WATER AND SEDIMENT BUDGETS UNVEILING CONTRASTING HYDRO-SEDIMENTARY PATTERNS IN A MOUNTAINOUS MEDITERRANEAN CATCHMENT

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Abstract

Mountain regions have a key role in the generation of runoff, and in the production and transfer of sediments to fluvial networks, especially in Mediterranean catchments where these processes are affected by marked changes in climate and land use (i.e. global change). This paper presents the water and the sediment budgets of the Ribera Salada (224 km²), a meso-scale Mediterranean forested catchment located in the Southern Pyrenees. Field monitoring follows an integrated basins scheme (five nested sub-catchments), where hydrological and sediment transport data were collected continuously over a two-year period (2012-2013). Precipitation was obtained using radar images, which allowed the elaboration of rainfall maps used to characterize the spatial distribution of rainfall across multiple scales. Results indicate that the catchment is hydrologically divided in two areas which show contrasting fluvial regimes: the upper part of the catchment is considered wet and has a constant flow regime, suppling the majority of the water, while the lower part is drier, with ephemeral tributaries and water losses into the alluvial aquifer of the main river channel. In contrast to water yield, most of the suspended sediment load (i.e. 80%) is supplied by the driest part of the catchment where sediment availability was greater and where there is a greater connectivity between sediment sources and the channel network. The sediment yield of the whole catchment and the respective sub-catchments sits in the lower bounds of values reported for the Mediterranean region, indicating the generally low intensity of hydrological and geomorphic processes in the area. Once more the sediment budget approach matched to sound hydrological data proves efficient to characterise sediment dynamics in river basins, with special interest in areas such as the Mediterranean mountain catchments, where the effects of global change appear to be more acute.

Keywords: sediment transport, hydrologic cycle, sediment budgets, rainfall maps, Mediterranean, Ebro basin
1. INTRODUCTION

Mountain areas play a key role in the generation of runoff (e.g. Viviroli et al., 2003; Viviroli and Weingartner, 2004), especially in basins with arid or semi-arid climates (López and Justribó, 2010). The Pyrenees are a well-known example of this, generating ca. ¾ of the runoff of the whole Ebro basin (83,500 km²) the third largest catchment in the Mediterranean basin. Hydrologists and water managers have repeatedly warned of important reductions of river flow (hereafter $Q$) in basin headwaters in the area (e.g. Gallart and Llorens, 2004; García-Ruiz et al., 2011). Interestingly, this phenomenon has been also reported elsewhere in the Mediterranean region (e.g. Pascual et al., 2015; Garcia et al., 2017). Flow reduction is mainly attributed to both changes in climate and, notably, the widespread natural afforestation that has taken place in mountain regions since the large scale land abandonment of the 1950s (e.g. Serrano-Muela et al., 2008; Lorenzo-Lacruz et al., 2012; López-Moreno et al., 2014; Buendía et al., 2016a and 2016b). Reductions in flow poses important threats for water resources, undermining the development of the whole region and the functioning of the fluvial ecosystems. Within this context, the elaboration of water budgets constitutes a major scientific and applied goal, which is essential to understand water production and yield and necessary to infer how human-related changes effects hydrological dynamics and fluvial processes (e.g. Jothityangkoon et al., 2001).

Precipitation is a key element for the construction of such budgets, as well as to help interpreting them. However, high-resolution spatially distributed precipitation data for mountainous areas are difficult to obtain, even if sophisticated interpolation procedures are used, because of the low density of rainfall stations (Barry, 2008). The spatial distribution of precipitation data can be improved using remote sensing tools (radar and satellite data; e.g. Leijnse et al., 2007; van de Beek et al., 2009; Otto and Russchenberg, 2011; Moreno et al., 2012). The quantitative estimation of precipitation by means of weather radar has become an advanced tool for meteorology (e.g. Wilson and Brandes, 1979; Fulton et al., 1998; Harrison et al., 2000; Tabary et al., 2007) and is particularly valuable for hydrological (e.g. He et al., 2011; Seo et al., 2015) and sediment budgeting applications (e.g. Tuset et al., 2016).
Sediments produced in mountain areas reach channel networks and are subsequently transferred downstream. The sediment budget of a drainage basin is the quantitative description of the rates of production, transport, and deposition of mineral detritus in a given period of time. Therefore, in order to construct a catchment scale sediment budget, the temporal and spatial variations of both transfer and storage processes need to be assessed. This task essentially requires i) the recognition and quantification of sediment sources, transport processes and the associated loads, ii) the recognition and quantification of storage elements, and iii) the identification of the linkages amongst them (Dietrich et al., 1982). A sediment budget is also an important tool for planning, since it allows managers to assess the impact of human activities, estimate the effects of climate change and detect the factors that control the changes in the fluvial system, between other applications (Charlton, 2008). Sediment budgets can take many forms, be constructed over several scales, and incorporate various levels of precision (Reid and Dunne, 2005). Of particular importance within the budget is the sediment flux that transits through the drainage network, and, eventually, reaches the basin outlet and leaves the system; this process is not constant in time (i.e. it occurs mainly during floods) and typically shows non-linear relations with streamflow (i.e. typically controlled by sediment supply and availability).

Understanding the sediment delivery process (i.e. the amount of sediment exported in relation to total upstream production) at the basin scale remains a challenge (see for instance the early review by Walling in 1983). The high variability in the relationship between basin area (hereafter $A$) and suspended sediment yield (hereafter $SSY$) implies that prediction of $SSY$ based on $A$ alone is troublesome, hence spatially (and temporary) distributed information on land use, climate, lithology, topography, dominant erosion processes and sediment connectivity is required (de Vente et al., 2007). Alternatively, the concept of sediment connectivity is used to explain the continuity of sediment transfer from sources to sinks in a given catchment, and the movement of sediment between different compartments within it: over hillslopes, from hillslopes to channels, and within channels (Bracken et al., 2015).
Sediment transport and associated yield in Mediterranean mountainous catchments are highly variable, being mainly controlled by irregular flashy flow regimes (i.e. floods) and changes on sediment availability, which, in turn, respond to marked variations in climate (temperature, rainfall), runoff, soil properties, geology and land and water uses. This hypothesis (based on the main findings after Conacher and Sala, 1998) frames the research presented here, aiming at constructing the water and the sediment budgets of the Ribera Salada, a meso-scale forested Mediterranean catchment located in the Southern Pyrenees. The Ribera Salada has experienced extensive afforestation due to the generalized land abandonment that has occurred in the Pyrenean region since mid-twentieth century. In this context, the Ribera Salada was established in 1997 as a long-term monitoring project with the primary objective of observing and quantifying water resources and sediment transport dynamics in Mediterranean forested mountain catchments (e.g. Verdú et al., 2000; Estruch, 2001; Poch et al., 2002; Balasch et al., 2005; Batalla et al., 2005; Loaiza-Usuga and Pauwels, 2008; Müller et al., 2008; Vericat and Batalla, 2010; Buendia et al., 2016; Tuset et al., 2016). All of these works described processes occurring in the upper half of the basin, from plot to catchment scale, with specific objectives different from those presented here. For the purpose of this paper, field monitoring followed an integrated-catchments approach, which was composed by five nested instrumented sub-catchments. There, hydrological and sediment transport data were collected continuously during the two years period. There are no water and sediment budgets reported for non-regulated and less-erodible catchments of this size in the Pyrenean area. The Ribera Salada offers an opportunity to identify sediment sources in such natural catchments and assess the spatial and temporal variability of the water and sediment transport regimes.

2. STUDY AREA

The Ribera Salada is a 224 km² mountainous catchment located in the Southern Pyrenees (NE Iberian Peninsula; Figure 1). The river flows into the Segre in the Rialb Reservoir. Elevation ranges between 460 m a.s.l. and 2386 m a.s.l., what drives marked climatic gradient across the
catchment, i.e. subalpine in the headwaters and Mediterranean in the main valley and the
lowlands. Mean annual precipitation (hereafter $P$) is 763 mm, ranging from 600 mm yr$^{-1}$ in the
valley bottoms to more than 1000 mm yr$^{-1}$ on mountain summits (Ninyerola et al., 2000). The
north-western part of the basin sits in the rain shadow of the Canalda sub-catchment (Tuset et
al., 2016). Maximum rainfall occurs in spring and the minimum in winter. Mean annual
temperature is 11°C, with values reaching -20°C in the winter headwaters and 35°C in the lower
part of the valley during summer.

The geology of the catchment consists of limestones, marls and Triassic and Eocene evaporites
folded in the header, and an extensive molassic sequence (i.e. conglomerates and sandstones) of
Eocene and Oligocene ages in the middle and lower parts of the catchment. The calcareous
sediments, which show high fracturing and karstification, form the substrate of the Port del
Comte hydrogeological unit (i.e. the largest in the area, Figure 1). This unit consists of two
major subunits: (i) Bòfia, which mainly discharges into the River Cardener (not included in
Figure 1), and (ii) Odèn (i.e. the largest of the two them), which directs its waters to the springs
of Can Sala and Sant Quintí (i.e. both belonging to River Fred sub-catchment, Figure 1). The
less extensive subunits of Bòfia SW, Llinars and Puig Subirà complete the hydrogeological
system of Port del Comte and feed, respectively, the rivers Fred and Canalda (Núñez et al.,
2004; Figure 1).

The catchment lies mostly on conglomerate supporting sandy–loamy soils, that typically have
depths less than 50 cm. Water retention capacity is low owing to the stoniness of these soils
(>20%, Verdú et al., 2000). The catchment is mostly forest (i.e. 70% wood; 9% shrubs; 8%
rocky outcrops; 3% pastures) with small areas of agriculture (9%) (see Table 1 for more detailed
information). Agriculture is located mainly on the plains of the interfluves and in the valley
bottoms, while forests occupy steeper slopes.

