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1 1 **RAINFALL, RUNOFF AND SEDIMENT TRANSPORT IN A MEDITERRANEAN**
2 2 **MOUNTAINOUS CATCHMENT**

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ABSTRACT

The relation between rainfall, runoff, erosion and sediment transport is highly variable in Mediterranean catchments. Their relation can be modified by land use changes and climate oscillations that, ultimately, will control water and sediment yields. This paper analyses rainfall, runoff and sediment transport relations in a meso-scale Mediterranean mountain catchment, the Ribera Salada (NE Iberian Peninsula). A total of 73 floods recorded between November 2005 and November 2008 at the Inglabaga Sediment Transport Station (114.5 km²) have been analysed. Suspended sediment transport and flow discharge was measured continuously. Rainfall data was obtained by means of direct rain gauges and daily rainfall reconstructions from radar information. Results indicate that the annual sediment yield (2.3 t km⁻¹ y⁻¹) and the flood-based runoff coefficients (4.1% on average) are low. The Ribera Salada presents a low geomorphological and hydrological activity compared with other Mediterranean mountain catchments. Pearson correlations between rainfall, runoff and sediment transport variables were obtained. The hydrological response of the catchment is controlled by the base flows. The magnitude of suspended sediment concentrations is largely correlated with flood magnitude, while sediment load is correlated with the amount of direct runoff. Multivariate analysis shows that total suspended load can be predicted by integrating rainfall and runoff variables. The total direct runoff is the variable with more weight in the equation. Finally, three main hydro-sedimentary phases within the hydrological year are defined in this catchment: (a) Winter, where the catchment produces only water and very little sediment; (b) Spring, where the majority of water and sediment is produced; and (c) Summer-Autumn, when little runoff is produced but significant amount of sediments is exported out of the catchment. Results show as land use and climate change may have an important role in modifying the cycles of water and sediment yields in Mediterranean Mountain Catchments.

Keywords: Rainfall, runoff, sediment transport, radar, meso-scale catchment, Ribera Salada, Ebro basin.

1. INTRODUCTION

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

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

The volume of runoff during a flood can be influenced by the antecedent rainfall conditions including soil saturation and humidity (e.g. López-Tarazón *et al.*, 2010; Yuan *et al.*, 2001), the precipitation during the event (e.g. Taylor and Pearce, 1982; Nu-Fang *et al.*, 2011), and other factors like rainfall intensity (e.g. Nu-Fang *et al.*, 2011) and the evapotranspiration and air temperature (e.g. Hibbert, 1967; Swank *et al.*, 2001; Serrano-Muela *et al.*, 2008). The

importance of some of these factors can be highly variable. For instance, temperature is a key factor since it modifies the generation of surface runoff during periods of snowmelt or in systems with frozen soils (Ollesch *et al.*, 2005). Additionally to these factors, land cover and land uses have a significant influence on the hydrological response of a catchment, directly or indirectly by interfering to the above indicated factors. The infiltration capacity of the soils is an example with a direct effect on the generation of runoff. High infiltration capacities in temperate forests (Mulungu *et al.*, 2005) generate a slower or delayed hydrological response when compared to other environments (e.g. González-Hidalgo and Echeverría, 1990).

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

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

132 *et al.*, 2011; Piqué *et al.*, 2014). Inter-annual variability of the SDR is often considerable but can
133 be also highly variable between catchments influenced by contrast sediment production
134 processes (i.e. erosion) and sediment loads (e.g. Vanmaercke *et al.*, 2012a).

135 As discussed previously, erosion rates are variable and these cannot be directly used to estimate
136 the sediment load at a given point. Consequently, as for instance was pointed out by
137 Vanmaercke *et al.* (2012b), it is necessary to study the dominant erosion processes in each
138 catchment according to the principal factors controlling these. Rodríguez-Blanco *et al.* (2010)
139 explained that a majority part of the suspended sediment load during an event can be explained
140 by the maximum discharge and the runoff. The relationships between rainfall, runoff and
141 sediment transport have been widely investigated. Several studies have found as the relationship
142 between suspended sediment transport and runoff, although might be significant in some
143 episodes, presents high variability (e.g. Rodríguez-Blanco *et al.*, 2010). In those cases
144 suspended sediment transport cannot be predicted by runoff intensity and the development of
145 rating curves to assess annual sediment loads (as per Walling, 1983) will not be fully
146 appropriate. Estrany *et al.* (2009) found that rainfall was the most important factor in controlling
147 the magnitude of suspended sediment concentrations in a small (1 km²) Mediterranean
148 catchment. However, Onderka *et al.* (2012) found, in a small (2.7 km²) pluvio-oceanic
149 catchment, that the mean suspended sediment concentrations (SSCs) are better correlated to
150 runoff.

151 Within this context, the main objectives of this study are: (a) to characterise rainfall, runoff and
152 sediment transport dynamics in a meso-scale Mediterranean mountain catchment during three
153 consecutive hydrologically contrasted years; (b) to analyse the relationship between key
154 variables of rainfall, runoff and sediment transport; and (c) to develop a multivariate statistical
155 analysis between sediment transport, rainfall and runoff to determine main variables controlling
156 sediment transport at the outlet of the catchment. This study is performed in the Ribera Salada, a
157 meso-scale Mediterranean mountain catchment in the Southern Pyrenees. As previously
158 reported (e.g. López-Tarazón *et al.*, 2010), although several studies have analysed the
159 relationships between rainfall, runoff and sediment transport, the most part of such studies have
160 been carried out in small scale agricultural catchments rather than in meso-scale forested
161 catchments. Therefore, this paper presents new insights into the mechanisms and processes that
162 dominate the hydro-geomorphological responses of Mediterranean mountain catchments.
163 Moreover, this work also incorporates a novel method to extract spatial distributed rainfall
164 fields by means of radar imagery. This new approach provides new opportunities to understand
165 the importance of the distribution of rainfall in generating runoff and sediment transport at large
166 spatial scales and at multiple temporal scales.

2. STUDY AREA

Research is carried out in the Ribera Salada, a medium-scale Mediterranean mountain catchment located in the Southern Pyrenees (NE Iberian Peninsula; Figure 1). The Ribera Salada has an area of 224 km² and flows into the Rialb Reservoir, located in the River Segre. The Segre is the main tributary of the River Ebro.

