also assessed. Significance in residual trends indicates the change in the studied variables resulting from afforestation alone (as per Gallart and Llorens, 2004).

2.4.3. Contribution of extreme events

In order to assess the temporal changes in the contribution of different event magnitude ranges to the total annual for rainfall, runoff and sediment yield, we followed the methodology used in Osborn et al., (2000) and López-Moreno et al., (2006). All days for each year for the studied period (1971-2014) were sorted in ascending order for discharge and cumulative frequencies were computed. We divided the ranked series into five main categories following US-EPA (2011): (i) low magnitude events, containing up to 20% of the total annual accumulated; (ii) dry conditions (from 20 to 40% of the total accumulated); (iii) mid-range conditions (from 40 to 60%); (iv) moist conditions (from 60 to 80%); and (v) high-magnitude events (from 80 to 100%; i.e. values equalled or exceeded less than 20% of the time).

The resulting time series containing the contribution of each magnitude class to the annual runoff, rainfall and sediment yield was tested for temporal trends using the non-parametric Mann-Kendall test. This provided a first approach into the evolution of high and low magnitude events, and hence allowed to determine whether the contribution of the largest and lowest annual values for each variable shows any temporal trend or remains stationary.

3. RESULTS

3.1. Land-use changes

Figure 2 and Table 1 show the main changes occurred in the Canalda basin between 1957 and 2009. Results showed that forest and grassland have been the main land use in the basin over the years, together accounting for more than more 50% of the total basin area. A decrease in farmland was observed, particularly between 1957 and 1993, when the area dedicated to agriculture dropped from 9.1 to 3.9 km^2 (corresponding to a decrease of c.a. 60%). A decrease was also detected in grassland area, with an overall decrease of 4.6 km^2 for the 43-year period (26% in relation to 1956 values).

On the other hand, forested areas increased from 32 km^2 in 1956 to 44 km^2 in 2009. Major changes in land use seemed to have occurred between 1957 and 1993. This period encompasses the start of the process of field abandonment and so the early and quick forest growth (e.g. Lasanta et al., 2000; Cerdà and Lasanta, 2005), which seems to slow down and show a more steady increase over the following decades. Note that no changes are observed between 2005 and 2009, although it is unknown whether this pause is due to the short time lag or to the start of the stabilization in forest growth.

3.2. Hydrology and sediment transport

A summary of the hydrology and sediment transport for the monitoring period used for model calibration and validation (2009-2013 for discharge and 2011-2013 for sediment transport) is shown in Table 2. Mean discharge for the monitoring period was 0.41 m^3s^{-1}, which can be considered an average value for the basin (Vericat and Batalla, 2010). Discharge values ranged from 0.04 m^3s^{-1} (in March 2012) to 9.7 m^3s^{-1} (in April 2013). Runoff varied markedly between the studied period, with a minimum of 6.5 hm^3y^{-1} in 2012 to a maximum of 14.6 hm^3y^{-1} in 2010. Mean water yield equates to 272 mm y^{-1} and a runoff coefficient of 35%, a value slightly above the mean value for the whole Ebro basin (Vericat and Batalla, 2010).

Mean Suspended Sediment Concentration (SSC) for the monitoring period (in this case from 2011-2013) was 8 mg l^{-1}, a relatively low value that suggests the low sediment availability in the basin.A high variability between years was observed in terms of sediment yield. For example total sediment yield in 2012 was 106 ton y^{-1}, while in 2013 sediment yield reached values above 300 ton y^{-1}. Mean annual sediment yield for the whole period was 212 ton y^{-1}, which corresponds to a specific yield of 3,3 ton y^{-1} km^2, a value that can be considered low according to Batalla et al., (2005).

3.3. Modelling results

The hydrological sub-model calibration returned good results, as shown in Figure 3a. For the calibration period, the model obtained a Nash and Sutcliffe (1970) efficiency (NSE) of 0.70 and a volume error of +22%. For the validation period, the NSE value was 0.61 and the volume error -9%. Overall, the adjustment between observed and modelled water discharge values is very good, especially regarding low flows. Nevertheless, the model seems to be underestimating some of the major water discharge peaks (e.g. the flood event in April 2013, Figure 3).

The hydrological sub-model estimated that, overland flow was virtually absent (less than 1%). The total flow at Canalda was composed by 19% interflow and 80% base flow. The high proportion of infiltration contrasting with a small amount of overland flow was corroborated by Poch et al., (2002), who reported very low runoff coefficients in the basin (e.g. lower than 5%). According to these authors, low runoff values in the basin are the result of two main processes: high interception and evapotranspiration losses (which may account up to 50% of losses, Llorens et al., 1997) and the intense fracturing of the underlying calcareous conglomerates. This is likely to affect soil erosion and so sediment export from hillslopes to the channel network, which are mainly driven by surface runoff.

The sediment sub-model was calibrated by adjusting its correction factors in order to reproduce the observed suspended sediment flow. The calibration obtained a NSE value of 0.33 and a volume error of +12%. Model validation also obtained a NSE value of 0.33 and a volume error of +5%. According to Moriasi et al., (2007), these results are considered acceptable for a sediment transport model.

Results from the sediment transport model are shown in Figure 3b. It can be seen that the adjustment is particularly good for almost all the series, especially during peak flows. This is particularly relevant, as large events play a major role in soil erosion and sediment transport processes (González-Hidalgo et al., 2010). Despite the acceptable performance of the model, and similar to the results obtained in the hydrological model, a certain underestimation is observed (for example during the event in April 2013). Obviously, both errors (water discharge and suspended sediment discharge) are related, since an underestimation in water discharge results in an underestimation of the sediment load. Also, suspended sediment concentrations during low flows are in general overestimated for the period from June 2011 to June 2012. However, the magnitude of the error is relatively small (Figure 3). Overall, the performance of the sediment transport model was lower than the hydrological model, most likely due to the non-linear relationship between water and sediment transport (Julien and Simons, 1985).

In order to validate further the model, a visual comparison of the observed and simulated sediment discharge versus water discharge scatter plots is shown in Figure 4. The model is capable of describing the general behaviour of the sediment cycle, being particularly accurate for water discharges greater than 1 m3/s. The overestimation of low suspended sediment flows is also visible in this plot, as for discharges between 0.1 and 1 $m^3 s^{-1}$ some errors can be devised. Nevertheless, it can be stated that the performance of the model is in general satisfactory.

3.4. Annual trends

3.4.1. Overall trends in climate, runoff and sediment yield

Figure 5 shows mean annual values for hydroclimatic variables considered between 1971 and 2014. A high inter-annual variability in the basin can be noted, with dry periods (below mean long-term value) followed by relatively wet years (above the long-term mean line). Low precipitation periods coincide with drought episodes that occurred in the Iberian Peninsula (e.g. 1980, 1983-1986, 1988-1992, 1998-1999 and 2005-2007) which largely affected rivers in the Central Pyrenees (Lorenzo-Lacruz et al., 2013).

In spite of the inter-annual fluctuations, precipitation records seem to follow a decreasing tendency, while temperature shows the opposite trends. Results of the Mann-Kendall test for the whole period (1971-2014) are shown in Table 3. The test suggested a downward trend for precipitation, although it did not prove to be significant at a reliable confidence level (i.e. *p*-value >0.1). Conversely, positive trends in temperature proved to be very strong, with results being significant at the 95% confidence level. TETIS model results for snowpack were also analysed, since it is an important driver of the hydrosedimentary response in this basin. Results indicated a significant decrease in this variable at the 95% confidence level.

Long-term mean annual values (for the 43 year period) runoff and sediment yield in the Canalda basin were 5.2 $hm^3 y^{-1}$ and 276 ton y^{-1} respectively. Annual runoff series showed a significant negative trend at the 95% confidence level. In contrast, results for the sediment yield were not as clear, and despite showing a decreasing trend, results did not prove to be significant (i.e. *p*-value >0.5).