Upstream valleys have a marked V-shaped form due to strong incision that occurred during the
Quaternary. Fluvial incision has formed confined channels on conglomerates (i.e. canyons),
mostly in the rivers Fred, Plana and Canalda. Further downstream, the channel widens while
flowing on the alluvial deposits of the Ribera Salada before it flows into the Segre (Figure 1).

The alluvial aquifer is bounded by detrital materials (i.e. particles of fragmented rock through processes of weathering and erosion) and terraces. Gravel mining has been particularly intense in the lower segment of the Ribera Salada during the 1980's and the 1990's (Batalla, 2003), where valley incisions of up to 3 m and the exposed bedrock are still visible (Tuset et al., 2015).

Flow regime is pluvio-nival with two maxima: one in spring and early summer caused by snow melt and convective localised storm-events, and the second in autumn owing to rainfall events mostly associated with the passage of polar fronts (Tuset et al., 2016). The mean discharge (hereafter $Q_{\text{mean}}$) for the period 1998-2008 at the Inglabaga section (114.5 km$^2$; see Figure 1 for location details) is 0.5 m$^3$ s$^{-1}$ ($\sigma = 0.260$ m$^3$ s$^{-1}$), equivalent to 145 mm of annual runoff and a runoff coefficient of 0.25 (Vericat and Batalla, 2010). It is important to remark that, at this section, the Ribera Salada encompasses half of the total basin area but has already collected waters from all the main tributaries since tributaries downstream from here are ephemeral. Within this context, one of the focal points of the paper is to understand the implications of this hydro-climatic discontinuity or distinction for the water and the sediment budgets.

3. MATERIALS AND METHODS

Methods included (a) field monitoring and computation of flow and suspended sediment fluxes, (b) remote sensing analysis, and (c) base-flow separation. The combination of these allowed collection of rainfall, runoff and sediment transport data across the entire Ribera Salada catchment (i.e. multiple stations/sub-catchments). Details of each of these methods are presented in the following sections.

3.1. Field monitoring and computation of flow and suspended sediment fluxes

Water flow and sediment transport in the Ribera Salada were monitored during 2 complete years (from January 2012 to December 2013) in five nested sub-catchments (Figure 1): Cogulers (2.4 km$^2$), Fred (26.8 km$^2$), Canalda (65.1 km$^2$), Inglabaga (114.5 km$^2$) and Altés (217.4 km$^2$).
catchments were chosen to examine the influence of different areas and river regimes on the overall basin water yield and sediment load. The first four sites represent the upper area of the catchment, characterised by perennial flows, whereas Altés closes the basin and represents the lower half of the basin where ephemeral streams only flow after thunderstorms. Water contribution from the upper part of the catchment ensures that the Ribera Salada mainstem never dries up.

Rainfall was measured at 15-minute intervals and recorded hourly in five rain gauges, three of them located within the basin limits and two outside of them (Figure 1). Two of the rainfall stations are operated by the Meteorological Service of Catalonia (i.e. Port del Comte, 2316 m a.s.l.; Lladurs, 785 m a.s.l.) and three by the Ebro Water Authorities (i.e. Cambrils, 1401 m a.s.l.; Oliana, 520 m a.s.l.; Pinell, 658 m a.s.l.). The spatial distribution of rainfall across the catchment was assessed from radar data and is described in the remote sensing section.

Water stage (or water level; hereafter $h$) was monitored by means of pressure transducers (Druck® 1730-PDCR), except in the Fred section, where it was measured using a capacitive water stage sensor/logger (TruTrack® WT-HR). Water stages were recorded every 5 minutes in Campbell CR10X and CR1000 data-loggers in exception to the station in the Fred where the sensor is built with an internal data-logger. $h-Q$ rating curves in the Canalda, Inglabaga and Altés sections were derived by means of 1d hydraulic modelling using HEC-RAS® V.4.1 (USACE, 2010). Since riverbed was mobile with high flows, topographic surveys were repeated to adjust the $h-Q$ rating curves (in exception of the Cogulers section were a 90º V-noch weir was installed and the formula by Kindsvater and Carter (1957) applied). Results were validated using periodic gaugings that were made by means of an electromagnetic flow metre (Valeport® 801) during base and high flows. In May 2012 an Ultrasonic Doppler Instrument (Starflow® 6526, range 21 mm s$^{-1}$ to 4500 mm s$^{-1}$) was installed in Canalda and it was used to obtain continuous $h$ and flow velocity ($v$); this complementary data was used to calibrate $Q$ estimates at this section. The Fred monitoring section is located in a canyon a few meters upstream from a ford that acts as a crested weir; to solve the $h-Q$ relation a theoretical drain curve of a
rectangular broad crested weir was applied; this yielded results in agreement with data obtained from direct gauging.

Water turbidity was recorded by means of ANALITE® wiper-equipped turbidimeters (NEP 9350; range: 0-3000 NTU) in four of the stations (Cogulers, Canalda, Ingabaga and Altés). Turbidity was registered every 5 min in Campbell® data-loggers CR10X and CR1000. Automatic water samplers (ISCO® 3700) were set to collect at least 0.5 litre samples during flood events at one-hour intervals. In addition, 1-litre manual samples were periodically collected during low flows and floods, and, at the Ingabaga site, suspended sediment was also sampled using a water stage sampler, designed after the initial model developed by Schick (1967). In total, 987 water samples were used to transform turbidity data (NTU) to suspended sediment concentration (hereafter SSC, mg l⁻¹) using a single linear relation. This single calibration can be justified by the fact that all probes were the same and that differences between the SSCs associated with a given NTU value between sites were very low (i.e. the coefficient of variation of these was 9.1% for low and high NTU readings). SSC during the whole study period only exceeded the turbidimeter range during four hours in Altés and one hour in Ingabaga and Canalda sections. In all cases, the ISCO® and the water stage sampler collected enough samples to fill the gaps of the turbidity series; any bias attributed to infilling is considered negligible.

Further, the representativeness of turbidity readings within the average concentration across the section was experimentally assessed in Altés by means of the ratio \( k = C_s / C_t \), where \( C_s \) is the mean SSC determined from evenly distributed vertical samples across the section (considered the cross-section average value) during floods events, and \( C_t \) is the mean SSC obtained at the same time from the vertical where water samples are regularly obtained as explained above (e.g., McLean et al., 1999; Vericat and Batalla, 2006). Three sets of vertically distributed samples were collected during a flood event on 23rd March 2012. The \( k \) ratio varied randomly with \( Q \), ranging from 0.91 to 1.11. Hassan and Church (in McLean et al., 1999) found that small no systematic bias is offsetting and has no significant effect on the computation of the annual
load; the low bias observed in Altés between Cs and C₁ suggests a notable degree of hydraulic mixing in the section, and so a reliable estimation of the suspended sediment load is ensured.

The organic matter (hereafter OM) content was assessed in the Altés section from thirty-nine samples obtained during a single 2 day flood event, following the methods reported by Tena et al. (2011). OM was highly variable, ranging from an average of 32% during low flow conditions before the flood started, to 10% during the flood peak and 52% during the falling limb. This high variability does not allow a justifiable criterion to subtract the content of OM from the whole data set. Therefore, OM was not subtracted from the SSCs and, consequently, this may cause an overestimation of the computed loads. Note that that flow and suspended sediment transport data from the Canalda section were already reported by Buendia et al. (2016b) and used for model calibration to assess the effects of climate variability and afforestation on catchment’s hydrology.

Finally, Q and SSC data obtained in each sub-catchment were used to compute basic statistic parameters (i.e. arithmetic mean and coefficient of variation) and to characterise water yields and sediment loads at different temporal scales (i.e. daily, monthly and annual). Linear regressions between the runoff volume and the sediment load for each of the contributing areas, together with the square of the Pearson’s correlation coefficient ($r^2$; Pearson, 1896) were calculated. The analyses were performed with Statistica© 7.0. In general, a p-value of 0.05 was set to consider a correlation statistically significant.

3.2. Remote sensing analysis

The amount and distribution of rainfall in the Ribera Salada sub-catchments were assessed by means of geo-referenced radar images. The resolution of the images was 1×1 km (for more information consult Tuset et al., 2016) (i.e. note that pixel size changed from 3×3 km in Tuset et al., 2016 to 1×1 km in this work, and it is due to the technical improvement of the radar sensors). Even so, we believe that this change has no direct effect on the estimates given the scale of the study reach in relation the spatial variability of the rainfall. The rainfall records
obtained in the rain gauges of the Ribera Salada (see location in Figure 1) (see section 3.1.) were used to validate the radar data as explained below.

A cross-validation procedure was performed according to Tuset et al. (2016) to assess the accuracy of the rainfall rasters (i.e. monthly rainfall values, hereafter $P_{m\text{pred}}$) obtained from radar data during the study period and for the study area. A ‘monthly potential error’ of the rainfall was calculated by using the direct data registered in five rain gauges (see Figure 1 for location details) as the reference data set (i.e. observed rainfall). In this case, the unit of RMSE is the millimetre, though it is important to note that the RMSE does not correspond to the absolute error. The main uncertainties in this validation are related to (a) the spatial resolution of the data (i.e. 1×1 km) and (b) the calibration of the radar fields (see more details in Tuset et al., 2016).

The RMSE was calculated for a total of 24 months (i.e. 1 value per each rain gauge per month during a period of two years, 120 monthly records).