Maximum altitude of the catchment is 2386 m a.s.l. and it debouches into the Segre at ca. 460 m a.s.l. These characteristics imply an important climate gradient along the catchment. Two principal domains can be identified: (a) subalpine climate in the summits, and (b) a Mediterranean climate in the rest of the valley. Mean annual precipitation in the catchment is 763 mm, although mean values around 1000 mm are recorded in the headwaters, and values lower than 600 mm have been registered in the lowermost parts of the catchment (Ninyerola *et al.*, 2000). The north-west part of the catchment presents a rain shadow influenced by the headwaters of the Canalda sub-catchment (Figure 1). Within this context, the catchment presents two main rainfall patterns. The north and the middle parts receive maximum rainfall during spring and summer (i.e. seasonal rainfall sequence: Spring, Summer, Autumn and Winter; SSAW), while spring and autumn are the wettest seasons in the southernmost part of the catchment (i.e. Spring, Autumn, Summer and Winter; SASW). Storms are frequent between May and September. Snow is present in the highest altitudes (1800-2200 m a.s.l.) in winter and early spring. Mean annual temperature in the central areas of the catchment is 11°C, while minimum temperatures around -20°C are registered in the winter in the headwaters, and can exceed the 38°C in summer in the lower most reaches of the catchment.

In terms of geology, the headwaters are dominated by folded Triassic to Eocene limestones (characterised by having a high fracturing and karsification); marls and evaporites (gypsum and salt) are also present. The central and lower parts of the foreland catchment comprise an extensive deformed Eocene–Oligocene molassic sedimentary sequence at the bottom of a mantle-thrust. The catchment lies mostly on conglomerate supporting sandy–loamy soils. Specifically, the soils of the Ribera Salada have depths less than 50 cm. Water retention capacity is low because the degree of stoniness is high (> 20%; Verdú *et al.*, 2000). The 90% of the catchment is occupied by forest (78% wood; 9% shrubs; 3% pastures) while agricultural lands represent the 10%; main forest species are *Pinus pinea* and *Pinus sylvestris* and they occupy a 39% and a 22% of the catchment, respectively.

Flow records in the Ribera Salada started in 1998 when the University of Lleida (UdL) and the Forest Sciences Center of Catalonia (CTFC) set up two nested experimental catchments: Canalda and Cogulers (65.8 and 2.6 km², respectively). These are located approximately 4 km

upstream from the Inglabaga Sediment Transport Station (i.e. ISTS; see the location of Canalda and ISTS catchments in Figure 1). The ISTS closes a catchment of 114.5 km² and its monitoring started in 2005. Flow and sediment transport data obtained there have been used for the particular purposes of this study. Flow data obtained during the period 2005-2008 in ISTS was correlated with data registered at the Canalda monitoring site. The ratio between ISTS and Canalda is around 1.7. This ratio was used to assess and characterise the long term (1998-2008) flow regime at ISTS. Results indicate that mean daily discharge at ISTS is 0.5 m³ s⁻¹ (σ , standard deviation = 0.26 m³ s⁻¹). This value is equivalent to an annual runoff of 145 mm (Vericat and Batalla, 2010).

Mean channel slope at ISTS is almost 1%. Fluvial sediments are composed of well-rounded gravels and cobbles. Median surface material (D_{50-s}) is around 56 mm while larger percentiles (e.g. 95) are in the ranges of cobbles (e.g. $D_{95-s} = 167$ mm). Although at the reach scale the river bed can be considered armoured, patches of sand and fine gravels (median size around 1.2 mm) are distributed across the reach and cover approximately 20% of its surface area (Müller *et al.*, 2008). These sedimentary structures are frequently entrained and re-configured (Vericat *et al.*, 2008).

3. METHODS

Methods are divided in three main components: (a) field data acquisition; (b) remote sensing, and (c) data validation, selection of variables and analysis. The details of these are presented independently in the following sections.

3.1. Field data acquisition

Three main data variables were obtained in the field: rainfall, flow discharge, and suspended sediment transport. Flow and suspended sediment transport data have been already published by Vericat and Batalla (2010), but in a paper that tackled clearly different objectives than the ones addressed in the present manuscript. They analysed the distinct role of bedload and suspended sediment transport in the annual sediment yield. Here, however, we aim at analysing rainfall, runoff and sediment transport relations by integrating flow and suspended sediment transport with the rainfall distribution across the catchment. In the particular case of this manuscript, it is worth to remark the approach we have followed to estimate the distribution of rainfall. This will be fully explained later in section 3.2.

Rainfall is measured at 1-hour intervals at the Port del Comte (2316 m.a.s.l.) and Lladurs (785 m.a.s.l.) meteorological stations, and at the Cambrils (1760 m.a.s.l.) rain station (see location in Figure 1) by means 3 rain gauges operated by a 3 data-logger. The distribution of rainfall across the catchment has been assessed by radar data as will be explained in the next section.

Flow depth and turbidity were continuously monitored at ISTS (see location in Figure 1) between November 2005 and November 2008. Water depth (h) was measured by means of a pressure transducer (Druck[®] 1730-PDCR) at 5-minute intervals and subsequently converted to a discharge (Q) using a specifically derived rating curve (h/Q relation). Discharge associated to different water stages was modelled using WinXpro[®]. Results have been validated with data from direct gauging (more details in Vericat and Batalla, 2010).

Turbidity was measured by means an ANALITE[®] NEP9350 turbidity probe equipped with a wiper. The range of the probe was 0-3000 NTU, equating to approximately 0-3 g l⁻¹. The sensor took a reading every minute and registered the average value every 5 minutes. Water depth and turbidity data was then registered by means of a Campbell[®] CR1000 data-logger. Turbidity data (NTU) was converted to SSC by means of a statistically significant lineal relation between NTU and SSC constructed from 367 water samples (see Vericat and Batalla, 2010). Water samples were obtained by means of an automatic water sampler (ISCO[®] 3700) and post-processed in the laboratory (filtered, dried and weighted). The root-mean-square error of the calibration between NTU and SSC is of 0.17 g l⁻¹. The measured SSC during the study period only exceed 40 minutes the turbidimeter range over the 3 years. Therefore, the bias attributed to this situation is considered negligible. Figure 2 shows the resulting hydrograph and sedigraph for the entire study period.