3.4.2 Trends in extreme events

Results indicated that most of the days contributed very little to the total amount of annual precipitation, runoff and sediment yield (i.e. events corresponding to C1), while a high percentage was concentrated in very few events (corresponding to C5; Figure 6). The number of events in each class decreased progressively. For example in the case of runoff, 40% of the time is required on average to accumulate 20% of the total annual runoff; while the final 20% (corresponding to high magnitude events) is transported during 6% of the time.

Results indicating the observed temporal trend in the contribution of each category to the total annual are shown in Table 4. Contrasting trends for each category were obtained, although most of them did not provide adequate statistical evidence (i.e. large *p*-values) to reach solid conclusions on trends in the data.

Small decreases in mid-range magnitude events (categories C2, C3, C4) were observed in precipitation and runoff, although such trends showed a low level of statistical significance. However, in the case of runoff, the contribution of category C3 seemed to show the largest reductions over time. Contrary to such downward trends, categories corresponding to low and high magnitude events (C1 and C5 respectively) showed a slight increasing trend, although again results did not prove to be significant.

In contrast, all categories but the low-magnitude one (C1) for annual sediment yield showed increasing trends, with C2 (mid-range magnitude) and C5 (high magnitude) showing a relatively high statistical significance. C1 was the only category for this variable that followed a fairly strong downward trend.

In order to further prove temporal changes in the distribution of sediment transport and annual runoff, we elaborated the cumulative frequency curve for both variables and for three consecutive periods (Figure 7). These three periods were determined according to the different land-use maps used in the modelling approach: 1971-1985; 1986-2000 and last 2001-2014 (since land-use changes in 2005 and 2009 were negligible, time intervals for these maps were aggregated).

These curves indicated changes in the frequency distribution of discharge series over time. Runoff proved to be more constant through time than sediment yield, which indicates that sediment is transported during relatively few events. Overall, runoff cumulative curves seemed to have moved left over time, suggesting that the same amount of runoff is generated during shorter periods. For example, while for the period 1971-1985 50% of the runoff is generated during approximately 20% of the time, for the most recent period (2001-2014) the same amount of runoff is generated during 10% of the time.

In the case of the sediment transport, a high load during limited periods of time is observed, which highlights the relevance of high magnitude events in sediment transport. For this variable, curves also seemed to move left-wards in the figure, although this pattern does not follow a consecutive (chronological) order as clear as in the case of the runoff (i.e. the 1971-1985 curve sits between the other two curves). This could be due to the fact that the periods 1971-1985 and 2001-2014 include two of the largest flood events that occurred in the basin during the whole study period (i.e. events in 1982 and 2008, see Figure 5), which were responsible for the majority of the sediment load transported during their respective time intervals.

A trend test was also performed in order to determine temporal changes in the mean value of each magnitude category. Results indicated a decreasing trend in the mean value of all runoff and rainfall categories as well as for sediment yield. Nevertheless, while changes in the magnitude of runoff categories proved to be strong, trends in precipitation and sediment yield did not prove to be significant.

Together, these observations may be suggesting an increase in the river's torrential behaviour, with an increase in the annual contribution of both, low flows and high flows, while the contribution of mid-range flows seem to have decreased. Sediment yield seemed to decrease over time, particularly during low-magnitude events, although results were not strong enough to reach firm conclusions. Last, a generalised reduction in runoff magnitude for all categories was detected, although it could not be explained by changes in precipitation, since no significant trends were found for this.

3.5. Seasonal trends

Results showing seasonal trends are shown in Table 6. Overall, positive significant trends were detected for temperature and for all seasons. Results for precipitation were less clear and seemed to follow a diverging seasonal behaviour: spring and summer showed strong significant trends at the 90% confidence interval. In contrast, decreasing trends in winter were weaker and not significant, while autumn showed and upward tendency at a very low confidence level (i.e. *p*-value >0.6).

Seasonal runoff trends mimicked the direction of annual changes for this variable. A strong decrease was detected throughout the year at a relatively reliable confidence level (between 90-95%) except for autumn, when decreasing trends did not prove significant. In the case of sediment yield, only spring showed a significant decrease at the 90% confidence level. Summer also showed a downward trend, while results suggested an increase during autumn and winter. However, trends for these three seasons were very weak and the test yielded results with a very low level of confidence.

3.6. Effects of climate change and afforestation

Results from the model using the *scenario* dataset (considering that no afforestation has occurred and agricultural land has remained constant over time) are shown in Table 3b. When runoff and sediment yield values of the *actual* and *scenario* datasets are compared, an increase in both variables is observed when no afforestation is taken into account (Figure 8). The non-parametric Kruskal-Wallis test was performed to test differences between values from the scenario and actual datasets. Results indicated a significant difference for runoff and sediment yield values for both datasets (H= 63.5 and p-value<0.001 for runoff and H= 5.6 and p-value = 0.01 for sediment yield). In the case of runoff, mean annual values for the whole period (1971-2014) in the *scenario* dataset were 24% larger than the *actual* dataset: from a mean annual runoff of 5.2 hm^3 y^{-1} in the *actual* dataset to 6.4 hm^3 y^{-1} in the *scenario* dataset. The increase in mean annual sediment yield was also notable, with annual sediment yield values in the *scenario* dataset nearly 80% larger than the *actual* dataset (from 276 ton y^{-1} in the *actual* dataset to 506 ton y^{-1} in the *scenario*).

Also, when no afforestation is considered, the decreasing temporal trend in runoff is weaker and becomes non-significant at the 95% confidence level. Results regarding annual sediment yield showed a reverse in trend direction: instead of decreasing values over time, results from the scenario dataset yielded positive trends, although they did not appear to be significant. Overall, afforestation at the Canalda basin seemed to be intensifying runoff reductions as well as preventing an increase in the sediment load.

ANCOVA results indicated that regression slopes between the *actual* and *scenario* dataset differed for both variables (F=197, p-value= <0.001 for runoff; and F=75, p-value= <0.001 for sediment yield). This confirmed the diverging tendencies for runoff and sediment yield when afforestation is not considered in the model. The relative effects of increased forested area were assessed by assessing trends in the residuals (i.e. year-to-year differences between the *actual* and the *scenario* datasets). Results confirmed previous results on the significant effect of afforestation, since values for both runoff and sediment yield showing significant decreasing trends (τ_{MK}= -0.95 and *p*-value < 0.001 for runoff, and τ_{MK}=-0.41 and p-value<0.001 for sediment yield).

Overall, a reduction in runoff of c.a. 20% in comparison with 1971 was observed in the *actual* dataset (including climate and land-use changes). However, such decrease can be almost attributed only to increased forested area: a reduction of around 1% is observed in the *scenario* dataset, and also such reduction did not prove to be significant. Thus, changes in runoff observed may be mainly attributed to the increased forested cover, which has led to a decrease of around 1.5 mm per unit of forest increase (in km^2) for the period 1971-2014.

In the case of the sediment yield, a mean reduction of around 8% was observed in the *actual* dataset in comparison with 1971 values. The sediment yield values from the *scenario* dataset at the end of the study period almost doubled the values in 1971 (Figure 8), which corresponds to an increase of almost 98%. However, such values should be interpreted with care, since none of these increasing trends showed statistical significance. Despite this, the trends seem to reflect the role of forest in protecting soil and hence preventing or reducing its erosion.

4. DISCUSSION

4.1. Climate trends

Increasing trends were particularly strong for temperature at both time scales (i.e. annual and seasonal), as has been already reported in previous studies in the Iberian Peninsula (e.g. de Castro et al., 2005). In contrast, diverging results were found for precipitation. Total annual values did not seem to decrease significantly for our study period. López-Moreno et al., (2011) also found similar results across the Ebro basin, where precipitation seemed to be relatively stable over time and only a few small areas showed a statistically significant decrease. At the seasonal scale, significant decreasing trends were found for spring and summer. The decrease in summer precipitation and the risk of summer drought has been already reported for central Europe and the Mediterranean area (IPCC, 2013; Meehl et al., 2007; Schneider et al., 2013) and Climate models project substantial summer precipitation reductions in the Mediterranean region (Bladé et al., 2011).