### 3.3. Base-flow separation

Base-flow (hereafter BF) was estimated by means of the software BFI+® digital filter version 3.0 (Gregor, 2010), which separates the stream flow into direct runoff (hereafter DR) and BF (Fendeková and Fendek, 2012; Vasileva and Orehova, 2012; Alhamed, 2014; Abo and Merkel, 2015). The method selected for this study was the ‘local minimum’ filter. In this case, broadly, minimum flow values were identified looking at the variability of the flow through time and based on two parameters described below. Minimum flows are considered the base flows and a linear interpolation between minimum flows is fitted in order to extract the BF (Sloto and Crouse, 1996). Input data were the time series of daily stream flow. The algorithm used by BFI+® to estimate the time duration of surface runoff from a storm event is based on two parameters - $N$ and $f$. The first is the product of an empirical relationship:

$$N = 0.8267 A^{0.2}$$  \hspace{1cm} (Eq.1)

where $N$ is the number of days after which direct surface runoff ceases, and $A$ is the drainage area in square kilometres (Sloto and Crouse, 1996). The average $N$ for all sub-catchments was 2
The unusual flow regime of the River Fred (as a result of transfers of water from the Oden subunit, Figure 1) dictated that a different method was appropriate. Here, DR was computed using an empirical relationship between catchment area and direct runoff computed from the other stations in which the flow regimes were not affected by external water transfers. This method allows to determine objectively when a flood occurs; i.e. when the software detects the DR generation. This represents an improvement over other more traditional methods (i.e. Graphical Separation Method, e.g. Hewlett and Hibbert, 1967; Maidment, 1993), as it allows the base flow to be obtained in an automatically, faster and objectively. The tool is especially useful to analyse long data sets.

4. RESULTS AND DISCUSSION

4.1. Rainfall

4.1.1. Validation of rainfall maps

$P_{m\text{pred}}$ obtained from radar images oscillates between almost 0.7 and 175.2 mm, while direct observations (hereafter $P_{m\text{obs}}$) based on the rain gauges ranged between zero and 209.5 mm. The $RMSE$ varies between 0.1 and 34.3 mm, with a mean value of 10.9 mm and a coefficient of variation (hereafter $CV$) of 0.7. $RMSE$s were related directly to the magnitude of the $P_{m\text{pred}}$, with three different patterns observed: (i) for $P_{m\text{obs}} < 50$ mm, $RMSE$ is low (i.e. 7.9 mm, value that represents less than the 32% of the average $P_{m\text{obs}}$ i.e. 24.7 mm); (ii) for 50 mm < $P_{m\text{obs}}$ < 125 mm, $RMSE$ almost doubles (i.e. 11.9 mm), although still representing a lower proportion compared to the $P_{m\text{obs}}$ (i.e. 14.6% on average); (iii) finally, for $P_{m\text{obs}}$ >125 mm, the $RMSE$ is around 23.8 mm and rain fields always underestimate the observed $P_{m\text{obs}}$ (i.e. 14.7% on average). This bias occurs almost exclusively for the Port del Comte rain gauge, which is located in the area where more rainfall is registered. It is worth stressing that rain fields are generated by means of the $EHIMI^\circledR$ software (Corral et al., 2009). The software includes an
algorithm that takes into account the route of the precipitation and so smooths the maximum rainfall in the spatial dimension in order to better model the storm’s path that, otherwise, could be misrepresented. Nevertheless, if the maximum rainfall occurs usually in the same location (in our case Port del Comte) due to, for instance, orographic factors, the EHIMI underestimates high rainfall magnitudes, especially in spring. Overall our results are in the order of those observed by Coll (2010) for the whole Catalonia (i.e. for an area of ca. 32,100 km² using multiple rain gauges distributed across different environments) and by Tuset et al., (2016) for the Ribera Salada catchment using a single rain gauge (Canalda) at the daily scale. These latter authors reported a Mean Absolute Error of 6 mm (i.e. data set included rainfall episodes registered between 2001 and 2005) and 4.3 mm (i.e. data set included rainfall episodes registered between 2005 and 2008), respectively. In the present study the Mean Absolute Error is around 7.6 mm, within the range of that reported above.

The good agreement between observed rainfall and estimates using radar images allows the study of the spatial variability of rainfall events with a reasonable accuracy. This provides the opportunity to identify localised rainfall cells that otherwise might be underestimated by single rainfall measurements (e.g. as for the 9 September 2012 event; Tuset et al., 2016), and identify rain shadows that are not in the range of rain gauges.

4.1.2 Rainfall patterns

4.1.2.1. Annual scale

The study period was characterized by moderate annual rainfall and temperature variability at the whole catchment scale. Overall 2012 was warm (i.e. between 1 and 1.5°C above the annual mean) and dry (i.e. 20% below the mean annual rainfall for the period 1961-1990; SMC, 2013), whereas 2013 experienced average temperatures and rainfall above the mean (SMC, 2014). Mean $P$ was 560 mm in 2012 and 677 in 2013 (i.e. annual average of 619 mm), obtained from daily rainfall maps (i.e. radar information). These values diverge from those reported by Ninyerola et al., (2000), who estimated a mean annual $P$ for the area of 765 mm using the data
from a network of 116 rain gauges (i.e. one every 195 km²). Despite the dense spatial coverage of meteorological stations used in their work, authors did not include rainfall data from the Ribera Salada, hence failing at detecting local rain shadows such as that in the north-western part of the catchment (Tuset et al., 2016); this suggests a likely overestimation of $P$. Our results differ from those reported by Ninyerola et al. (2000) and this can be related to rainfall computation. In our case, instead of single values from rainfall stations, maps of rain fields calculated from radar images were used. Such divergence reinforces the importance of sufficient data coverage in environments where rainfall is highly variable in space.

Mean rainfall for the whole study period was 640 mm in Cogulers, 550 mm in Fred, 709 mm in Canalda, 610 mm in Inglabaga and 619 mm in Altés. Rainfall increases with altitude (i.e. positive altitudinal gradient), and eastwards (i.e. longitudinal gradient caused by a rain shadow). These patterns agree with those reported by Tuset et al. (2016) who analysed the hydrological response of the Ribera Salada for the 2005-2008 period; they also follow the classic general patterns of Lauscher (1976) who described vertical precipitation profiles using long-term data from 1300 grouped stations (i.e. tropical, equatorial, transition and mid-latitude patterns). Mid-latitudes generally show strong rainfall increases with altitude, although the general tendency may be modified by leeward or windward slope location (Barry, 2008).

### 4.1.2.2 Seasonal and monthly patterns

The seasonal rainfall regime follows a spring-summer-autumn-winter sequence (equivalent to 36, 30, 18, and 16% of the total annual precipitation, respectively) (see Table 2 for full details). It is notably that the maximum can occasionally occur in summer, especially in the headwaters or in small areas (e.g. as in Cogulers in summer 2012). The rain shadow in the north-west and the positive altitude gradient were also observed at the seasonal scale. Snow is present in the highest altitudes (>1800 m a.s.l.) in winter and early spring (Tuset et al., 2016).

### 4.2. Flow, water yield and runoff

#### 4.2.1. Annual scale
Flow and water yield

The average long-term \( Q \) in Canalda and Inglabaga is 0.41 m\(^3\) s\(^{-1}\) and 0.50 m\(^3\) s\(^{-1}\), respectively (Vericat and Batalla, 2010; Buendia et al., 2016a). \( Q_{\text{mean}} \) for the monitoring period was 0.20 m\(^3\) s\(^{-1}\) and 0.46 m\(^3\) s\(^{-1}\) in 2012 and 0.50 m\(^3\) s\(^{-1}\) and 1.08 m\(^3\) s\(^{-1}\) in 2013, respectively. Figure 2 shows the resulting hydrographs and sedigraphs in all sub-catchments (i.e. Coguliers, Fred, Canalda, Inglabaga and Altés sub-catchments) for the entire study period. \( Q \) in Canalda was lower in 2012 than the sub-catchment average, in agreement with the lower rainfall observed in the headwaters. This contrasts with \( Q \) in Inglabaga which had an average value, compensating the low contribution from Canalda with a higher water supply from the Fred (i.e. 0.27 m\(^3\) s\(^{-1}\) and 0.58 m\(^3\) s\(^{-1}\), respectively) (Figure 2). In turn, \( Q \) in these two large sub-catchments during 2013 (the only sections where long-term reference values exist) was above the long-term mean.

Water yield (hereafter WY) for the whole basin (i.e. measured at the downstream Altés section, outlet of the basin) was 15.4 hm\(^3\) and 30.6 hm\(^3\) for 2012 and 2013, respectively, equivalent to a mean specific \( Q \) of 0.003 m\(^3\) s\(^{-1}\) km\(^2\). This value is low compared to that reported for the neighbouring Cardener (200 km\(^2\) and located east of the Ribera Salada) that has similar basin area where long-term data exists; in the Cardener, where mean specific \( Q \) of 0.010 m\(^3\) s\(^{-1}\) km\(^2\) (ACA, 2014), three times the runoff volume generated in the Ribera Salada during the same period. The headwaters of the two catchments are adjacent, draining along of the Massif of Port del Comte (see Figure 1), which is the main source of water in the Ribera Salada. Precipitation in the two catchments was very similar during the study period (i.e. 595 mm in the River Cardener and 619 mm in the Ribera Salada). The transmission losses occurring in the alluvial aquifer (see Figure 1) are very high in the lower stretch of Ribera Salada. This is corroborated by specific discharge values - in Inglabaga the value is around 0.007 m\(^3\) s\(^{-1}\) km\(^2\), very similar to the one obtained for the Cardener basin. However, the value halves (0.003 m\(^3\) s\(^{-1}\) km\(^2\)) when the specific \( Q \) for the outlet of the catchment is calculated, indicating high transmission losses between Inglabaga and Altés, as it is fully discussed later.
According to the previous works (e.g. 5 years, Regüés et al., 2000; 10 years, Batalla et al., 2005; 10 years, Martínez-Casasnovas et al., 2012), the length of the data series from the Ribera Salada during the study period might be deemed short, challenging the representativity of the results. However, there is no data in the catchment to further assess this, in exception of that rainfall data, indicating that the period was slightly dryer-than-average. According to the relationship between precipitation and runoff found by Tuset et al. (2016), could lead to a hydrological contribution smaller than the mean annual runoff. Nevertheless, as it will be later shown, data length was not an obstacle to validate the research hypotheses. Flows lower than the annual average have been frequently recorded in recent years in the Ribera Salada (Buendia et al., 2016b). These authors estimated a reduction of 20% in annual runoff production in the last 20 years in the Canalda sub-catchment. Precipitation reduction and evapotranspiration due to the increase of both forest area and temperature have been identified as determining factors in water yield decrease (Kundzewicz et al., 2007; Buendia et al., 2016b). This tendency has also been detected in other Pyrenean basins (e.g. Gallart and Llorens, 2004; Serrano-Muela et al., 2008; Lorenzo-Lacruz et al., 2012). Changes do not only affect the total volume but also the intra-annual dynamics. Specifically, the discharge regime shows an increase of river’s torrential behaviour (i.e. runoff production occurs in shorter periods of time) and an increase of the role of low and high flows in the annual contribution (Buendia et al., 2016b). Current scenarios predict water inputs will become increasingly intermittent in the Mediterranean area (e.g. Schneider et al., 2013; Acuña et al., 2014), what can cause a further increase in torrentiality. The frequency of moderate rain is expected to reduce which, in addition to the increase of the forest cover, might hinder the production of high flow discharges. Under these circumstances, sediment load variability would also be smoothed. This reduced variability has also been observed in the Ribera Salada in dry years by Vericat et al. (2008); Batalla et al. (2010) and Vericat and Batalla (2010), as well as in neighbouring catchments (e.g. Regüés et al., 2000; Rovira and Batalla, 2006; Gimenez et al., 2012).
Figure 3A schematically shows the distribution of the mean annual water yield in all sub-basins, and indicates the proportion of each year in the total yield. Significant differences are observed between catchments. Table 3 indicate that, in fact, the Ribera Salada is hydrologically divided into two contrasting areas: 1) The upper part of catchment (i.e. the wet basin) displays a permanent flow regime in which all the tributaries contribute water constantly and where $WY$ is positively correlated with catchment area; in contrast, 2) in the lower part of the catchment, flow decreases as the catchment area increases (see table 3 and figure 3A). In the latter area (i.e. the dry basin), tributaries flow only after rainfall events (i.e. streams are ephemeral) and, even though the main channel never dries out, water yield and specific yield both reduce.