3.2. Remote sensing

The amount and distribution of rainfall in the 3 main sub-catchments draining at ISTS (i.e. Canalda, Fred and Inglabaga; see Figure 1) were assessed by means of geo-referenced radar images. The Canalda and Fred catchments are nested to the Inglabaga sub-catchment. The resolution of the radar images was 3×3 km. High-resolution daily rainfall maps were obtained by means of the calibration of radar data. Basically, two years of radar data were correlated with direct rainfall records from weather stations. Different specific statistical analysis were performed to develop the calibration (see more details in Coll, 2010; Coll *et al.*, 2010; Velasco-Forero *et al.*, 2009; Schiemann *et al.*, 2010). This calibration has been developed by The Center of Applied Research on Hydrometeorology (CRAHI) of the Polytechnic University of Catalonia (UPC). Figure 3 represents an example of a rainfall map for the upper Ribera Salada Catchment where the spatial distribution of the rainfall across the catchment can be observed. Additionally,

rainfall records obtained in the meteorological and rainfall stations described in 3.1 are also added. Differences between observed (rainfall stations) and estimated (radar) rainfall are indicated as a reference. In the following section we give details on how rainfall estimates from radar data were validated.

3.3. Data validation, selection of variables and analysis

In this section we provide details on (i) the validation of the rainfall fields obtained from radar data during the study period, (ii) the selection and estimation of rainfall, runoff and sediment transport variables; and (iii) the statistical analysis performed between variables stated in (ii).

3.3.1. Validation of rainfall fields during the study period

A cross-validation was performed in order to assess the accuracy of the rainfall rasters obtained from radar data during the study period. As previously indicated, these rasters were elaborated by the CRAHI and details about their calibration and validation are provided by Coll (2010). Here we only aim at calculating the potential error on the rainfall estimated during the study period in our study area by using the data registered in the meteorological and rainfall stations as the reference data set (observed rainfall). An intersection of the points where the stations are located with the rainfall cells is performed and the differences between observed (i.e. registered) and estimated (i.e. modelled) rainfall calculated. Differences were analysed by the Root Mean Square Error calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_{obs,i} - P_{est,i})^2}{n}}$$

where P_{obs} are the observed rainfall values for a period in a station i and P_{est} are the estimated or modelled values for the same period provided by the raster data set at the location of the same station i . The RMSE (or as it is occasionally found the Root Mean Square Deviation, RMSD) is frequently used to measure the difference between the values predicted by a model and the values actually observed from the environment that is being modelled (e.g. Holschlag, 2001; Chu and Shirmohammadi, 2004; Singh *et al.*, 2005; Isik, 2013). The RMSE aggregates the residuals into a single measure of predictive power. In this case, the unit of RMSE is the millimetre. However, it should be noted 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. 3×3 km) and (b) the calibration of the radar fields. The RMSE was calculated for a total of 47 independent days.

3.3.2. Rainfall, runoff and sediment transport variables

Several rainfall, runoff and sediment transport variables were calculated for a total of 75 flood events. Two considerations need to be introduced before we describe the selected variables. First, in this study we considered a flood the hydrological event in which discharge exceeds 1.5 times the base flow at the beginning of the rainfall. This criterion has been widely used in the literature (e.g., García-Ruiz *et al.*, 2005; López-Tarazon *et al.*, 2012; Lana-Renault *et al.*, 2007; Nadal-Romero *et al.*, 2008a). Second, once floods were independently identified, a base flow separation was performed in order to obtain the surface (i.e. quick or direct) runoff for the event. This separation was made by means of the graphical approach after transforming flow values into logarithms (e.g. Barnes, 1939; Maidment, 1993; Sujono *et al.*, 2004). The method is based on the identification of breakpoints on the logarithmic falling limbs of the hydrograph. A line connecting the initial point of the surface runoff (rising limb) to these breakpoints determines the volume of surface runoff (top) and base flow (bottom) (e.g. Hewlett and Hibbert, 1967 and Maidment, 1993).

A total of 19 variables describing the pre-event conditions (2), rainfall (6), runoff (8) and sediment transport (3) associated to each flood event have been calculated (see Table 1).

Pre-event condition variables are: base flow discharge at the beginning of the flood event (Q_0) and the average water temperature at ISTS during the day of the event.

Rainfall variables include total precipitation of the event for the whole catchment (P_d), daily precipitation of the first day of the event for each sub-catchment (P_{d1}) and the antecedent rainfall observed during the 7 days previous to the event for each sub-catchment (P_{d7}). It is worth to mention that three sub-catchments have been used to analyse the distribution of the rainfall upstream from ISTS (i.e. CA: Canalda; FR: Fred and IN: Inglabaga; Figure 1). These variables were calculated using the daily spatially distributed rainfall data sets (i.e. rainfall rasters). In case that more than one flood was registered in a day, daily values were weighted based on the values registered in the rainfall stations where hourly data was available. The proportion of the total rainfall per each flood event in relation to the daily precipitation was estimated and interpolated (spline) using ArcMap 9.3[®]. Weights were applied to the daily values provided by the rainfall rasters in order to determine the volume of rainfall associated to each flood. This spatial segregation of the rainfall offers the opportunity to improve the analysis of the variability of the precipitation, not only altitudinally but longitudinally. At the same time, the segregation provides insights into the influence of the physical nature of each sub-catchment in the hydrological and sedimentary response that occurs in each flood event. Additionally, data from the rainfall stations were used to assess three variables that were not possible to be calculated with the daily rainfall rasters: duration of precipitation (P_{dur}), maximum hourly

rainfall intensity ($I_{\max_{60}}$), and kinetic energy (EcI_{60}) of the maximum hourly intensity. The EcI_{60} was calculated by means of the following equation:

$$EcI_{60} = \left(\left(\sum EF * P \right) I_x \right)$$

$$EF = 0,29[1 - 0,72 * \exp(-0,05 * I)]$$

where, EF is the kinetic energy ($\text{MJ ha}^{-1} \text{ mm}^{-1}$) following the approach by Brown and Foster (1987) for the 30-minutes maximum rainfall intensity; I is the intensity of rain for a period of 60 minutes (mm h^{-1}); P is the accumulated precipitation for the same, and I_x is the maximum intensity of rainfall within these 60 minutes.