Results on the varying contribution of low and high magnitude rainfall events did not provide a clear evidence of the change of their contribution to the total annual rainfall. A slight decrease in the frequency of high-magnitude rainfall events was detected, although such trend was not significant in our case of study. The mean value of each rainfall magnitude category also seemed to decrease, although trends were not significant for any of them. Despite the torrential behaviour and the spatio-temporal variability in rainfall is an intrinsic characteristic of Mediterranean weather, some projections from global scenarios have indicated an increase of high intensity rainfall episodes (Stojkovic et al., 2014). For example, Alpert et al., (2009) also indicated for Spain that the rainfall categories at both distribution extremes (i.e. light and heavy/torrential events) increased their contributions to the total annual rainfall.

Overall, precipitation trends were controversial, since annual values did not show a decreasing significant trend, although such trends were relatively marked for spring and summer. In the Iberian Peninsula, González-Hidalgo et al., (2011) found important differences in the magnitude and direction of precipitation trends, mainly driven by the length of the study period and the geographical location studied (Llasat and Quintas, 2004). However, a spatially generalised decreasing trend was reported for March and June in these studies. Such pattern was found to lead to a redistribution of precipitation throughout the year, reducing the wet season length (resulting from the negative tendency in March) and concentrating the precipitation at the beginning of the wet season in October.

4.2. Trends in streamflow

Our results indicated an overall decrease in annual streamflow in the Canalda basin of around 20%, which agrees with earlier studies in the Pyrenees (Gallart and Llorens, 2004, García-Ruiz et al., 2008, Lorenzo-Lacruz et al., 2012). For example, Beguería et al., (2006) reported a runoff reduction of around 30% for the past 50 years in the Pre-Pyrenean region.

Decreasing trends were observed at the annual time scale and were also particularly strong for spring and summer. To some extent, such reductions could be attributed to the reduced rainfall also detected for these seasons as well as to the increased evaporative demand during summer (Kundzewig et al., 2007). In addition, reductions in the snowpack observed in the basin may also be influencing the observed decrease in spring. Several studies have already reported a reduction in the snowpack in the Pyrenees during the second half of the 20th century due to increased winter temperatures (e.g. López-Moreno, 2005), which subsequently results in less snowmelt during this season.

The study of changes in the contribution of high flows suggested increasing trends in the contribution of high and low flows to the total annual runoff, while the frequency of mid-range flows seemed to decrease. Despite such results yielded a low significance level, frequency curves seemed to confirm this observation. This could be indicating a possible increase in the torrential behaviour of the river, with a large proportion of the total annual flow accumulated during shorter periods of time. Such pattern could be the result of the increase in the frequency of torrential storms and an increase of occurrence of low-flow periods.

Some studies in the Mediterranean project that river flows in this region are likely to become more intermittent in the future (e.g. Schenider et al., 2013), and hence tend to compress most of the runoff in a few number of events. Despite this, our results diverge from those found in a number of rivers in the Spanish Pyrenees, where a marked decrease in the contribution of high flows has been detected (López-Moreno et al. 2006). Nevertheless, these studies also detected an increase in the frequency of low flows and a decrease of moderate events, as observed in the Canalda basin. The decrease in the contribution of moderate events may be influenced by the increased in forest cover: while vegetation may not have relevant effects in terms of interception during very intense rainfall events, it might notably reduce the intensity of events with moderate intensity (e.g. de Roo et al., 2003).

Discrepancies in the results regarding high flow events could be mainly due to the different area studied. Previous studies have been undertaken in basins located in the northern part of the Pyrenees, while the Canalda basin has a greater Mediterranean component. In addition, López-Moreno et al., (2006), acknowledge some uncertainties at the catchment level: peak flow occurrence may also be affected by other factors such as catchment size, forested area or lithology, which have not been considered and may be influencing the different response of the basins to *extreme* events.

The reduction of the magnitude of all flow categories was evident, particularly for low and high flows. Such decrease cannot be explained by precipitation, since categories for these variables did not show such a marked trend. Therefore, changes in the magnitude of flows shall be attributed to the growth of forest occurred during the second half of the 20^{th} century. This has led to an increased importance of interception and transpiration, as already suggested in López-Moreno et al., (2006). The reduction of peak flows has resulted in a stabilization and revegetation of flood plains and formerly active gravel bars, as has been observed in other basins (Beguería et al., 2006) and can also be confirmed by field observations in the Canalda basin.

4.3. Trends in sediment yield

In spite of the significant scatter resulting from seasonal causes and hysteretic patterns, discharge and suspended sediment transport have been reported to show a significant relationship in the Canalda basin (Batalla et al., 2005). Therefore, overall reductions in streamflow will consequently result in a decrease in the amount of sediment transport. The temporal decrease in sediment load in Canalda was quite subtle. However, results from sediment transport models usually show controversial results due the number of drivers influencing soil erosion and sediment transport as well as deposition in the channel and the flood plain. Also, low geomorphic activity, along with the wide variability in the annual sediment yield reported in the basin (e.g. from 16 to 41800 tons y^{-1} according to Batalla et al., 2005) may also be influencing the identification of marked trends. Soil erosion rates of the Ribera Salada River catchment are rather low compared to other Pyrenean or Mediterranean catchments or plots (i.e. González-Hidalgo et al., 2007), due to the high infiltration rates observed within the catchment. Specific sediment loads have also been reported to be relatively low when compared with similar Mediterranean counterparts (i.e. 12 ton km^{-2}; Vericat and Batalla, 2010). Other studies have also indicated a reduction in sediment resulting from the revegetation and stabilization of fluvial channels (Beguería et al., 2006), which have also been observed along the mainstem of the Ribera Salada. Decreases in the annual sediment yield found in our study are in line with results from other studies indicating a reduction in the sediment transport, which has resulted in a decrease in siltation rates in the Pyrenean reservoirs (e.g. López-Moreno, 2003).

Müeller et al., (2009) applied the hydrological and sediment model WASA-SED (Mamede, 2008) in the Canalda basin for the years 1999-2000 with the aim of assessing the relative effects of climate and land use change. Due to the limited amount of information available when their study was carried out, the model was not calibrated, although its results were considered plausible. In terms of water discharge, both models obtained similar results. For example, the two largest events of the years 1999 and 2000 (12/11/1999 and 10/6/2000) were estimated to have peak discharges of 4.2 and 2.1 $m^3 s^{-1}$ respectively by TETIS, while for WASA-SED they had a peak discharge of slightly above and slightly below 4 $m^3 s^{-1}$ respectively. Concerning sediment transport, Müller et al. (2009) provided values of suspended sediment yield of 0.315 t $ha^{-1} yr^{-1}$ and 0.370 t $ha^{-1} yr^{-1}$ for the years 1999 and 2000 respectively, while the TETIS model returned values of 0.130 5 ton $ha^{-1} yr^{-1}$ and 0.136 ton $ha^{-1} yr^{-1}$ respectively. It is difficult to establish which model obtained the most accurate results without knowing the observed value, but it can be stated that, at least, both models returned values of the same order of magnitude, which is a partially satisfactory result, given the large uncertainty affecting this kind of processes. Nevertheless, Müller et al. (2009) acknowledged the limitations of their study by stating that the lack of data did not allow giving a more accurate picture of the sediment transport. To some extent, the present study attempts to fill this gap by employing more accurate daily suspended sediment data to calibrate and validate the TETIS model, in order to provide a more reliable tool for land-use change impact analysis. Despite the limitations, these authors detected an increase in sediment yield of up to 76% when no changes in land use were considered in the analysis (i.e. no afforestation), a percentage of the same order of magnitude that the one found in this study.

The frequency analysis indicated the same trends as in the case of runoff, with most of the sediment transport concentrated in few events. However, in this case, low magnitude events seemed to decrease its contribution to the total annual sediment load, which may be the result of the reduced transport capacity of declining low flows. The amount of sediment transported by large events also followed a decreasing pattern, potentially driven by the decrease in peak flows and hence the flow competence of large events (i.e. stream’s ability to transport sediment). Altogether, results might be suggesting that, apart from showing an overall decrease, sediment transport becomes more compressed over time, and hence shows an increasing dependence on flood events. For example, Batalla et al., (2005) reported that the major part of the annual load is transported by discharges equalled or exceeded less than 10% of the time. Bussi et al., (2014) also reported a trend towards a dependence on large events under different scenarios of climate change. These results highlight the increasing importance of floods in the long-term sediment load of Mediterranean basins.