As stated, $WY$ in the wet part of the Ribera Salada increases with the increase of the contributing area (see equations 2 and 3; Figures 4A and B). However, $WY$ of the Fred is 23% larger than that for instance measured in Canalda despite it having a smaller catchment area (see table 3). This difference stems from the fact that there exists a water transfer from the Odèn hydrogeological unit (with a recharge area of 42.7 km$^2$) to the Fred sub-catchment through the sources of Can Sala and Sant Quintí, being one of the fastest-flowing source systems amongst the aquifers in the Alt Segre and the Alt Llobregat regions (i.e. karst areas, Figure 1). This inter-catchment transfer makes the Fred the main tributary of the Ribera Salada, supplying constant and abundant water. The area of the sub-catchments that are affected by the Odèn subunit have been re-calculated (i.e. real contributing area) to account for the effects of this contributing area to the $WY$ (Table 3), with results showing a lineal relationship with high degree of statistical significance (see Figures 4C and D). Equations 4 and 5 represent the relationships between the modified contributing area (real) and $WY$ for 2012 and 2013 respectively. These equations were subsequently used to estimate the real contribution of the sub-catchments that are affected by the Odèn subunit (i.e. contribution without taken into account the transfer from this subunit). Results indicate that, overall, the Odèn subunit supplies a volume of water equating to 40% of the annual water yield of the whole Ribera Salada (Table 3).
Our estimates are low in comparison with those reported by Núñez et al. (2004), who estimate the annual $Q$ from the two springs of the Odén subunit (i.e. Sant Quintí and Can Sala) at 0.52 m$^3$s$^{-1}$ (16.4 hm$^3$; data from 1998-99). This value is 30% higher than that estimated for 2013, despite the lower rainfall observed in 1998-99 (Sánchez and Torrecilla, 1999). Differences may be explained by the different frequency for which flows were registered i.e. continuous in our case and monthly in Sánchez and Torrecilla (1999). Additionally, no details of the calculation method for $Q$ are given by Núñez et al. (2004) or Sánchez and Torrecilla (1999).

In contrast, annual WY decreases in the dry part of the Ribera Salada catchment (see Figure 4A and 4B). This is due to both the ephemeral character of the downstream tributaries, the amount of rainfall in this part of the catchment, and the transmission losses as the river flows from Inglabaga to the outlet of the catchment (i.e. Altés section; see table 3).

Hydraulic relation between the river and the aquifer

Figure 5A shows the relationship between the daily flows in Altés and Inglabaga. Three patterns can be identified by looking how the observations depart from the 1:1 relationship. We hypothesise that these patterns indicate different hydraulic relation between the river and the aquifer. These relations basically depends on the saturation state of the aquifer, the distribution and magnitude of the rainfall, and the magnitude of the high flows in Inglabaga (i.e. influent, the river feeds the aquifer; effluent, the aquifer feeds the river): (i) For $Q<0.8$ m$^3$s$^{-1}$ (i.e. 75$^{th}$ percentile of the flow duration curve in Inglabaga, 521 days), the river turns from influent to effluent (i.e. as long as the water contributions do not come from the floods of the dry sub-basin tributaries; 7% of days) depending on the relationship between the river and the aquifer levels; (ii) For $0.8<Q<3.5$m$^3$s$^{-1}$, water transfers are from the river to the aquifer (influential), with observed higher $Q$ in Inglabaga than in Altés (i.e. the level of the water table is lower than the level of river water surface and the tributaries flood flows are absorbed by the aquifer); and (iii) For $Q>3.5$ m$^3$s$^{-1}$, flow increases between Inglabaga and the catchment outlet (i.e. occasionally, during significant rainfall events, when $Q$ at the outlet may double that registered in Inglabaga; effluent pattern). The runoff generation in the lower part of the basin exceeds the infiltration
capacity of the alluvial aquifer. However, as indicated by Figure 5B, the specific daily flows registered at the outlet never exceed the values observed on Inglabaga, indicating that the relative amount of runoff in Altés is always smaller than in the Inglabaga, i.e. for a given catchment area the production of runoff is smaller, mainly driven by a different rainfall regime together with differences in land cover and use, and hydro-geological properties (e.g. the role of the aquifer acting as a water sink in the lowermost part of the catchment). Similar hydrological patterns were described by Rovira et al. (2005) in the River Tordera (Catalan Coastal Ranges, 894 km²) and Bronstert et al. (2014) in the River Isábena (Central Pyrenees, 445 km²), where transmission losses play an important role in the water budget of the catchment.

Altés, the section located at the outlet of the basin, differs from the trend observed in the stations upstream as can be seen in Figure 4. These differences are attributable to the hydrological duality (i.e. perennial vs ephemeral regimes) observed in the different parts of the catchment. Several authors (e.g. Dunne and Leopold, 1978; Pazzaglia et al., 1998) reported $Q$ scaling nearly linearly with drainage area (in this case, all parts of the drainage catchment contribute approximately with the same volume of water, Fleckenstein et al., 2004). However, various anthropogenic and natural variables that may cause runoff to scale non-linearly with catchment area. For instance, urban areas with impervious soils (Wolman, 1967; Leopold, 1968; Hollis, 1975; Galster et al., 2006) may increase water production. Galster et al., (2006) studied the scale effect in basins of the United States and listed the cases in which non-linearity between drainage area and $WY$ was more likely. In general, these differences are attributed to differences in surface imperviousness, to the spatial distribution of the rainfall across the catchment, and the transmission losses associated to local hydro-geological conditions, with the latter mainly influencing the streamflow regime of the Ribera Salada.

Direct Runoff

In the upper part of the catchment, the mean annual Direct Runoff ($DR$) increases with catchment area (Table 4). This result agrees with Searcy (1960) who reported that $DR$ tends to be proportional to the size of the drainage area. In the lower part of the Ribera Salada, the $DR$
decreased in the drier year due to aquifer recharge during floods (e.g. 2012; from 3 hm$^3$ to 2.7 hm$^3$) whereas increased in the wet year, since the water table level of the aquifer and the DR generation were higher (e.g. 2013; from 9 hm$^3$ to 13.6 hm$^3$). While no data are available to substantiate this interpretation, it can be deduced from differences observed between registered $Q$ and, especially, from flood hydrographs, in which the two patterns can be seen and, occasionally, the peak of $Q$ may even disappear between the two sections (e.g. Figure 6).

In the upper part of the catchment, the mean annual base flow ($BF$) increases with drainage area, whereas in the lower part $BF$ is negligible (i.e. the ephemeral tributaries do not contribute to it) (Table 4); even in the wet 2013 (Table 4), $BF$ progressively diminished from Inglabaga to the Altés section. Overall, runoff in Ribera Salada is composed mainly by the $BF$ from the perennial upstream catchment and the $DR$ from the dry part of the basin that has a flashy response to local intense precipitation. An exception to this is Cogulers that, despite having a perennial regime, has a negligible $BF$ due to its small contributing area.

Finally, the Ribera Salada catchment, despite not being heavily altered, suffers water withdrawals mostly for local domestic and agricultural uses. Withdrawals are legal and authorized by the basin authority (see details in the SITEbro http://iber.chebro.es/SitEbro/sitebro.aspx and CHE website, 2013). At the sub-catchment scale, the maximum annual withdrawn is 0.41 hm$^3$ from Canalda, 0.07 hm$^3$ from the Fred, 0.21 hm$^3$ from Inglabaga and 0.82 hm$^3$ from the Altés sub-catchment, which altogether equates to a total annual of 1.51 hm$^3$ (i.e. 8.7% and 4.2% of the 2012 and 2013 WY of the whole Ribera Salada, respectively). However, these water withdrawals are insufficient to account for the 4 hm$^3$ difference between Inglabaga and Altés in 2013; this reinforces the previously stated hypothesis on the importance of the alluvial aquifer in the overall basin’s water budget. Unfortunately, available data from the SITEbro do not allow for a more detailed temporal assessment (i.e. daily or monthly) of the withdrawals.