A total of 10 runoff variables were calculated: flood duration (Fdur), total volume of surface runoff (TR), peak discharge (Qp), mean flood discharge (Qm), base flow water volume (Qb), ratio between the peak discharge and the base flow at the beginning of the flood (Q_p/Q_0), and the flashiness index of the first peak of the flood (FI), estimated as the rate of increment of discharge per unit of time (as per Batalla and Vericat, 2009).

Finally, sediment transport variables include mean suspended sediment concentration (SSCmean), maximum suspended sediment concentration (SSCmax), and the total suspended sediment load (TL). All variables are summarized in table 1 indicating their correspondent units.

3.3.3. Statistical analysis

Relationships between rainfall, runoff and suspended sediment transport were analysed through Pearson correlations (Pearson, 1896) and a multivariate regression analysis. The analyses were performed with Statistica[®] 7.0. Pearson correlations include the relationships between (1) pre-event conditions and rainfall variables with runoff, (2) pre-event conditions and rainfall variables with suspended sediment transport, and (3) runoff variables and suspended sediment transport. The Pearson correlation coefficient is a measure of linearity between two or more variables. A p-value of 0.01 was established to considering the correlations statistically significant.

The multivariate regression method analyses the relationship between the independent variables (i.e. pre-event conditions, rainfall and runoff) and the dependent variable (i.e. suspended sediment transport) for all flood events. In this case we adopted the stepwise approach and we selected the backward elimination method of continuous predictors. Tolerance for the inverse

matrix is considered a value of $F > 5$ (López-Tarazón *et al.* 2010; Estrany *et al.* 2010). This value determines how significant the contribution of a variable in the regression equation is. In this case the statistically significant level for the inclusion of variables is set to a p-value of 0.05. β and B coefficients were obtained from the multivariate analysis. β regression coefficients are standardized unlike coefficients B. This allows us to compare the relative contribution of each independent variable in the prediction of the dependent variable, and its interpretation is similar to the partial correlations. Coefficients B are used to develop the regression equation. Finally, in order to verify the predictive power of the resultant multivariate regression (i.e. model goodness) nine (three per year) flood events that were randomly excluded from the multivariate analyses were used as a validation data set.

4. RESULTS AND DISCUSSION

4.1. Flood events

A total of 75 flood events were observed between November 2005 and November 2008. Four of these events were excluded because of equipment malfunctioning. A total of 21 events were recorded during the first year (i.e. November 2005-November 2006), 18 during the second year, while 32 floods occurred in the last year. Seasonally, 11% of the floods were recorded in autumn, 17% in winter, 44% in spring and 28% in summer. In eight occasions the ISTS recorded two or more flood peaks on the same day. The distribution of the floods during the study period shows that the hydrological regime of the Ribera Salada is characterised as a rain-snow fed regime with two maxima: one in spring-summer characterised by snow melt and convective localised storm-events; and the second in autumn attributed to rainfall from polar fronts.

In the following sections we describe the dynamics of rainfall, runoff and sediment transport during the study period based on the variables presented in table 1. These variables are correlated and the results of the different multivariate analyses are presented (sections 4.2 to 4.5). Finally, results were integrated to describe the general sediment transport patterns observed in the Ribera Salada in relation to rainfall and runoff (section 4.6).

4.1.1. Rainfall

We first provide a summary of the validation performed to the radar data set. Later, we describe the characteristics of the rainfall associated to each of the analysed flood events.

4.1.1.1. Data validation

Daily rainfall data obtained from the radar was validated with the direct data obtained in the Cambrils rainfall station (see figure 1). Radar data sets were provided with the fields already transformed to rainfall (after Velasco-Forero *et al.*, 2009; Coll 2010 and Coll *et al.* 2010). Therefore, this exercise is considered a validation for the particularities of the study reach and period. All daily rainfall events between March 2006 and November 2008 were used to calculate the RMSE considering the data registered in Cambrils as the observed rainfall, and the rainfall extracted from the radar as the predicted or modelled precipitation. Validation started in March 2006 because it was the period in which the Cambrils rainfall station was set up.

A total of 47 daily records were used. These records are related to different rainfall events observed in the catchment. The daily precipitation oscillates between almost 0 to 37.6 mm. The RMSE varies between 0.2 and 10 mm, with a mean value of 3.5 mm and a standard deviation of 2.7 mm. Figure 4 shows the relationship between the observed and estimated daily precipitation. These values are in the order of the ones observed by Coll (2010) for the whole Catalonia (across 32,114 km² and using multiple rain gauges distributed across different environments). This author reported a Mean Absolute Error (MAE) of 6 mm. The data set included several rainfall episodes registered between 2001 and 2005. In our case, the mean MAE for the 47 analysed events is 4.3 mm. The good agreement of the radar estimates allows the study of the spatial variability of rainfall events with an acceptable precision. As it has been introduced before, this provides the opportunity to identify localised rainfall cells that can be underestimated by spot or single rainfall measurements. As an example, on August 28th 2008, the ISTS registered a flood attributed to a localised summer storm that was not registered in any of the rainfall stations but that it could be observed in the radar data set.

4.1.1.2. Rainfall dynamics

Table 2 contains the rainfall variables of the analysed floods. Results show the high variability of rainfall across space and time in the catchment. Some of the differences between sub-catchments may be controlled by the size of them (Canalda has an area of 65.8 km², Fred 39.9 km² and Inglabaga 8.9 km²). Among the variables, rainfall intensity, however, is not controlled by catchment size. The largest $I_{max_{60}}$ (i.e. 30.8 mm h⁻¹, registered on the 15th May 2006) was calculated at the rain gauge of Lladurs, located in the Inglabaga sub-catchment (Figure 1). Rainfall intensity is calculated using data from the rain gauges instead of the radar data sets (see methods section). These observations point out the more marked Mediterranean character of the lower part of the catchment. Maximum intensities were registered between the end of spring and the end of summer. The rain gauge in Lladurs, despite collecting the highest rainfall intensity, has less annual rainfall when compared with Port del Comte rainfall station (Figure 1), located at the catchment headwaters (i.e. $P_{Lladurs} = 643$ mm, $P_{Port\ Comte} = 1066$ mm). Therefore, we

conclude that the Inglabaga sub-catchment is characterised by a more strong Mediterranean character than the upstream sub-catchments, which implies that the distribution of the annual precipitation is concentrated in a smaller period of time, characterised often by high rainfall intensities. Similar patterns were observed in other catchments. For instance, Gallart *et al.* (2002) reported that the monthly number of rainy days in the Vallcebre experimental catchment (4.2 km²) ranges from less than 5 to up to 10; clearly a small number when compared with more temperate environments where rainfall is present more often (e.g. Oeurng *et al.* 2010). These particularities control the production and transfer of sediments through the catchments and will, ultimately, affect the export of sediment (e.g. Mano *et al.*, 2009). In contrast, more temperate catchments have less variability, implying more regularity in these processes (e.g. Oeurng *et al.* 2010). In the following section we analyse the runoff and the sediment transport dynamics in relation to rainfall patterns.