The relative role of woodland in annual sediment yield was evident when trends were compared with a hypothetical scenario of no afforestation, under which annual sediment loads increased markedly. Despite the low significance of the trends found, woodland proves to be preventing the erosion in the basin and driving the observed reduction in sediment load. The way in which afforestation has occurred may have also influenced the sediment patterns observed. Ubalde et al., (1999) observed that most of the changes from agricultural areas to woodland were taking place in north-facing and high slopes, while agriculture was concentrated in low-lands. This may be suggesting that those areas more prone to erosion due to its increased slope have been covered by forest, potentially leading to a decreased in soil loss.

5. FINAL REMARKS

Increased forest cover in mountainous basins has been reported to play a major role in the hydrosedimentary response observed and hence determine the availability of water resources as well as the amount of sediment load. Given the increased importance of water resources under the projected climate scenarios in the Mediterranean, numerous studies have been undertaken in order to provide new prospects on the relationship between climate, land use and hydrological and sediment transport processes. Such studies have been undertaken at different spatial scales, from experimental plots or basins to large catchment sizes (see Walling, 1999 for a comprehensive review). Overall, results evidence the sensitivity of erosion and sediment transport processes to changing climate and hydrological behaviour of basins. However, results are still controversial, mainly regarding the sedimentary response of basins, for which trends may not be evident (as has been the case in our study). Given the complex relationship between rainfall, runoff, soil detachment and subsequent transport, extrapolation of the results found at a single basin may not be directly extrapolated to other basins. The identification of trends will strongly depend on the geographical location of the basin, as well as the characteristics of the basin and the length of the series analysed. Also, the scale at which the studies are undertaken may greatly influence the trends observed. Rainfall and sediment yields in arid and semi-arid areas have been reported to be highly scale-dependent, (e.g. Kirkby et al., 1996, Mayor et al., 2011). This dependency, along with the diverging results found, arises the question of which scale is the most appropriate to assess changes in the hydrosedimentary response of basins. Such scale should be able to show the observed trends without being masked by a large intra- and inter-annual variability.

In this paper we have provided an insight into the effects that recent forest growth and climate change have exerted on the hydrological and sediment transport regime in the Canalda basin, a mountainous basin representative of the physical characteristics and land-use changes that most southern Pyrenean basins have experienced in the last half of a century. Overall, results have indicated that increased forest areas are the major driver of reduced streamflows and the magnitude of peak floods. Precipitation seems to have remained constant over time, although redistribution throughout the year may be occurring, with reduced rainfall mainly in spring and summer. Results regarding sediment loads were not significant, although decreases were detected over the studied period.

Under future climate projections, soil erosion as well as availability of water resources are among the main environmental problems in the Mediterranean areas. Climate scenarios in the Mediterranean point towards an intensification of torrential and temporally variable rainfall events as well as an increased erosion and desertification. How such changes in combination with changes in the territory will affect the response in river basins is not yet well understood, particularly regarding the assessment of the effect on sediment loads.

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REFERENCES

Allen, R., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No 56, FAO, Rome.

Alpert, P, Ben-gai, T., Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., Manes, A., 2009. The paradoxial increase of Mediterranean extreme rainfall in spite of decrease in total values. *Geophysical Research Letters*, doi: 10.1029/2001GL01355.

Andrés-Doménech, I., Múnera, J.C., Francés, F., Marco, J.B., 2010. Coupling urban event-based and catchment continuous modelling for combined sewer overflow river impact assessment. *Hydrology and Earth System Sciences*, 14: 2057–2072. doi:10.5194/hess-14-2057-2010

Arnáez, J., Oserín, M., Ortigosa, L. y Lasanta, T. (2008): Cambios en la cubierta vegetal y usos del suelo en el Sistema Ibérico Noroccidental entre 1956 y 2001: los Cameros (La Rioja, España). *Boletín de la Asociación de Geógrafos Españoles*, 47: 195-211

Batalla, R.J., Garcia, C., Balasch, C., 2005. Total sediment load in a Mediterranean mountainous catchment (the Ribera Salada River, catalán Pre-Pyrenees, NE Spain). *Zeitschrift für Geomorphologie*, 49: 495-514.

Begueria S, López-Moreno JI, Lorente A, Seeger M, Garcia-Ruiz JM. 2006. Assessing the effect of climate oscillations and land-use changes on streamflow in the central Spanish Pyrenees. *Ambio*, 32: 283-283.

Benyon R, Theiveyanathan T and Doody T (2006) Impacts of Plantations on groundwater in south-eastern Australia. *Australian Journal of Botany*, 54: 181-192.

Bladé, I., Liebmann, B., Fortuny, D., Jan van Oldenborh, G., 2011. Observed and simulated impacts of the summer NAO in Europe: implications for projected drying in the summer Mediteerranean region. *Climate Dynamics*, DOI 10.1007/s00382-011-1195-x

Burn, D.H., Hannaford, J., Hodgkins, G.A., Whitfield, P., Thorne, R., Marsh, T.J., Hydrologic Reference Networks II. Using Reference Hydrologic Networks to assess climate driven change. *Hydrological Sciences Journal*, 57: 1580-1593.

Bussi, G., Rodríguez-Lloveras, X., Francés, F., Benito, G., Sánchez-Moya, Y., Sopeña, A., 2013. Sediment yield model implementation based on check dam infill stratigraphy in a semiarid Mediterranean catchment. *Hydroogy and Earth System Sciences*, 17: 3339–3354. doi:10.5194/hess-17-3339-2013

Bussi, G., Francés, F., Horel, E., López-Tarazón, J.A., Batalla, R.J., 2014. Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. Journal of *Soils and Sediments*, 14: 1921–1937. doi:10.1007/s11368-014-0956-7

Calder IR. 1993. Hydrologic effects of land use change. In: Maidment, D.R. (ed.): Handbook of Hydrology. New York, McGraw-Hill, 13.1 – 13.50.

Castro De M, Martín-Vide J, Alonso S. 2005. El clima de España pasado, presente y escenarios de clima para el siglo XXI. In: Moreno-Rodríguez, J.M. (Eds). Evaluación preliminar de los impactos en España por efecto del cambio climático. Ministerio de Medio Ambiente y Universidad de Castilla-La Mancha, 1–64.

Cerdà, A., Lasanta, T., 2005. Long-term erosional responses after fire in the Central Spanish Pyrenees. 1. Water and sediment yield. *Catena*, 60: 59-80.

Chase, T.N., R.A. Pielke Sr., T.G.F. Kittel, R.R. Nemani & S.W. Running (2000). Simulated impacts of historical land cover changes on global climate in northern winter. *Climate Dynamics*, 16: 93-105.IPCC; 2007

Cowpertwait, P., Ocio, D., Collazos, G., de Cos, O., Stocker, C., 2013. Regionalised spatiotemporal rainfall and temperature models for flood studies in the Basque Country, Spain. *Hydrology and Earth System Sciences*, 17: 479–494. doi:10.5194/hess-17-479-2013

Delgado, J., Llorens, P., Nord, G., Calder, I. R. & Gallart, G. (2010) Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: The Cardener River basin (NE Spain). *Journal of Hydrology*. 383, 125–134.

Déqué, M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: Model results and statistical correction according to observed values. *Global Planetary Change*, 57: 16–26. doi:10.1016/j.gloplacha.2006.11.030

Douglas, E.M., Vogel, R.M., Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology*, 38: 413-423.

Engelund, F., Hansen, E., 1967. A monograph on sediment transport in alluvial streams. Monogr, Denmark Tech Univ, Hydraul Lab.

Estruch, J., 2001. Informació del territorio i càlcul de l'escolament superficial mitjançant el model HEC-1. Aplicació al mapa de sòls 1:50000 de la conca de Canalda (el Solsonès). *Butlletí de la Institució Catalana d'Història Natural*, 69: 95-116.