4.2.2. Seasonal and monthly patterns
Seasonal WY at the outlet of the catchment (Altés) attains the maximum in spring with 12.9 hm$^3$ whereas the minimum occurs in summer with 2.9 hm$^3$ (i.e. equivalent to 56.2% and 12.8% of the annual WY, respectively). WY in autumn and, especially, in winter is more variable (Table 2) and, besides the seasonal rainfall volume, depends on the altitude of the snow line, the snow accumulation in the headwaters and the start of the snowmelt (i.e. March and April).

The low runoff in Cogulers sub-catchment, and the loss of flow occurring in the transition between the wet and the dry parts of the Ribera Salada basin are worthy of discussion. In the Cogulers, runoff in spring attains 82% of the annual value whereas this season accounts for only half of the runoff in the other sub-catchments. Minimum water yield occurs in summer in Cogulers and Altés, and in autumn in Canalda, Fred and Inglabaga (Table 2). Water yield in Cogulers is very low throughout the year; here, groundwater seepage is constant but not abundant and surface runoff is restricted to short periods of time (i.e. events with abundant runoff generation, e.g. the wet spring of 2013, when the soils are very saturated; or events with very high rainfall intensity, e.g. 8-9 September 2013, where infiltration rate was more than overcome by the intensity of precipitation). The small size of the basin implies that groundwater supply is limited and, at the same time, the high percentage of forest cover (i.e. >85%) limits the amount of surface runoff. Other authors have reported similar responses in nearby catchments (Gallart et al., 1997; Lana-Renault et al., 2007 in the Pyrenean Vallcebre and Arnás basins, respectively). Further downstream (Inglabaga-Altés), the mainstream river transfers part of its flow into the aquifer in spring and especially in summer when the aquifer is at its lowest (see values for dry sub-catchment in Table 2); transmission losses give the summer the lowest WY (in Altés), while the lowest WY in Inglabaga is observed in Autumn (Table 2). May registers the maximum WY in the Ribera Salada catchment, while the minimum is recorded in February, except in the lower part of the catchment (i.e. dry sub-basin) where it occurs in August. In summer, high temperatures recorded in the valley bottom increase evapotranspiration, altering the water regime generated in the upper half of the basin.

4.2.3. Water budget
Table 5 shows the mean annual values of precipitation ($P$, mm), runoff ($Q$, mm), real evapotranspiration ($E_{Tr}$, mm) and water withdrawals (WW, mm), as well as the runoff coefficient ($\alpha$) and the percentage of Forest Area (FA) in each of the sub-catchments upstream from the Inglabaga section for the two study years. The recharge area of the Odèn subunit is considered an external component for the purpose of these calculations; its contribution, together with $P$, are considered the inputs in the water balance equation. On average, in the ‘wet catchment’ approximately ¼ $P$ transforms into streamflow ($\alpha = 0.27$) whereas the remaining ¾ evaporates; this assumes that deep percolation returns to the drainage network and that the soil water content is identical at the beginning and at the end of the year. Overall $E_{Tr}$ is directly proportional to the FA which, in turn, shows a negative relation with $\alpha$ (Table 5). Water losses are similar to values reported elsewhere in the Mediterranean region; e.g. the Catalan Water Agency (ACA, 2016) estimated a $\alpha_{\text{mean}}$ of 0.23 for rivers of the Eastern Catalan Basin for the period 1940-2008 (values ranging between 0.05 and 0.50 depending on the specific hydro-climatic characteristics of each catchment, with higher values typically corresponding to the wetter basins within the region).

4.3. Sediment transport

4.3.1. Annual scale

Previous studies have estimated a Specific Sediment Yield (hereafter SSY) in Cogulers, Canalda and Inglabaga sub-catchments (i.e. wet sub-catchments) of 1 Mg km$^{-2}$ yr$^{-1}$, 3 Mg km$^{-2}$ yr$^{-1}$ (1998-2000; Balasch et al., 2005) and 4.2 Mg km$^{-2}$ yr$^{-1}$ (2005-2008; Vericat and Batalla, 2010), respectively. Buendia et al. (2016b) estimated a long-term sediment yield for a 43-year period in the Canalda sub-catchment of 276 Mg year$^{-1}$, equivalent to a SSYs of 3.8 Mg km$^{-2}$ yr$^{-1}$. In the present study, the total SSY at the catchment outlet was 4030 Mg, resulting in an annual average of 2015 Mg, i.e. SSY of 9.3 Mg km$^{-2}$ yr$^{-1}$. Vanmaercke et al. (2012) placed the 25th percentile of the SSYs in the Mediterranean region (from data obtained in 186 sites from Portugal to Turkey)
for catchments with an area between 100 and 1000 km² at ca. 100 Mg km⁻² y⁻¹, with a minimum value below 1 Mg km⁻² y⁻¹. Buendia et al. (2016c) analysed the SSY of 116 river sections across the Iberian Peninsula with data both from bathymetrical records from reservoirs and sediment transport records. They found that catchments with an area between 100 and 1000 km² had a mean SSY of 287 Mg km⁻² y⁻¹ (CV=155%, n = 50), a value that places the Ribera Salada in the 20th percentile of the Iberian Peninsula SSYs distribution. These values show that the sediment export capacity of the rivers in the north-eastern section of the Iberian Peninsula is lower than in the rest of the Mediterranean region, with the exception of the catchments draining highly erodible landscapes such as badlands, as for instance the River Isábena (439 km², SSY = 544 Mg km⁻² y⁻¹, López-Tarazón et al., 2012), Ésera (894 km², SSY = 337 Mg km⁻² y⁻¹, Lobera et al., 2016) and Cinca (849 km², SSY = 74.2 Mg km⁻² y⁻¹, Béjar et al., 2018). Overall, SSY in the Ribera Salada is low when compared to other Iberian Peninsula catchments, and generally to most of the Mediterranean rivers. This indicates the relatively low intensity of the dominant hydrological and geomorphic processes in the catchment. Even so, values in the same range have previously reported in catchments of the Catalan Ranges (e.g. Anoia: 5.5 to 75 Mg km⁻² y⁻¹, Farguell and Sala, 2005; Arbúcies: 35 Mg km⁻² y⁻¹, Batalla et al., 2005).

In the Ribera Salada, most of the sediment is transported during floods. The proportion of the flood-transported sediment load to the annual load (SSY) is 97% in Cogulers, 90% in Canalda, 86% in Inglabaga and 97% in Altés during the study period. In the Altés and the Cogulers stations, 90% of the suspended sediment load is carried in 3% of the time, while in Canalda and Inglabaga, 90% of the load is transported in 10% and 25% of the time, respectively (Figure 7).

Average SSY ranges from 3.8 Mg in Cogulers (SSY = 1.6 Mg km⁻² y⁻¹), to 340 Mg in Canalda (5.2 Mg km⁻² y⁻¹), 510 Mg in Inglabaga (4.4 Mg km⁻² y⁻¹) and the reported 2015 Mg (9.3 Mg km⁻² y⁻¹) at catchment outlet (Altés) (Table 2 and figure 3B). Thus, the dry part of the catchment contributes more than ¾ of the annual sediment load of the whole Ribera Salada, despite occupying little less than 50% of the basin area. Contrary to most of the general relations between area and SSY presented in the literature, the SSY in the Ribera Salada
catchment increases with area, a pattern that de Vente et al. (2007) attributed it to basin in which channel erosion was the dominant source of material. Moreover, Dedkov (2004) indicated that this is also pattern a typical in river basins where agriculture is limited or non-existent. The Ribera sits in this sedimentary pattern but the limited number of monitoring sections (n = 4) and years for which data is available (n = 2) precludes further generalizations of the results obtained here.

4.3.2. Seasonal and monthly patterns

The sedimentary regime observed at the outlet of the Ribera Salada shows a seasonal maximum i.e. spring with 1570 Mg, followed by summer with 350 Mg (average values for all study period, Table 2), equivalent to 78 and 17 % of the annual total, respectively. Sediment load during winter and autumn is much lower (3 and 2%, respectively). Tuset et al. (2016) observed the same sedimentary regime in the Inglabaga sub-catchment (i.e. Ribera Salada) for a 3-year study period. The difference between spring and summer depends on the volume and the intensity, together with the spatial and time distribution and type of precipitation; in turn this controls the predominant type of flood (snowmelt-prone flood in combination with rainfall events in spring, and thunderstorms in summer). Similar behaviour was described by Lenzi et al. (2003) for rivers in the Alps, while López-Tarazon et al. (2012), Lobera et al. (2015) and Béjar et al. (2018) also reported spring maxima in nearby Pyrenean catchments. This general pattern may, however, be altered if a particularly intense storm occurs, as in the summer of 2012 when ca. 100 mm of rain was recorded in 3 hours (equating to a 10-yr return period, as per Casas et al., 2005) producing huge amount of sediments and placing the summer as the leading sediment producing season (see table 2). This general sedimentary regime applies to the rest of the sub-catchments too.

In spring, precipitation is usually high and together with snowmelt is capable to mobilising and transporting sediments that have been prepared during winter freeze and thawing cycles, mostly from banks and foot slopes with limited vegetation protection. This process has been observed in all the sub-catchments of the Ribera Salada, despite the differences in sediment availability
and connectivity due local variations in vegetation cover, lithology and topography. Dietrich and Dunne (1978) suggested that weathering is a critical limiting factor in the long-term movement of sediment in mountain environments, and this may be particularly true in steep slopes with shallow soils over bedrock, as is the case of the Ribera Salada (i.e. weathering is less crucial where primary sediment sources are deep soils, unconsolidated sediments, or tectonically shattered rock, such as recently glaciated sediments, Swanson et al., 1982). In turn, the harvest of grass in summer leaves the soil without protection and prone to erosion if local thunderstorms occur. Consequently, sub-catchments with higher proportion of cultivated areas experience a SSY increase in summer e.g. the lowermost area of the basin where agriculture concentrates in the floodplain (i.e. dry sub-catchment with 13.5% of cultivated land; see Table 1 and 2 and Figure 8).