4.1.2. Runoff

Runoff patterns between November 2005 and November 2008 are analysed by means of the data collected at ISTS (Figure 1). This station integrates the 3 sub-catchments for which rainfall was previously described. Table 2 summarises the values of the runoff variables calculated for each of the flood events. Total flood-based runoff (TR) varies between 250 m³ and 0.46 hm³, with an average of 0.05 hm³ ($\sigma=0.09$ hm³). Figure 5 shows monthly flood-based runoff. Two maximums are observed, one in May (i.e. TR= 0.13 hm³, $\sigma = 0.14$ hm³, N= 11), and the other between December (0.13 hm³, $\sigma = -$, N= 1) and January (0.10 hm³, $\sigma = 0.18$ hm³, N= 5; see Table 3). These months are also the months in which the largest runoff coefficients are obtained (Table 3). Runoff coefficients (RC) display a high inter-annual variability, with values oscillating between 0.1% and 37.5% (Table 2), with an average of 4.1% ($\sigma = 7.4\%$). May is the month with the higher RC (i.e. RC = 11.9%; $\sigma = 13.0\%$; Table 3). RC represents the proportion of rainfall that is converted into runoff, integrating all processes controlling the generation of flow across the entire catchment. RC is controlled by multiple factors, between them geology and soils, land uses and the precedent or initial conditions. Antecedent rainfall (rainfall registered the 7 days before the event; i.e. Pd7) is significant in spring. Largest monthly Pd7 values (for the whole cathment) are obtained in April and May (i.e. 26 and 34 mm respectively, Table 3). In this period water content in the soils also increases due to the snow melt. Therefore, although we do not have data to support this statement, results suggest that the content of water in the soils before the flood events in spring is generally higher than in the rest of the year, conditions that determine the high RC observed in this season. Mean values at around or lower than 5% are obtained in the rest of the year (Table 3). The RCs calculated in the Ribera Salada are considered low amongst different experimental catchments located in NE of the Iberian

Peninsula with a Mediterranean mountainous climate character. For instance, Latron *et al.* (2008) presented runoff coefficients between 4 and 39% in the Vallcebre experimental catchment (4.17 km²), López-Tarazón *et al.* (2010) found an average runoff coefficients of 6% in the Isábena catchment (445 km²), while Serrano-Muela *et al.* (2008) determined an annual runoff coefficients of 11 %, 25% and 69% for the catchments of San Salvador (0.92 km²), Arnás (2.86 km²) and Araguás (0.45 km²) respectively. All of these catchments have a percentage of forest cover between 60 and 100%. The differences between the runoff coefficients reported in the literature and the observed in the Ribera Salada is explained by the spatial coincidence between the zone of maximum rainfall (i.e. mean annual rainfall of 1000 mm) and the area of greater infiltration capacity of the catchment (i.e. the headwaters). The headwaters of the Ribera Salada are dominated by a fractured Eocene limestone substrate that occupies 34% of the study area. Verdú *et al.* (2000) concluded that the Canalda sub-catchment did not generate appreciable surface runoff due to the high porosity of the substrate. Poch *et al.* (2002) presented another study of the sub-catchment Canalda which found that there is a high interception of rainfall and high fissuration of the substrate that produces a meagre hydrological response.

Peak discharge varies between 0.34 and 9.3 m³ s⁻¹ (Figure 2A), with an average of 2.01 m³ s⁻¹ ($\sigma = 1.79$ m³ s⁻¹). Base flows (Q_0) oscillate between 0.10 and 3.67 m³ s⁻¹, with an average of 0.79 m³ s⁻¹ ($\sigma = 0.79$ m³ s⁻¹). The relationship between the magnitude of the peak discharge and the base flow (i.e. Q_p/Q_0) varies between 1.5 and 16.7, with an average of 3.3 ($\sigma = 3.1$). All values are greatly influenced by the seasonality of the year. Spring floods are characterized to provide the largest volume of water (TR) and also recorded the largest peaks (4.35 m³ s⁻¹, $\sigma=2.01$ m³ s⁻¹; Table 3). However, spring does not present the largest Q_p/Q_0 because in this season, as discussed above, the content of water in the soils is rather high and, consequently, has high and constant values of Q_0 . The maximum Q_p/Q_0 is obtained in summer when floods are characterised by having an initial low base flow (Table 2).

The duration of floods is variable through the year. Winter floods normally last for several days (see FDur in Table 2), being influenced by snow-melt processes at relatively low altitudes. Duration is reduced in the other seasons, reaching its minimum on summer where floods do not last more than 8 hours, being characterised by convective-localised thunderstorms. These patterns are also observed in other Mediterranean mountainous catchments such as Vallcebre (Gallart *et al.*, 2002).

4.1.3. Sediment Transport

Flood-based SSC_{mean} was 91 mg l⁻¹ ($\sigma = 0.12$ mg l⁻¹, Table 2, Figure 2B). Maximum SSC_{mean} was registered on 15th of August 2006 (i.e. 673 mg l⁻¹). The SSC_{max} varied between events; the