Francés, F., Vélez, J.I., Vélez, J.J., 2007. Split-parameter structure for the automatic calibration of distributed hydrological models. *Journal of hydrology*: 332, 226–240. doi:10.1016/j.jhydrol.2006.06.03

Gallart F, Llorens P. 2002. Water resources and environmental change in Spain. A key issue for sustainable catchment management. In: Garcia-Ruiz, J.M., Jones., A.A.A., Arnáez, J. (Eds), Environmental change and water sustainability. IPE (CSIC), Zaragoza, pp. 11-20.

Gallart F, Llorens P. 2004. Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula. *Physics and Chemistry of the Earth*, 29: 769-773.

García-Ruiz, J.M., Regüés, D., Alvera, B., Lana-Renaul, N., Serrano-Muela, P., Nadal-Romero, E., Navas, A., Latron, J., Martí-Bono, C., Arnáez, J., 2008. Flood generation and sediment tranposr in experimental catchments affected by land use changes in the central Pyrenees. *Journal of Hydrology*, 356: 245-260.

García-Ruiz, J.M., Lana-Renault, N., 2011. Una revisión de los efectos hidrológico y erosivos del abandono de tierras de España. *Geographicalia*, 59-60: 125-135.

Gessesse B, Bewket W, Bräuning A. 2014. Model-based characterization and monitoring of runoff and soil erosion in a reponse to land use/land cover changes in the Modjo watershed, Ethiopia. *Land Degradation and Development.* doi: 10.1002/ldr.2276.

González-Hidalgo, J.C., Peña-Monné, J.L., de Luis, M., 2007. A review of daily soil erosion in Western Mediterranean areas. *Catena*, 71: 193–199. doi:10.1016/j.catena.2007.03.005

González-Hidalgo, J.C., Batalla, R.J., Cerdà, A., de Luis, M., 2010. Contribution of the largest events to suspended sediment transport across the USA. *Land Degradation and Developpment*, 21: 83–91. doi:10.1002/ldr.897

Herrera, S., Gutiérrez, J.M., Ancell, R., Pons, M.R., Frías, M.D., Fernández, J., 2012. Development and analysis of a 50-year high-resolution daily gridded precipitation dataset over Spain (Spain02). *International Journal of Climatology*, 32: 74–85. doi:10.1002/joc.2256

Herrera, S., Fernández, J., Gutiérrez, J.M., 2014. Update of the Spain02 Gridded Observational Dataset for Euro-CORDEX evaluation: Assessing the Effect of the Interpolation Methodology. *International Journal of Climatology*. In review.

IPCC, 2013. Working Group I contribution to the IPCC 5th Assessment Report "Climate Change 2013: The Physical Science Basis". 12th Session of Working Group I and the 36th Session of the IPCC, 26 September 2013, Stockholm (Sweden).

Julien, P.Y., Simons, D.B., 1985. Sediment transport capacity of overland flow. Trans. ASAE.

Julien, P.Y., 2010. Erosion and sedimentation, 2nd ed. Cambridge University Press.

Kahya E, Kalaci S. 2004. Trend analysis of streamflow in Turkey. *Journal of Hydrology*, 289: 128-144.

Kendall MG. 1975. Rank Correlation Measures. Charles Griffin, London, 202 p.

Kirkby, M.J., Imeson, A.C., Bergkamp, G., Cammeraat, L.H., 1996. Scaling up processes and models from the field plot to the watershed and regional scales. *Journal of Soil and Water Conservation*, 51: 391–396.

Kundzewig ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z, Shiklomanov IA. 2007. Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working group II to the Fourth Assessment Report of the Intergovernmental Panel on Cliamte Change. In: Parry, M.L., Canziani, F., Palutikof, J.P., Van der Linden, P.J., Hanson, E.D, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Lasanta, T., García-Ruiz, J.M., 1996. Erosión y recuperación de tierras en áreas marginales. Instituto de Estudios Riojanos, SEG, Logroño.

Lasanta, T., Vicente, S., Cuadrat, J.M., 2000. Marginacio´n productiva y recuperacio´ n de la cubierta vegetal en el Pirineo: un caso de estudio en el Valle de Borau. *Boletín de la Asociación de Geógrafos Españoles*, 29: 5 – 28.

Llasat MC, Quintas L. 2004. Stationarity of monthly rainfall series since the middle of the XIXth century. Application to the case of Peninsular Spain. *Natural Hazards*, 31: 613-622.

Llorens, P., Poch, R.M., Latron, J., Gallart, F., 1997. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area. I. Monitoring design and results down to the event scale. *Journal of Hydrology*, 199: 331-345.

Loaiza, J.C., 2007. Soil hydrology in the Ribera Salada Catchment (Catalan Pre Pyrenees) Application of hydrologic models for the estimation of hydrologic transitional regimes. Unpublished PhD thesis. Universitat de Lleida, Lleida, Spain.

López-Moreno, J.I., Beguería, S., Valero-Garcés, B., García-Ruiz, J.M., 2003. Intensidad de avenidas y aterramiento de embalses en el Pirineo Central Español. *Ería*, 61: 159-167.

López-Moreno, J.I., 2005. Recent variations of snowpack depth in the Central Spanish Pyrenees. Artic, *Antartic and Alpine Research*, 37: 253-260.

López-Moreno, J.I., Begería, S., García-Ruiz, J.M. 2006. Trends in high flows in the central Spanish Pyrenees: response to climatic factors or tol and-use change?. *Hydrological Sciences Journal*, 51: 1039-1050.

López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M., 2011. Impact of climate evolution and land use change on water yield in the Ebro basin. *Hydrology and Earth System Sciences*, 15: 311-322.

López-Tarazón, J.A., Batalla, R.J., Vericat, D., Francke, T., 2009. Suspended sediment transport in a highly erodible catchment: The River Isábena (Southern Pyrenees). *Geomorphology*, 109: 210-221.

Lorenzo-Lacruz J, Vicente-Serrano SM, López-Moreno JI, Morán.-Tejada E, Zabalza J. 2012. Recent trends in Iberian streamflows. *Journal of Hydrology*, 414-415: 463-475.

Lorenzo-Lacruz, J., Morán-Tejeda, E., Vicente-Serrano, S.M., López-Moreno, J.I., 2013. Streamflow droughts in the Iberian Peninsula between 1945 and 2005: spatial and temporal patterns. *Hydrology and Earth System Sciences*, 17: 119-134.

Mamede, G., 2008. Reservoir sedimentation in Dryland Catchments: modelling and Management. PhD thesis. University of Potsdam.

Mann HB. 1945. Non-parametric tests against trend. *Econometrica*, 13: 245-259.

Marey-Pérez MF, V Rodríguez-Vicente. 2008. Forest transition in Northern Spain: Local responses on large-scale programmes of field-afforestation. *Land Use Policy*, 26: 139-156.

Mayor, A.G., Bautista, S., Bellot, J., 2011. Scale-dependent variation in runoff and sediment yield in a semiarid Mediterranean catchment. *Journal of Hydrology*, 397: 128–135.

Meehl GA et al. (2007) Global climate projections. In: Solomon S et al. (eds) Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, pp 747–845

MIMAM, 2000. Estrategia Forestal Española. Ministerio de Medio Ambiente, Madrid, 250 pp. http://www.mma.es/portal/secciones/biodiversidad/montes_politica_forestal/estrategiamonte/descargas_efe.htm>.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harme, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASAE*, 50: 885–900.

Müeller, E.N., Francke, T., Batalla, R.J., Bronstert, A., 2009. Modelling the effects of land-use change on runoff and sediment yield for a meso-scale catchment in the Southern Pyrenees. *Catena*, 79:288-296

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecastin through conceptual models - Part 1 - A discussion of principles. *Journal of Hydrology*, 10: 282–290. doi:10.1016/0022-1694(70)90255-6

Orozco, M., 2003. Hidroquímica de aguas superficiales y usos del suelo en la cuenca de la Ribera Salada (El Solsonès, NE España). Unpublished PhD thesis. Universitat de Lleida, Lleida, Spain.