At the monthly scale, the largest sediment load in the whole basin was observed in April (958 Mg corresponding to a total runoff of 4.3 hm$^3$) and May (603 Mg, 7.1 hm$^3$), whereas minima occurred in February and August (3 Mg, 0.7 hm$^3$, both cases). July and September also registered relatively high sediment loads (113 and 235 Mg, respectively) but associated with low runoff volumes (1.2 and 1.1 hm$^3$, respectively). Figure 9 shows the figure-of-eight hysteresis in the Ribera Salada sedimentary cycle, a phenomenon that suggests the concurrence of several sediment sources with different contribution-sedimentation-depletion periods. These periods are: (i) From the beginning of spring to June (i.e. clockwise hysteresis) the catchment supplies large amounts of sediment that is progressively exported mostly under snowmelt flows; (ii) In summer (i.e. counter-clockwise hysteresis), sediment mobilization occurs during individual intense precipitation episodes although magnitudes are relatively low, that produce high peak flows and relatively low volumes of runoff; and (iii) From November to March, when water and sediment yield is usually negligible. This cycle was reported for the Ribera Salada by Tuset et al. (2014).

4.3.3. The role of floods
More than any other aspect of a river’s hydrology, floods may reflect the response of a drainage to factors controlling flows. In the case of the Ribera Salada separation of DR and BF allowed determination of when a flood occurred, estimation of the SSY transported during each episode as a DR and elucidation of the role of floods in the sediment export of the basin. Here a flood is defined as the daily event for which DR is detected (i.e. for this we used the BFI+® 3.0 software).

Using this definition, 35 flood events were recorded between January 2012 and December 2013 in the Altés section (encompassing the whole catchment). In the Inglabaga section, the number of floods was 43 for all the study period. In Canalda, Fred and Cogulers, the number of floods was lower (i.e. 33, 31, and 30, respectively). Results suggest that in the wet basin the number of floods is directly proportional to the size of the catchment.

Sediment transport has high inter-annual variability, with 15% of the total SSL transported in 2012 and the remaining 85% transported in 2013. Intra-annual variability is notable, with a single event (i.e. 30\textsuperscript{th} April 2013) capable of transporting up to 56% of the SSL (i.e. 2275 Mg).

The flood-based SSY in Altés, Inglabaga, Canalda and Cogulers were 9.0 Mg km\textsuperscript{-2} yr\textsuperscript{-1}, 3.8 Mg km\textsuperscript{-2} yr\textsuperscript{-1}, 4.7 Mg km\textsuperscript{-2} yr\textsuperscript{-1} and 1.2 Mg km\textsuperscript{-2} yr\textsuperscript{-1}, respectively (see Supplementary Materials for a detailed analyses in terms of the hydro-sedimentary response at the event scale). Similar to the total load, most of the flood-based sediment yield (14.8 Mg km\textsuperscript{-2} yr\textsuperscript{-1}) is produced in the dry sub-catchment, reaching 80% of the flood-based production. Sediment production within the Inglabaga sub-catchment depends on the source area, with Fred and Plana (i.e. sub-catchment adjacent to the Fred and Canalda sub-catchments) having the lowest yield (2.5 Mg km\textsuperscript{-2} yr\textsuperscript{-1}; difference between the production of Canalda and Inglabaga). The large proportion of rocky channels in this area reduces the source areas, which, in densely-forested sub-catchments, are the main sediment source.

4.3.4. Sediment budget
There are no direct measurements of soil erosion in the Ribera Salada for the study period. Even so, Verdú et al. (2000) modelled erosion dynamics in the Canalda sub-catchment and estimated values from 4.4 to 25.5 g per ha and mm of rain, depending on land use. The extrapolation of these results to the mean precipitation registered in 2012 and 2013 (see table 2) yields erosion values between 0.003 and 0.016 Mg ha$^{-1}$ y$^{-1}$ for the whole study period. These values again plot in the lower range of the erosion rates measured in the Mediterranean area (from 0.006 to 1 Mg ha$^{-1}$ y$^{-1}$ at the plot scale; Vanmaercke et al., 2012). Erosion values differ greatly from the SSL estimated at both Inglabaga and Altés sections (0.05 and 0.09 Mg ha$^{-1}$ y$^{-1}$, respectively) (Table 2). The difference between erosion and yield point out the current hydro-sedimentary response of the basin and helps the conceptualisation of its sediment budget, with the sediment contribution from the drainage network accounting for almost all the sediment exported from the catchment. This agrees, for instance, with work by Kronvang et al. (2013) who reported bank erosion as the dominant source of sediment (i.e. between 90-94%) in the River Odense (Denmark), though in a more humid region than the Ribera Salada. Direct runoff in headwaters of the Ribera Salada (i.e. in the Canalda sub-catchment) is rare and highly localised, despite some slopes showing erosion forms such as rills and gullies at the limit of the subalpine zone (i.e. meadow-dominated landscape at 2000 m a.s.l.). These features indicate a degree of local sedimentary activity, although this is best considered marginal at the basin scale.

The mobilised sediments do not leave the area because they are quickly fixed by grass. From the headwaters to the Inglabaga section (i.e. an area that includes Cogulers, Canalda and Fred sub-catchments), the dense forest cover greatly limits soil erosion; here rills and gullies can only be found in some mountain tracks and on the artificial slopes after strong rainfall, so the river’s sediment load is almost exclusively due to erosion of river channel and banks. The physiography of Fred, Canalda and, hence, Inglabaga sub-catchments, which is mainly composed by rock-carved channels (Figure 1), indicates sediment depletion, and may explain the low sediment yield of this wet upper part of the Ribera Salada when compared to other Mediterranean catchments (see 4.2.1.). These results are in line with several works (Dedkov and
Moszherin, 1992; Dedkov and Mozzherin, 1996; Dedkov, 2004), indicating that in low-modified mountain streams, (i) the intensity of erosion (i.e. sediment yield) depends directly on the amplitude of the relief and that (ii) these rivers are characterized by low suspended sediment yields. The upper half of the Ribera Salada is a supply limited catchment that, besides structural factors such as high soil infiltration capacity, faces sediment depletion from the source areas mostly due to afforestation of abandoned croplands and meadows (20% of the basin area has been afforested in the last 50 years after land abandonment; Buendia et al., 2016b). This hungry-water dynamic generates bank erosion and incision in the main channel causing, for instance, the disconnection of lateral bars which over recent decades have been intensively colonized by shrubs and, occasionally, woody vegetation.

The mean SSY in the lower, dry half of the Ribera Salada is four times higher than that of the upstream area, despite having the same area and a lower $Q$. Field observations suggest that this higher SSY is likely a function of the greater availability of sediment stored in the alluvial deposits of the main valley and owing to soft sedimentary rocks (sandstones and clayrocks in the hillslopes), as well as due to apparent high connectivity between the sediment sources (e.g. riverbanks and adjacent agricultural fields) and the stream courses.

Additionally, major gravel mining occurred in the river some decades ago, with an estimated $>300,000 \text{ m}^3$ extracted as aggregate between 1987 and 2000; Batalla and Martín-Vide, 2006). This may have altered the sediment transport dynamics of the lower part of the basin. Gravel-mining mainly affects the coarse part of the sediment load, so the fine fractions that are transported in suspension and which are the main focus of the current paper may have been affected less. Nonetheless, the river (i.e. slope, geometry, pattern) is still recovering to pre-extraction situation, a fact that may affect the transfer of the suspended load through the reach. This recovery process may take decades until the pre-extraction channel configuration is reached (provided that other physical factors i.e. runoff, sediment supply, remain unaltered).
5. CONCLUSIONS

This work presents the water and the sediment budgets of a mountainous Mediterranean catchment located in the Southern Pyrenees for a two-year period. The study period was characterized by a moderate rainfall variability with a relatively dry 2012 and a wetter 2013. The work focused on the quantification of the water and the sediment flows through five nested sub-catchments. Measurements of flow and sediment transport covered a wide range of discharges, ranging from base flow to small and medium floods. Rainfall obtained from radar proved useful in the Ribera Salada where precipitation is highly variable in space and time and where individual rain gauges are not capable to capture such variability. The main conclusions of the work are drawn as follows:

1. The Ribera Salada consists of two well differentiated areas with contrasting hydrological regimes. The upper area (the wet basin) has a relatively constant flow regime that is basically controlled by a relatively even rainfall distribution, snowmelt and water transfers from the hydrogeological units. In this upper sub-catchment (52.7% of the total basin area), water yield is positively correlated to catchment area, so all parts of the catchment contribute approximately the same volume of water per unit area. The direct runoff from of each sub-catchment increases with basin area too. In contrast, tributaries in the lower dry part of the catchment (47.3% of basin area) only supply water during rainfall events; as a result of this, flow in the mainstem river decreases as the catchment area increases. The aquifer shifts from being effluent to influent: direct runoff decreases in dry periods due to the alluvial aquifer recharge during floods and increases in wet periods when the level of the aquifer is high.

2. The sediment yield of the whole catchment and the respective sub-catchments sits close to the lower bounds of values reported for the Mediterranean region. This illustrates the low intensity of the dominant hydrological and geomorphic processes in the area. The sediment yield in the dry part of the catchment is four times than that observed upstream, even though the runoff is lower. The increment is explained by the higher availability of sediment and the higher connectivity between the sediment sources (mostly agricultural fields) and the fluvial network.
Overall, the Ribera Salada shows a positive relationship between the sediment yield per unit area and the basin area. The sediment load is transported mainly during floods, and come from channel and banks in the upper part of the catchment and overland flow and erosion from the agricultural areas adjacent to the ephemeral downstream tributaries and the main valley, respectively. The upper basin is a supply limited system that faces long-term sediment depletion mostly due to afforestation that has taken place since the 1950s. This phenomenon causes incision in the main channel and geomorphic changes in the valley where formerly active sedimentary deposits (e.g. lateral bars) experience disconnection from the river channel and vegetation encroachment occurs.