highest SSC_{max} attained almost 3 g l⁻¹, while a total of 5 floods reached concentrations exceeding 2 g l⁻¹. These values are relatively low when compared with catchments with similar size but with different land uses and geology. For instance, in the case of the Isábena catchment López-Tarazón *et al.* (2012) measured concentrations up to 1 g l⁻¹ during base flows and 300 g l⁻¹ during floods. That catchment is characterised by having an area of *badlands* on Eocene Marls that are the main source of sediments, although it occupies a very small part of the catchment; and controls the production, transfer and transport of fine sediment through the channel network. Therefore, in such environments, SSC shifts between hydraulically to supply-limited conditions in relation to the processes occurring in the main source of materials; and, consequently, the channel acts as source and sink of fine sediments in relation to the supply of sediments from the *badlands* (see López-Tarazón *et al.*, 2011 and Piqué *et al.*, 2014 for a full description of these cycles). These patterns have also been observed in other catchments with similar characteristics, as Vallcebre and Araguas (Gallart *et al.*, 2002; Nadal-Romero *et al.*, 2008b). Processes in forested catchments such as the Ribera Salada are rather different. Land uses in these catchments not only controls the generation of runoff but also the erodibility of the soil that, ultimately affects erosion, sediment production, transfer and transport. These catchments are characterised by relatively low SSCs with less seasonality. Local processes control sediment availability and most of the time the catchments show a supply-limited character (e.g. Douglas *et al.*, 1999; Bruijnzeel, 2004; Francke *et al.*, 2008). The lack of connectivity of the sediment sources and the difficulty in generating Hortonian flows explain the low sediment production in Ribera Salada. Only unusual high magnitude events are able to produce enough runoff to connect the system with the sources of sediment (hollows, first order stream, foothill deposits). These events may also generate large floods in the channel network that, in turn, may be able to entrain river bed sediments and increase sediment availability from local sources (e.g. bank erosion; subsurface fine material once the surface armour layer of the bed is entrained).

Total flood-based suspended sediment load (TL) transported during the study period (2005-2008) is around 780 tones. Sediment transport presents a high intra-annual variability (Figure 5; Table 3): 75% of the TL was transported between November 2007 and November 2008. Inter-annual variability is also notable, as it can be seen in the annual summaries in table 3. Single events are capable to transport up to the 24% of the TL during the whole study period. The flood event occurred on May 25th 2008 is an example of this; this flood transported 188 tons, 1/3 of the annual TL.

The specific sediment yield in the Ribera Salada is 2.2 t km⁻² y⁻¹. This value is very low when compared with other Mediterranean catchments. For instance, according to Vanmaercke (2012a)

the sediment yield of Mediterranean catchment with catchment areas between 10 and 100 km² vary between 0.9 and 3000 t km⁻² y⁻¹. Back to high dynamic Mediterranean catchments such the Isábena, López-Tarazón *et al.* (2012) reported an average sediment yield of 530 t km⁻² y⁻¹, while Mano *et al.* (2009) estimated an average yield of 383 and 381 t km⁻² y⁻¹ on the Asses and Bléone catchments in France (657 and 905 km², respectively). Our observations points out the low geomorphological activity of the Ribera Salada.

4.2. Relations between pre-event conditions, rainfall and runoff

In this section we first explore the correlation between pre-event conditions, rainfall and runoff variables by means of statistical coefficients. Later, we perform a multivariate analysis between these variables taking as dependent the ones related to runoff.

Table 4 shows the Pearson correlation matrix between pre-event conditions, rainfall and runoff variables. Here we only describe and discuss the main statistically significant correlations that we have found. Total flood duration (Fdur) shows the highest degree of correlation; this variable is positively correlated with rainfall duration (Pdur) and negatively with water temperature at ISTS, implying that the duration of the event increases with rainfall duration, and that floods tend to be longer in colder periods (winter).

In turn, rainfall duration (Pdur) is correlated with antecedent flood base flow (Qb). Antecedent rainfall conditions expressed as the rainfall during the seven days before the flood (i.e. Pd7), correlates with Qm and with RC. The strength of the correlations increases in the Fred sub-catchment (FR); a fact that indicates that the hydrological response in this sub-catchment have a greater impact on the hydrological response of the whole of the catchment. Correlation obtained for the Canalda sub-catchment (CA) is clearly influenced by the high porosity of its headwater soils and rocks, as discussed before. The Canalda sub-catchment has important fractures and karsification, facilitating water percolation to the Fred sub-catchment through a tilted syncline (Gil and Núñez, 2003). Interestingly, the peak discharge (Qp) is correlated with the antecedent rainfall at the three sub-catchments and also with the kinetic energy in the Fred sub-catchment. Finally, the intensity and the kinetic energy of the rainfall recorded in the three sub-catchments are statistically correlated with the Qp/Q₀.

A multivariate analysis between pre-event conditions, rainfall and runoff variables was also performed (Table 5). Only the variables that are statistically significant are presented. A total of 8 flood-based runoff variables were correlated with the 2 pre-event conditions variables and with a total of 8 rainfall variables. In this particular case, as explained in the methods section, the multivariate regression describes the independent contribution of each variable to the magnitude of the dependent variable. The major limitation of this regression technique is that it

can only determine the relationships but it does inform on the underlying causal mechanism. In the Ribera Salada, the coefficients of determination (R^2) of the multivariate regressions vary between 0.27 and 0.91. The average value for all equations is 0.65. This value is not extremely high but in the range found others mountainous Mediterranean catchments (e.g. Isábena catchment with an average of 0.52; López-Tarazón, 2010). The forms of the equations are presented in table 5. Here we only highlight some of the main results.

The multivariate regression with the highest coefficient of determination is the one associated to the mean flood-based discharge. The Q_m has a strong correlation with the base flow and the antecedent rainfall conditions at the Canalda and the Inglabaga sub-catchments. Although these three variables explain a great proportion of the variability of the Q_m , the β coefficients show that the base flow is the variable that has more weight in the resultant equation. The relevant role of Q_m is found in the majority of the obtained equations. The peak discharge (Q_p) is statistically correlated with 4 variables. The base flow still the one with the highest weight on the equation although rainfall intensity in the Inglabaga sub-catchment presents also a significant weight followed by the antecedent conditions in the Canalda and in the Fred sub-catchments. TR and Q_b define the total volume of superficial runoff and groundwater, respectively. Results show that, in both cases, the multivariate equations are capable to explain more than 60% of the variance of the dependent variable. The total runoff is again directly proportional to the initial state of the catchment, the duration of the rainfall event and the contribution from the Canalda sub-catchment (Table 5). These results, together with the previous analysis, show that the conditions of the river just at the beginning of the event (expressed by the base flow) determine the degree of hydrological susceptibility of the system. In summer, high intensity rainfall events determine the magnitude of the flows, while in winter and the beginning of spring the amount of rainfall is the variable that dominates the magnitude of Q_p .