Osborn TJ, Hulme M, Jones PD and Basnett TA (2000) Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology*, 20: 347- 364.

Piao, S., P. Friedlingstein, P. Ciais, N. de Noblet-Ducoudre´, D. Labat & S. Zaehle (2007). Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends. *PNAS*, 104: 15242-15247.

Poch, R.M., Pratdesaba, E., Rius, J., 2002. Hydrology of forest soils in El Solsonès (Catalonia): contribution to the catchment water resources. In: Rubio, J.L., Morgan, R.P.C., Asins, S., Andreu, V. (Eds.). Proceeding of the third International Congress Man and Soil at the Third Millenium. Geoforma Ediciones, Logroño, 2002.

R Development Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN: 3-900051-07-0 http://www.R-project.org/

Roo de, A.D., Schumuck, G., Perdigao, V. & Thielen, J. (2003) The influence of historic land use changes and future planned land use scenarios on floods in the Oder catchment. *Physics and Chemistry of the Earth*, 28: 1291-1300.

Salazar, S., Francés, F., Komma, J., Blume, T., Francke, T., Bronstert, A., Blöschl, G., 2013. A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions. *Natural Hazards and Earth System Sciences*, 12: 3287–3306. doi:10.5194/nhess-12-3287-2012

Schneider, C., Laizé, C.L.R., Acreman, M.C., Flörke, M., 2013. How will climate change modify river flow regimes in Europe? *Hydrology and Earth System Sciences*, 17: 325-339.

SSS, 1993. Soil Survey Manual. Soil Survey Division Staff. Soil Conservation Service. U.S. Department of Agriculture. Handbook 18.

SSS, 2006. Keys to Soil Taxonomy. 9th Edition, SSS Soil Conservation Service. Agric. US Gov printing office. Washington, D.C.

Stojkovic, M., Ilic, A., Prohaska, S., Plavsic, J., 2014. Multi-temporal Analysis of Mean Annual and Seasonal Stream Flow Trends, Including Periodicity and Multiple Non-Linear Regression. *Water Resources Management*, 28: 4319-4335.

Tao H, Gemmer M, Bai Y, Su B, Mao W. 2011. Trends of streamflow in the Tarim River Basin during the past 50 years: Human impact or climate change*? Journal of Hydrology*, 400:1-9.

Ubalde, J.M., Rius, J., Poch, R.M., 1999. Monitorización de los cambios de uso del suelo en la cabecera de cuenca de la Ribera Salada mediante fotografía aérea y SIG (El Solsonés, Lleida, España). *Pirineos*, 153-154: 101-122.

USACE (U.S.A.C.O.E.) 2010. HEC-RAS, Hydrologic Engineering Centers River Analysis System, Usuer's Manual, Version 4.1. U.S. Army Corps of Engineers, Davis, 790 p. Available in: http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf (fecha de acceso: 05/02/2014)

US-EPA (2011). An Approach for Estimating Stream Health Using Flow Duration Curves and Indices of Hydrologic Alteration. Protocol document for assessing stream health using stream flow duration curves and flow based hydrologic indices. Agrilife research and extension, Texas A&M System. March 2011.

Vanham, D., Rauch, W., 2009. Mountain water and climate change. In: Climate Change and Water- International Perspectives on Mitigation and Adaptation. Joel Smith, Carol Howe and Jim Enderson (Eds) page 21-40, ISBN 9781843393047

Vericat, D., Batalla, R.J., 2010. Sediment transport from continuous monitoring in a perennial Mediterranean stream. *Catena*, 82: 77–86. doi:10.1016/j.catena.2010.05.003

Viola, F., Daly, E., Vico, G., Cannarozzo, M., Porporato, A., 2008. Transient soil-moisture dynamics and climate change in Mediterraean ecosystems. *Water Resources Research*, 44: 1-12, W11412, doi: 10.1029/2007WR006371.

Viviroli, D., Weingartner, R., 2004. The hydrological significance of mountains: from regional to global scale. *Hydrology and Earth System Sciences Discussions*. Copernicus Publications, 8: 1017-1030

Walling, D.E. 1999. Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, 410: 223-240

Wang S, Zhang Z, McVicar TR, Guo J, Tang Y, Yao A. 2013. Isolating the impacts of climate change and land use change on decadal streamflow variation: Assessing three complementary approaches. *Journal of Hydrology*, 507: 63-74.

Zhang L, Dawes WR, Walker GR. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*, 37: 701-708.

Figure 1. Location of (a) the Ribera Salada basin within the Iberian Peninsula and the Ebro basin; (b) Canalda basin within the Ribera Salada. Location of the meteorological stations used in the TETIS model and the monitoring station and the basin outlet is also shown.

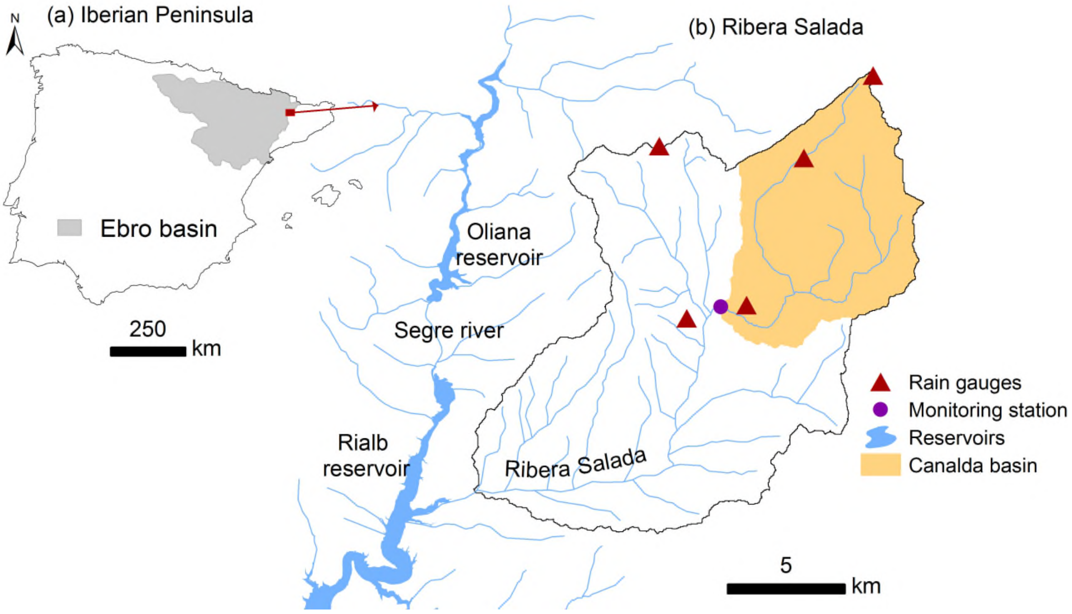

Figure 2. Land cover changes in the Canalda basin between 1957 and 2009 for the Canalda basin.

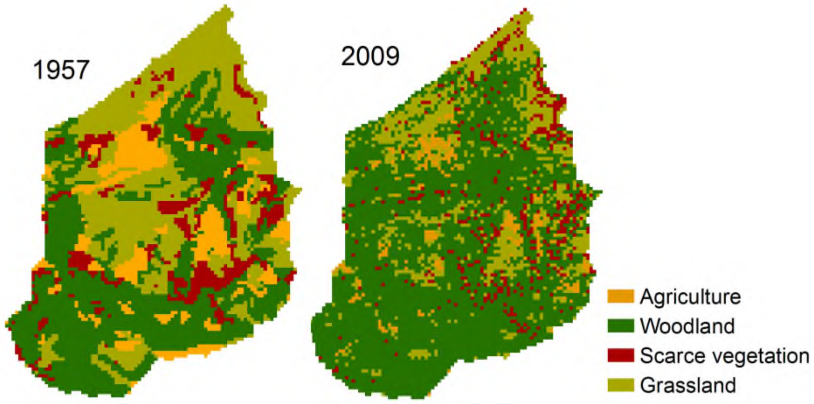

Figure: 3. Calibration and validation results for the hydrological (discharge, Q, m^3s^{-1}) and sediment transport sub-model (Suspended Sediment Concentration, SSC; $mg \cdot l^{-1}$) at the Canalda monitoring station. Left hand diagrams show observed *vs*. simulated values for each variable, while the diagrams on the right show boxplots for observed and simulated values.