The water and the sediment budgets presented here indicate that the Ribera Salada is a basin with low geomorphic activity, a circumstance that is certainly not usual in the Mediterranean area. Results provide valuable scientific knowledge on water and sediment dynamics that still scarce in this highly contrasted hydroclimatic region, ranging from wet mountain headwaters to dry lowlands. Overall, and owing to the amount of data available at various catchment scales (from one to hundreds of km²), the Ribera Salada offers a particular but, at the same time, attractive environment to further examine the effects of land use and climate changes, which are expected to be particularly acute in this transitional riverscapes.

Acknowledgements

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of Lleida. Part of the instrumentation was funded by the project ‘Sediment Export from Large Semi-Arid Catchments: Measurements and Modelling’ (SESAM), funded by the Deutsche Forschungsgemeinschaft (DGF). Authors are especially indebted to David Estany for his invaluable assistance during fieldwork, and Chris Gibbins for a complete revision and discussion of the first draft of this manuscript.
Notations

\[ A \] Drainage area (\( \text{km}^2 \))
\[ BF \] Base-Flow (\( \text{m}^3 \text{ s}^{-1} \))
\[ C_i \] Mean concentration determined from a single vertical section (\( \text{mg} \text{l}^{-1} \))
\[ Cs \] Mean suspended sediment concentration (\( \text{mg} \text{l}^{-1} \))
\[ CV \] Coefficient of Variation
\[ DR \] Direct Runoff (\( \text{hm}^3 \))
\[ ETr \] Real Evapotranspiration (\( \text{mm} \))
\[ f \] Standard value (i.e. 0.9; dimensionless)
\[ FA \] Forest area (\%)
\[ h \] Water depth (\( \text{m} \))
\[ WW \] Licensed Water Withdrawals (\( \text{mm} \))
\[ K \] Ratio between \( Cs \) and \( C1 \) (dimensionless)
\[ n \] Number of days after which direct surface runoff ceases (days)
\[ NTU \] Nephelometric Turbidity Units
\[ OM \] Organic Matter
\[ P \] Mean precipitation (\( \text{mm} \))
\[ P_{m_{\text{obs}}} \] Monthly rainfall observed (\( \text{mm} \))
\[ P_{m_{\text{pred}}} \] Estimated monthly rainfall (\( \text{mm} \))
\[ Q \] Runoff (\( \text{m}^3 \text{ s}^{-1} \))
\[ Q_{\text{max}} \] Peak discharge (\( \text{m}^3 \text{ s}^{-1} \))
\[ Q_{\text{mean}} \] Mean discharge (\( \text{m}^3 \text{ s}^{-1} \))
\[ \alpha \] Runoff coefficient (\%)
\[ RMSE \] Root Mean Square Error (\( \text{mm} \))
\[ SSC \] Suspended Sediment Concentration (\( \text{mg} \text{l}^{-1} \))
\[ SSC_{\text{max}} \] Maximum Suspended Sediment Concentration (\( \text{g} \text{l}^{-1} \))
\[ SSL \] Suspended Sediment Load (\( \text{Mg} \))
\[ SSY \] Suspended Sediment Yield (\( \text{Mg} \))
\[ SSY_{\text{s}} \] Specific Suspended Sediment Yield (\( \text{Mg} \text{ km}^{-1} \text{ y}^{-1} \))
\[ TR \] Total flood-based Runoff (\( \text{hm}^3 \))
\[ WY \] Water Yield (\( \text{hm}^3 \))
\[ X_{\text{est},i} \] Estimated (modelled) values for the same period provided by the raster data set at the location of the same station \( i \) (\( \text{mm} \))
\[ X_{\text{obs},i} \] Observed rainfall values for a period in a station \( i \) (\( \text{mm} \))
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Figure captions

Figure 1. Ribera Salada sub-catchments with the location of the monitoring sections and the rainfall gauges, and a synthesis of the hydrogeological system of the Ribera Salada (modified from Núñez et al., 2004). Note that the proportion of the arrows were extracted from Núñez et al. (2004). The inset map shows the location of the Ribera Salada in the Ebro Basin and in the Iberian Peninsula. Note that the coordinates at the outlet of the catchment are indicated as reference.

Figure 2. Hydrograph and sedigraph recorded at monitoring sections during the 2-yr study period (see location in Figure 1). A summary table is included as inset where $Q_{\text{mean}}$ indicates the mean discharge for the all study period (2012-2013), $Q$ shows characteristic $i$ percentiles, $SSC_{\text{mean}}$ indicates the mean suspended sediment concentration, and $SSC_i$ shows characteristic $i$ percentiles of the Suspended Sediment Load (SSL). Data are plotted at 1-hour interval.

Figure 3. The (A) water and (B) sediment budgets of the Ribera Salada for the study period (2012-2013). The annual distribution of the water and sediment load are shown for each sub-catchment (note that water and sediment fluxes displayed by the arrows are scaled according to their absolute magnitude). The Odèn hydrological subunit (see Figure 1) is also included (in grey).

Figure 4. Relationships between water yield ($WY$) and basin area in (A) 2012 and (B) 2013. In the upper wet part of the basin (blue), the $WY$ is positively correlated with the area (i.e. continuous line), whereas in the lower dry half of the basin (yellow), $WY$ decreases as the catchment area increases (i.e. dashed line). Relationships between $WY$ and adjusted contribution area (i.e. including the Odèn hydrogeological subunit area in the sub-catchments that receiving water fluxes from this) in 2012 (C) and 2013 (D). Equations 4 and 5 are statistically significant at $p<0.05$, whereas, equations 2 and 3 are significant at $p$-value 0.15 and 0.10, respectively. These equations were subsequently used to assess the real contribution of the sub-catchments affected by the transmission from the Odèn subunit (see Table 3 and text for more details).

Figure 5. (A) Relationship between daily discharge ($Q$ in m$^3$ s$^{-1}$) in Inglabaga and Altés sections for 2012 and 2013. Data above 14 m$^3$ s$^{-1}$ is not included to improve readability. The figure shows three hydraulic patterns between the river and the alluvial aquifer: (i) For $Q < 0.8$ m$^3$ s$^{-1}$, the river turns from effluent to influent depending on the relationship between the river and the aquifer levels (light blue box); (ii) For $0.8$ m$^3$ s$^{-1}$ > $Q$, water transfers are from the river to the aquifer (blue box), and (iii) For $Q > 3.5$ m$^3$ s$^{-1}$, flow increases between Inglabaga and the catchment outlet (grey box; see section for a complete description of the observed hydrological patterns). (B) Relationship between specific daily discharge (in 1 s$^{-1}$ km$^{-2}$) in Inglabaga and Altés sections for 2012 and 2013. Note that in both cases the 1:1 relation is plotted as reference.

Figure 6. Daily discharge ($Q$ in m$^3$ s$^{-1}$) in Inglabaga and Altés sections from 1st March to 24th April 2013. In general, discharge in Altés is lower than in Inglabaga, although some floods can have a larger peak $Q$ in the outlet than in Inglabaga. The aquifer is recharged with the flow supplied from upstream (Inglabaga) and the tributaries draining the dry basin, especially during floods.
Figure 7. Suspended sediment load frequency curves at the sub-catchment scale for all the study period (January 2012 to December 2013). Note that the x-axis uses a log-scale to improve the visualization of the differences between sub-catchments.

Figure 8. (A) Relationship between Suspended Sediment Load (SSL) and sub-catchment area. Overall, the empirical relation overestimates the sediment production capability of the upper wet Canalda and Inlabaga catchments (where agriculture is residual) and underestimates it in the dry sub-catchments. (B) Relationship between Suspended Sediment Load (SSL) and the area occupied by agriculture in each sub-catchment, suggesting a high dependency between the agricultural area and the catchments sediment yield (see the coefficients of determination, i.e. equations 6 and 7). Statistical relations are statistically significant at p<0.05.

Figure 9. Monthly hysteresis of the suspended sediment load (2012-2013) in the (A) Altés and (B) Inlabaga sections. Each number corresponds to one month, where: 2 = February, 6 = June, 8 = August and 11 = November, as reference.
Table 1. Main characteristics of the five experimental sub-catchments. Information generated from the Land Cover Map of Catalonia v3 (Ibàñez and Burriel, 2010) and Geological map of Catalonia 1: 250,000 v2 (ICGG, 2019)

<table>
<thead>
<tr>
<th></th>
<th>Cogulers</th>
<th>Wet basin</th>
<th>Dry basin</th>
<th>Output of the basin</th>
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<tr>
<td></td>
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<td>Cogulers</td>
<td>Fred</td>
<td>Canada</td>
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<tr>
<td><strong>Area (km²)</strong></td>
<td>2.4 (0%)</td>
<td>26.8 (29%)</td>
<td>65.1 (39%)</td>
<td>114.5 (34%)</td>
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<td>Limestone, clayrocks and conglomerates</td>
<td>Sandstones and clayrocks</td>
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<td><strong>Time concentration of rainfall (min)</strong></td>
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<td>63</td>
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<td><strong>Altitude interval (m)</strong></td>
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<td>654-2387</td>
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<td><strong>Wood (% catchment area)</strong></td>
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<td>52.8</td>
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<td>3.7</td>
<td>23.5</td>
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<td><strong>Pasture (% catchment area)</strong></td>
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<td>2.9</td>
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<td><strong>Agricultural land (% catchment area)</strong></td>
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<td>3.9</td>
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<td><strong>Bare rock (% catchment area)</strong></td>
<td>5.0</td>
<td>12.7</td>
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<td><strong>Others (% catchment area)</strong></td>
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<td>0.2</td>
<td>4.1</td>
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1 In brackets, the percentage of the total area occupied by limestone.
2 Lithology of the sub-catchment up to the most immediate upstream monitoring section.
3 Calculated based on the California Cuverts Practice method (1942). Essentially it is Kirpich’s equation (Kirpich, 1940); developed for small mountain basins in California (U.S. Bureau of Reclamation, 1973).
4 This comprises (i) rocky terrain (i.e. massive conglomerate), (ii) forest with vegetation cover <20%, (iii) bare soil and (iv) scree.
Table 2. Mean values of the Precipitation (P), Water Yield (WY) and Suspended Sediment Load (SSL) for each sub-catchment in the period 2012-2013. The table does not include the SSL of Fred sub-catchment and the Precipitation (P) and Water Yield (WY).