The role of the base flow on the hydrological response of the Ribera Salada at ISTS is similar to the observed in previous studies by, for instance, Cosandey (1980, 1986). In these early studies, she found that the magnitude of the flood events in a humid temperate catchment was highly correlated to the base flow prior to the flood, being directly influenced by saturated areas. The influence of the base flow in the Ribera Salada decreases during winter and summer months when respectively low temperatures and high rainfall intensities reduce the normal high infiltration capacity of the catchment, as discussed above. Rainfall in the Canalda sub-catchment has a more prominent role in the volume of the floods (TR), while the intensity of the precipitation in the Fred sub-catchment has a direct influence on the magnitude of the peak discharges (Q_p).

4.3. Relations between rainfall and sediment transport

Selected rainfall variables were correlated with sediment transport variables. Table 6 shows the Pearson correlation matrix indicating the degree of significance of the correlations. The total sediment load (TL) at ISTS is highly correlated with the total rainfall (Pd) and the precipitation recorded during the first day of the event in the Fred and Canalda sub-catchments. SSCmax has a statistically significant correlation with $I_{\max_{60}}$ and EcI_{60} in the Inglabaga sub-catchment. These correlations indicate that this sub-catchment acts as an important source of sediments at the flood-scale, and that rainfall intensity and erosivity, and the precipitation of the first day of the event at the Inglabaga catchment determine the magnitude of the suspended sediment concentrations. Highest SSCmax are obtained during convective rainfall events with a high sedimentary response. SSCmean follows a similar pattern, being correlated with the precipitation of first day of the event in the Inglabaga sub-catchment, and with rainfall intensity and Kinetic energy in the Fred and Inglabaga sub-catchments. These results point out the role of the Inglabaga and Fred sub-catchments in acting as the main sediment source at ISTS. The proximity and characteristics of these two catchments (i.e. main land use is agriculture together with pasture and shrubs with a relatively high structural connectivity) play a key role in controlling sediment availability and the magnitude of the concentrations. However, in the Canalda sub-catchment, the higher infiltration capacity of the soils, together with the length of the channel network (i.e. distance to ISTS), reduces its role in supplying fine sediments at the flood-scale. This limitation is exacerbated in summer when convective storms with short durations do not have the capacity to transfer the sediments to the downstream end of the study site. However, the total load of a given flood (TL) is correlated with the amount of rainfall at the two largest sub-catchments Fred and Canalda, what explains the hydraulically driven character of the catchment with relatively low sediment production. In turn, the relatively small area of the Inglabaga sub-catchment might be the reason of the no significant correlation between rainfall on this catchment and the total load at ISTS (TL).

A multivariate analysis between rainfall and sediment transport variables has been performed. Results are presented in table 7. Only the variables that are statistically significant are presented. The coefficients of determination of the regression equations vary between 0.30 and 0.51. The variable that presents the highest coefficient of determination is SSCmean. This variable is controlled by three rainfall variables, having the three of them ca. the same weight on the general equation (i.e. similar β coefficients). In this equation, the negative sign of the β coefficient for the rainfall registered during the first day of the event at the Canalda catchment (Pd1-CA) indicates, again, the low sedimentary activity in this catchment. This variable was not correlated on the Pearson analysis presented in table 6; however, when all variables are analysed

together this has a significant weight on the resulting multivariate analysis. As discussed above, the Pearson correlation matrix indicated that Canalda supplies the water required to transport the majority of the sediment that is supplied from the Fred and Inglabaga sub-catchments. These two catchments, in turn, control the magnitude of SSC_{max}. The negative influence of Pd1 in Canalda to the SSC_{mean} indicates that, while the Inglabaga and Fred sub-catchments control the amount of sediment supplied to the channel network, the observed precipitation during the first day of the event in Canalda exerts an important the dilution effect, contributing to a reduction of the magnitude of SSC_{mean} at ISTS.

4.4. Relations between runoff and sediment transport

Table 8 shows the Pearson correlation matrix between runoff and sediment transport variables. Flood-based total sediment load (TL) is statistically correlated with five of the variables. The highest correlation is given by the peak flow, a fact that indicates the hydraulic influence on the total suspended sediment load. Maximum SSC is driven mainly by flood intensity, expressed by the peak discharge, by the proportion of the peak in relation to the base flow and by flashiness (i.e. the speediness of the flow raising the peak of hydrograph). Similar results were observed for the mean SSC although in this case the peak discharge and the proportion of the peak in relation to the base flow have higher correlation values.

The multivariate analysis for the three sediment transport variables provides determination coefficients between 0.53 and 0.84. The results of the β coefficients and the final form of the equations are shown in table 9. In general, these results evidence that runoff variables are, in general, better correlated with sedimentary dynamics. The total suspended sediment load (TL) is mainly correlated (i.e. largest β coefficients) with total runoff (TR) and, to a lesser extent, with flood peak (Q_p) and the total volume of base flow during the flood (Q_b). Additionally, the multivariate model is also influenced, following in this case a negative relation, by F_{dur}, Q_m and RC. The negative sign of these coefficients may indicate both that the catchment is generally supply limited and that an increase of the total runoff does not necessarily generate a proportional increase of the sediment load. This situation is more common in winter where RC and F_{dur} are greater, and also during the spring where the sequence of rainfall episodes causes an exhaustion of the available sediments. The multivariate equation for SSC_{max} is determined by peak and mean discharges, and the total volume of base flow during the flood, indicating, again, that the magnitude of SSCs is hydraulically driven. Flood intensity increases SSCs magnitude, while high water yield dilutes sediment concentration.

4.5. Relations between pre-event conditions, rainfall, runoff and sediment transport

In this section we present the multivariate analysis between pre-event conditions, rainfall, runoff and sediment transport variables. Pre-event conditions, runoff and sediment transport variables correspond to the ones registered at ISTS, whereas rainfall variables are derived from spatially distributed data (i.e. radar rasters) obtained at multiple spatial and temporal scales, and from local data based on the measurements taken at the rainfall monitoring stations (see Figure 1 and Table 1). Therefore, the objective is to derive multivariate equations that statistically predict the sedimentary response of the system in terms of TL, SSC_{max} and SSC_{mean}. In order to test the predictive power of the resultant equations, a total of 9 floods (17% of the total) were excluded from the analysis and used as a validation data set. These nine floods were randomly selected i.e. three floods per study year form the validation data set.