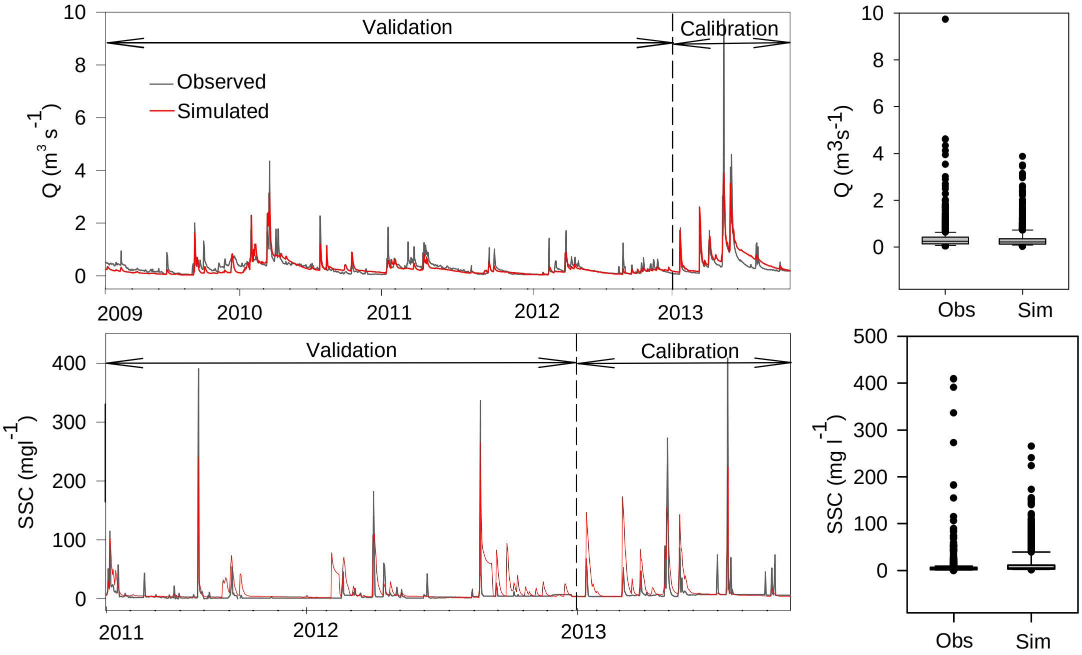

Figure 4. Observed and simulated Q-SSC relationship.

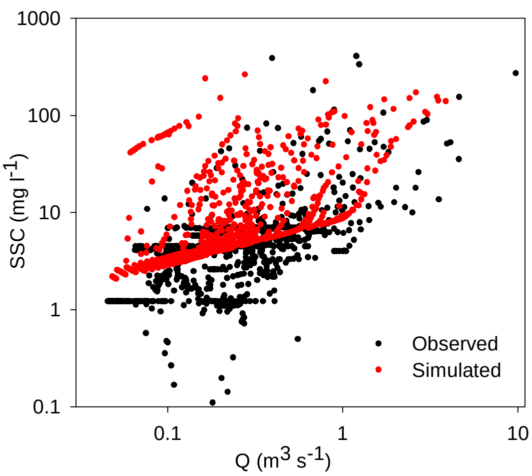

Figure 5. Annual series for (a) Precipitation (Prec; mm/year), (b) Temperature (Temp; ºC); (c) Runoff (R; $hm^3 y^{-1}$) and Sediment Yield (SY, ton y^{-1}). Red line indicated the smoothed series for each variable (using LOESS with a time span of 0.2 –i.e. 8.6 years-); horizontal dotted line indicate the long-term mean for each variable.

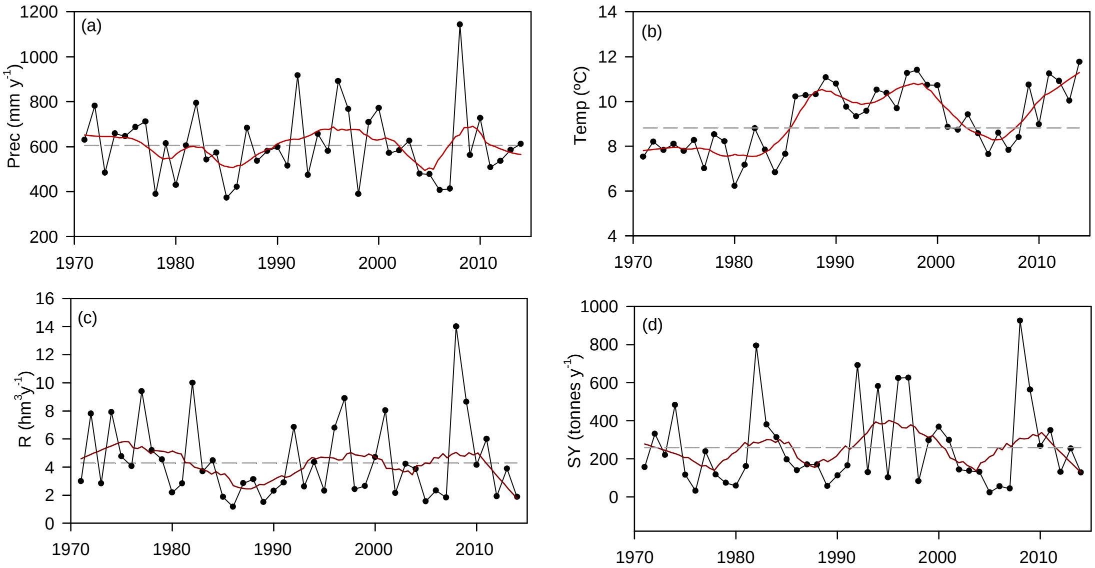

Figure 6. Boxplots showing the number of days (in %) for each class and variable for the whole study period (1971-2014). *P*: Precipitation (blue); *R*: Runoff (green) and *SY*: Sediment Yield (grey). *C1*: 0-20% of the total annual accumulated; *C2*: 20-40%; *C3*: 40-60% *C4*: 60-80% and *C5*: 80-100%.

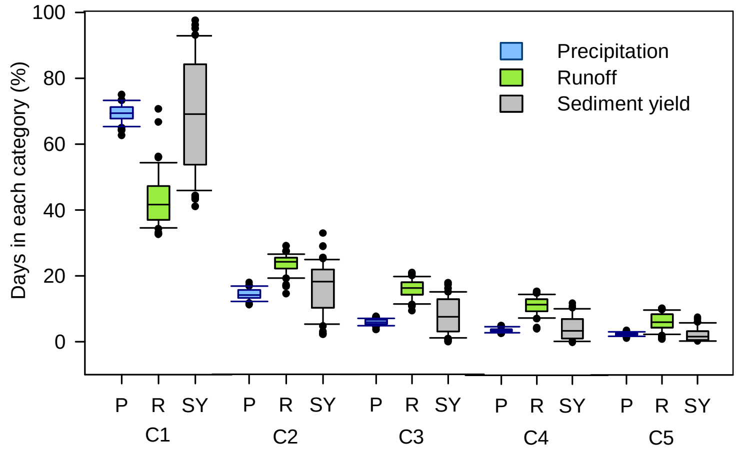

Figure 7. Cumulative runoff and sediment yield (%) for each of the three periods considered. Solid lines indicate runoff values while dotted lines refer to sediment yield.