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<th>Dry basin¹</th>
<th>Output of the basin</th>
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¹ Area between the Inglabaga and the Altés monitoring sections.
² Includes the water contribution from the Odèn subunit hydrogeological.
³ Rainfall average of the all contribution area, including the rainfall within the surface of Odèn hydrogeological subunit.
Table 3. Annual water yield ($WY$) and associated mean discharge ($Q_{\text{mean}}$) in all sub-catchments in 2012 and 2013 and the average of the two years.

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A$ (km$^2$)</td>
<td>$WY$ (hm$^3$)</td>
<td>$Q$ (m$^3$ s$^{-1}$)</td>
</tr>
<tr>
<td>Cogulers</td>
<td>2.4</td>
<td>0.05</td>
<td>0.002</td>
</tr>
<tr>
<td>Fred$^1$</td>
<td>26.8 (21.7)</td>
<td>8.7 (2.5)</td>
<td>0.28 (0.08)</td>
</tr>
<tr>
<td>Canalda$^2$</td>
<td>65.1 (60.6)</td>
<td>6.3</td>
<td>0.20</td>
</tr>
<tr>
<td>Odèn subunit</td>
<td>42.7</td>
<td>6.1</td>
<td>0.19</td>
</tr>
<tr>
<td>Fred River + Odèn SU$^3$</td>
<td>64.4</td>
<td>8.7</td>
<td>0.28</td>
</tr>
<tr>
<td>Inglabaga$^2$</td>
<td>114.5 (143.1)</td>
<td>15.9</td>
<td>0.50</td>
</tr>
<tr>
<td>Altès$^2$</td>
<td>217.4 (245.6)</td>
<td>15.4</td>
<td>0.49</td>
</tr>
</tbody>
</table>

1 In brackets, the results without the Odèn hydrogeological subunit area and its water contribution.
2 In brackets, the results without the Odèn hydrogeological subunit area and its water contribution.
3 Overall contribution of the Fred sub-catchment and the Odèn hydrological subunit.
Table 4. Direct runoff (DR), base flow (BF) and water yield (WY) in all the sub-catchments in 2012 and 2013 and the average of the two years.

<table>
<thead>
<tr>
<th>Area (km²)</th>
<th>2012</th>
<th></th>
<th></th>
<th>2013</th>
<th></th>
<th></th>
<th>Average</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DR (hm³)</td>
<td>BF (hm³)</td>
<td>WY (hm³)</td>
<td>DR (%)</td>
<td>BF (hm³)</td>
<td>WY (hm³)</td>
<td>DR (%)</td>
<td>BF (hm³)</td>
</tr>
<tr>
<td>Cogulers</td>
<td>2.44</td>
<td>0.03</td>
<td>0.02</td>
<td>0.05</td>
<td>64</td>
<td>0.52</td>
<td>0.11</td>
<td>0.64</td>
<td>81</td>
</tr>
<tr>
<td>Fred⁴</td>
<td>20.1</td>
<td>0.6</td>
<td>1.9</td>
<td>2.5</td>
<td>24</td>
<td>2.1</td>
<td>2.76</td>
<td>5.9</td>
<td>36</td>
</tr>
<tr>
<td>Fred</td>
<td>20.1</td>
<td>0.6</td>
<td>8.1</td>
<td>8.7</td>
<td>7</td>
<td>2.1</td>
<td>16.3</td>
<td>18.4</td>
<td>12</td>
</tr>
<tr>
<td>Canalda</td>
<td>45.8</td>
<td>1.4</td>
<td>5.0</td>
<td>6.4</td>
<td>22</td>
<td>4.3</td>
<td>10.1</td>
<td>14.4</td>
<td>30</td>
</tr>
<tr>
<td>Ingabaga²</td>
<td>84.1</td>
<td>3.0</td>
<td>6.8</td>
<td>9.8</td>
<td>31</td>
<td>9.0</td>
<td>12.6</td>
<td>21.6</td>
<td>42</td>
</tr>
<tr>
<td>Ingabaga</td>
<td>84.1</td>
<td>3.0</td>
<td>12.9</td>
<td>15.9</td>
<td>19</td>
<td>9.0</td>
<td>25.0</td>
<td>34.1</td>
<td>26</td>
</tr>
<tr>
<td>Altés</td>
<td>186.5</td>
<td>2.7</td>
<td>12.6</td>
<td>15.4</td>
<td>18</td>
<td>13.6</td>
<td>16.8</td>
<td>30.6</td>
<td>44</td>
</tr>
</tbody>
</table>

¹ Percentage of direct runoff (DR) in relation to the total water yield (WY).
² Water contribution from the Odén hydrogeological subunit is not included.
Table 5. Area (km²), precipitation (P, mm), runoff (R, mm), real evapotranspiration ($ET_r$, mm), authorized water withdrawals ($WW$, mm), runoff coefficient ($\alpha$) and percentage of forest area ($FA$) in each sub-catchment of the Ribera Salada. Altés does not have R, $ET_r$ and $\alpha$ data due to the lack of underground water records in the dry sub-catchment.

<table>
<thead>
<tr>
<th></th>
<th>Area¹ (km²)</th>
<th>P (mm)</th>
<th>$R$² (mm)</th>
<th>$Q + Q_{Oden}$³ (mm)</th>
<th>$WW$⁴ (mm)</th>
<th>$ET_r$⁵ (mm)</th>
<th>$\alpha$ (%)</th>
<th>FA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cogulers</td>
<td>2.4</td>
<td>640</td>
<td>141</td>
<td>141</td>
<td>0.0</td>
<td>499</td>
<td>22</td>
<td>85.5</td>
</tr>
<tr>
<td>Fred¹</td>
<td>21.6</td>
<td>550</td>
<td>195</td>
<td>626</td>
<td>3.4</td>
<td>351</td>
<td>36</td>
<td>57.9</td>
</tr>
<tr>
<td>Canalda</td>
<td>61.7</td>
<td>706</td>
<td>168</td>
<td>168</td>
<td>6.6</td>
<td>531</td>
<td>25</td>
<td>70.1</td>
</tr>
<tr>
<td>Inglabaga</td>
<td>101.4</td>
<td>655</td>
<td>155</td>
<td>247</td>
<td>6.8</td>
<td>493</td>
<td>25</td>
<td>65.3</td>
</tr>
<tr>
<td>Altés</td>
<td>204.3</td>
<td>619</td>
<td>-</td>
<td>112</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>72.4</td>
</tr>
</tbody>
</table>

¹ It does not include the recharge area of the Odèn subunit.
² Basins' annual runoff.
³ Annual water contribution from each sub-catchment (including the contribution from Odèn subunit).
⁴ $WW$: Authorized annual water withdrawals.
⁵ $ET_r$: Real annual evapotranspiration ($ET_r = P - R - WW$).
Figure 1
Figure 2.

**COGULERS**

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Q [m³/s]</th>
<th>SSC [mg/L]</th>
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</thead>
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<td>Qₚ ₇ / ₉₀</td>
<td>1.96</td>
<td>2.9</td>
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<tr>
<td>Qₚ ₉₀ / ₉₅</td>
<td>21.02</td>
<td>5.6</td>
</tr>
<tr>
<td>Qₚ ₉₅</td>
<td>326.19</td>
<td>23.6</td>
</tr>
<tr>
<td>Qₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑₑᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉᵉ=e</td>
<td>11.21</td>
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**FRED**

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</tr>
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<td>0.43</td>
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<tr>
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<td>1.36</td>
<td>0.33</td>
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<tr>
<td>Qₚ ₉₅</td>
<td>2.31</td>
<td>0.33</td>
</tr>
<tr>
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**CUNADA**

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**INGLABAGA**

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**ALTES**

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<td>Qₚ ₉₀ / ₉₅</td>
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<td>18.0</td>
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<td>0.74</td>
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Figure 3.

A) ODÈN SUBUNIT

COGULERS

CANAŁDA

INGLABAGA

HALF-WET BASIN

HALF-DRY BASIN

RIVER SEGRE

Annual water yield (hm³)

- 2012
- 2013

Annual sediment load (t)

- <10
- 10-1000
- >1000

B) COGULERS

CANAŁDA

INGLABAGA

Annual water yield (%) 2012

52%

Annual sediment load (%) 2012

52%

58%

54%

86%

84%

Catchment Scale (km²) 1 km²
Figure 4.

A) $WY = 0.1188A + 1.5484$ (Eq. 2)  
$R^2 = 0.78$

B) $WY = 0.2529A + 3.6759$ (Eq. 3)  
$R^2 = 0.81$

C) $WY = 0.1126A + 0.1351$ (Eq. 4)  
$R^2 = 0.98$

D) $WY = 0.2372A + 0.8337$ (Eq. 5)  
$R^2 = 0.99$
Figure 5.

A) Daily discharge, $Q$ ($m^3 s^{-1}$)

B) Influent pattern

Effluent pattern
Figure 6.
Figure 7.
Figure 8.

A) $y = 1.6617x - 15.535$ (Eq. 6)

$R^2 = 0.88$

B) $y = 16.589x + 5.153$ (Eq. 7)

$R^2 = 0.99$
Figure 9.

A) Suspended Sediment Load, SSL (Mg) vs. Runoff (hm$^3$) for Altés (Dry Sub-catchment).

B) Suspended Sediment Load, SSL (Mg) vs. Runoff (hm$^3$) for Inglabaga (Wet Sub-catchment).