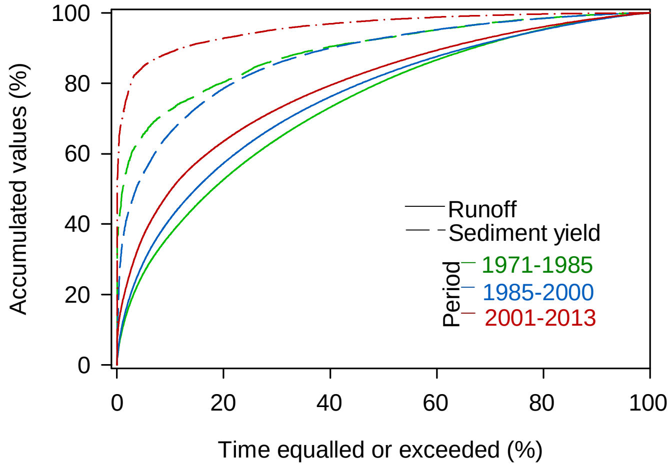

Figure 8. Annual runoff (R; $hm^3 y^{-1}$) and sediment yield (SY, ton y^{-1}) for the *actual* (grey) and *scenario* (red) datasets. Lines show the smoothed values using LOESS (time span: 0.2).

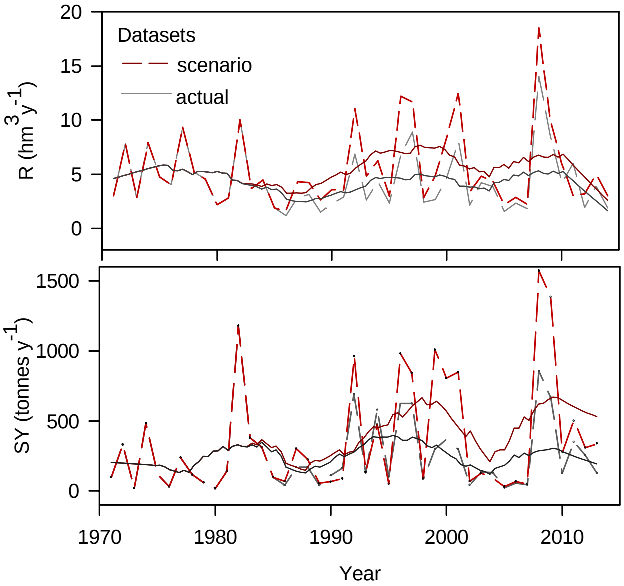

Table 1. Area (A) occupied by each land use in the Canalda basin over the study period (in km^2 and in relation to the total area -%-). The percentage of change ($\%\Delta^i$) is also shown with respect to the previous land use map as well as with respect to 1957 (as indicated by the superindex '*i*'). Note that land uses in 2009 have not changed in relation to the previous map from 2005 and so percentages are kept the same.

	1957		**1993**			**2005**				**2009**
Land use	**A (km^2)**	**A(%)**	**A (km^2)**	**A(%)**	**$\%\Delta^{57}$**	**A (km^2)**	**A(%)**	**$\%\Delta^{93}$**	**$\%\Delta^{57}$**	**A (km^2)**
Farmland	9.1	14	3.9	6	-57	2.6	4	-33	-71	2.6
Woodland	31.9	49	38.4	59	+20	44.2	68	15	+39	44.2
Grassland	17.6	27	15.6	24	-11	13.0	20	-17	-26	13.0
Non-productive	6.5	10	7.2	11	+10	5.2	8	-27	-20	5.2

Table 2. Summary of discharge and sediment yield data in the Canalda basin during the monitoring period (2009-2013). Q_{mean}±SD: Mean discharge and standard deviation; Q_{max}: Maximum discharge; Q_{min}: Minimum discharge; R: Annual Runoff; SSC_{mean}±SD: Annual mean Suspended Sediment Concentration and Standard Deviation; SSC_{max}: Maximum Suspended Sediment Concentration; SY: Annual Sediment Yield; Prec: Precipitation. *Sediment transport record starts in June 2011 (SY data for this year corresponds to the period June-December 2011).

Year	Q_{mean}±SD m^3s^{-1}	Q_{max} m^3s^{-1}	Q_{min} m^3s^{-1}	R hm^3y^{-1}	SSC_{mean} ±SD mg l^{-1}	SSC_{max} mg/l	SY ton y^{-1}	Prec mm
2009	0.48 ± 0.39	3.5	0.05	45	-	-	-	820
2010	0.47 ± 0.37	4.3	0.06	14.6	-	-	-	923
2011*	0.29 ± 0.25	1.9	0.05	9.22	7 ± 3	390	65	703
2012	0.21 ± 0.19	1.7	0.04	6.45	6 ± 2	336	106	695
2013	0.57 ± 0.89	9.7	0.06	13.59	12 ± 3	408	360	697

Table 3. Mean annual values and standard deviation for the studied variables and results from the Mann-Kendall trend test (Kendall's τ and *p*-value) for (a) the actual dataset (including climate variability and land sue changes) and (b) the scenario dataset (which considers a constant land use over time). Note that climate variables are the same for both datasets. %Δ indicates the percentage of change in mean annual values of runoff and sediment yield in the scenario dataset in relation to the values obtained in the actual dataset

Variable	**(a) Actual dataset**			**(b) Scenario dataset**		
	$\bar{X}\pm\sigma$	τ_{MK}	***p*-value**	$\bar{X}\pm\sigma$	τ_{MK}	***p*-value**
Precipitation (mm)	602 ± 134	-0.07	0.52	-	-	-
Temperature (ºC)	8.8 ± 1.8	0.45	<0.001	-	-	-
Snowpack (mm)	9.2±11.3	-0.48	<0.001	-	-	-
Runoff ($hm^3 y^{-1}$)	5.2 ± 3.5	-0.11	0.06	6.4 ± 4.5	-0.01	0.77
Sediment Yield (ton y^{-1})	276 ± 371	-0.06	0.57	506 ± 719	0.17	0.46

Table 4. Temporal trends in the contribution of each class to the total annual precipitation, runoff and sediment yield.

Magnitude	Category	% Accumulated	Precipitation		Runoff (hm3)		Sediment Yield (t)	
			t_{MK}	*p*-value	t_{MK}	*p*-value	t_{MK}	*p*-value
Low	C1	0-20%	0.004	0.97	0.06	0.61	-0.16	0.15
Mid-range	C2	20-40%	-0.04	0.71	-0.04	0.59	0.19	0.07
	C3	40-60%	-0.002	0.99	-0.17	0.12	0.13	0.26
	C4	60-80%	0.06	0.59	-0.03	0.82	0.11	0.33
High	C5	80-100%	0.06	0.46	0.06	0.49	0.17	0.11

Table 5. Temporal trends in the magnitude of each class.

Magnitude	Category	% Accumulated	Precipitation		Runoff (hm3)		Sediment Yield (t)	
			τ_{MK}	***p*-value**	τ_{MK}	***p*-value**	τ_{MK}	***p*-value**
Low	C1	0-20%	-0.03	0.81	-0.28	0.009	-0.2	0.11
Mid-range	C2	20-40%	-0.04	0.66	-0.15	0.16	-0.37	0.23
	C3	40-60%	-0.07	0.48	-0.26	0.01	-0.27	0.38
	C4	60-80%	-0.04	0.66	-0.21	0.04	-0.29	0.45
High	C5	80-100%	-0.07	0.48	-0.22	0.03	-0.28	0.16

Table 6. Mann Kendall results for the analysis of seasonal trends for the period 1971-2014.

Season	**Precipitation**			**Temperature**			**Runoff (hm3)**			**Sediment Yield (t)**		
	$\bar{x}\pm\sigma$	τ_{MK}	***p*-value**	$\bar{x}\pm\sigma$	τ_{MK}	***p*-value**	$\bar{x}\pm\sigma$	τ_{MK}	***p*-value**	$\bar{x}\pm\sigma$	τ_{MK}	***p*-value**
Spring	206±76	-0.18	0.11	11±2	0.46	<0.001	1.5±1	-0.24	0.03	88±125	-0.21	0.06
Summer	147±77	-0.11	0.10	17±2	0.28	0.008	0.8±0.6	-0.25	0.02	27±36	-0.09	0.41
Autumn	194±63	0.09	0.42	4±2	0.51	<0.001	1.3±1.8	-0.13	0.26	110±307	0.05	0.66
Winter	73±42	-0.05	0.67	2±2	0.45	<0.001	1.2±1.3	-0.19	0.09	67.7±137.4	0.11	0.32