Multivariate results are presented in Table 10. The coefficient of determination of the three equations ranges between 0.54 and 0.94. Statistically, TL is the variable that can be better predicted by the multivariate equation. A total of 5 variables (4 related to runoff and 1 related to rainfall) form the equation. Again, as explained above, the amount of water in the system, expressed by the base flow, the runoff coefficient and the duration of the rainfall have a negative influence on the TL. This is related to the supply limited character of the catchment. More water implies dilution and a proportional decrease of the TL during a given flood. The volume of runoff is the variable presenting more weight in the equation. Mean monthly TL is presented in Figure 5. The figure shows 3 maxima; the first and most important is obtained in May (although high values are observed between the whole April-June period); the second one in August and, finally, the third in October. April, May and June are characterized by a high volume of direct runoff that causes erosion through concentrated runoff and, ultimately, sediment availability. RC increases as water availability does and has an inverse effect on the total load registered at ISTS. This process is controlled by changes on sediment availability and exhaustion. On August, floods have little runoff, with low base flows and RC. These floods are caused by convective rainfall storms i.e. short and highly intense episodes. The flashiness during these storms is important and peak flows have are of high magnitude. The location of the maximum kinetic energy of the rainfall is concentrated in the valley bottom and shows an altitudinal negative gradient (i.e. the energy is reduced as altitude is gained). Therefore, rain erosivity, and thus the potential for sediment production, is basically concentrated in the low parts of the catchment. Some of the sediment eroded from upstream does not reach the outlet of the catchment due to the short duration of summer floods. These materials are deposited in the channel network and will be mobilised in subsequent flood events. Therefore, sediment availability will be determined by the location of rainfall events and their intensity and duration. Only three floods were observed in October during the study period. Although this small number of observations, results pointed out that TL in this period could be highly controlled by

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705 local sources of sediments attributed to summer processes. Between December and January a
706 significant runoff contribution in each flood (TR) is observed. However, the small magnitude of
707 the peak flows and the long duration of the rainfall decrease the TL registered at ISTS. As
708 discussed above, the high number of freezing days frost and the lack of high rainfall intensities
709 during this period control the erodibility of the soils and the erosivity of the rainfall, ultimately
710 decreasing the TL.

711 The multivariate equation for the SSCmax explains 54% of the variance. Peak flow (Q_p) is the
712 most important factor controlling SSCmax. In contrast, the mean flood discharge (Q_m) and the
713 kinetic energy in the Canalda sub-catchment implies a reduction of the magnitude of SSCmax.
714 Although we do not have a clear evidence on the reasons of the inverse relation between the
715 kinetic energy at Canalda and SSCmax at ISTS, we hypothesize that this is attributed to the fact
716 that the high energy in the Canalda sub-catchment implies that rainfall is concentrated in the
717 headwaters of the catchment rather than in the lowermost reaches, areas that are considered the
718 main source of sediments. Consequently, as discussed above, the sediment production in
719 Canalda during these events is rather low and affects inversely the SSCmax. Finally, the
720 multivariate analysis for the mean suspended sediment concentration (SSCmean) explains 74%
721 of the variance, where the peak discharge (Q_p) and the total volume of precipitation of the event
722 (P_d) have a positive weight in the equation. The sign and weight of the rest of the variables
723 reinforce the dilution effect that has been presented and discussed in the previous sections.

724 The predictive power of the equations presented in table 10 is assessed by means of the
725 observations obtained for the nine floods that were not included in the multivariate analysis (3
726 per each hydrological year). Table 11 presents the observed (i.e. Obs) and estimated (i.e. Est)
727 values per each of these floods. Additionally, the upper and lower 95% confidence bounds
728 (statistical intervals) have been calculated. The residual (i.e. Res.) of each variable ($Obs - Est$) is
729 calculated and compared with the confidence interval. The percentage of error (% error) per
730 each variable and flood is calculated based on the observed and residual values (i.e. Res/Obs
731 expressed in %). Residuals are highly variable (Figure 6). Two general patterns can be
732 observed. These are common for the three multivariate equations: (a) the predictive power of
733 the equations is higher for low magnitude values, and (b) larger residuals are always attributed
734 to overestimation. This exercise is limited to the number of floods used as observed values. It is
735 worth to mention that we are not aiming at developing a general model for the Ribera Salada
736 catchment. Here we only critically analyse the predictive power of the models. As it has been
737 discussed in the previous sections, the intra-annual variability of the sedimentary dynamics is
738 rather high and it is controlled by processes that operate at multiple temporal and spatial scales.
739 Therefore, results could differ substantially if a larger data set of observed values was available

but, in any case, results point out that small magnitude sediment transport dynamics could be predicted with more reasonable accuracy, while large magnitude events are still uncertain since the multiple process that interact to produce them.

4.6. Intra-annual sediment transport patterns

As it has been discussed, the dynamics of the total sediment load (TL) are clearly connected to the hydrological patterns observed in the catchment. In this section we summarize the main sediment transport patterns observed in the Ribera Salada. A total of three distinct periods can be identified: a) winter, b) spring, and c) summer-early autumn (see figure 5). These patterns are in agreement, for instance, with the ones observed by Balasch *et al.* (2005). The relationship between the flood-based total sediment transport load and total runoff per each of these periods is presented in figure 7. Following we describe and analyse the main characteristics of these periods.

a) Winter period (November to February). This is characterised as a cold period in which sedimentary dynamics are rather low or marginal. Mean flood-based SSC_{mean} for this period is 18 mg l⁻¹. A total of ca. 30 tonnes were transported such months (i.e. 3.8% of the total load during the three study years). Total flood based runoff in winter is 0.94 hm³, representing the 28.2% of the total flood based runoff for the whole period. Figure 7a shows the relationship between flood-based runoff and sediment load for the floods registered in this period. A statistical significant correlation is found between both variables. Rainfall intensities are low although events can be large and associated to snowmelt processes. Temperatures are most of the time below freezing and control some properties of the soils that in turn may affect the generation of runoff and the erodibility of the soil (e.g. Ollesch *et al.*, 2005). A close eye to the sediment transport variability through the floods shows that the hysteresis loops in these events are (according to the early classification by Williams, 1989) clockwise (25%), counter-clockwise (19%), linear (19%), 8-figure (6.3%) and undefined (31%). These patterns indicate an erratic response of the catchment with always very low magnitude processes.

b) Spring period (March to June). This is the period that contributes most to the annual runoff and sediment load. We consider this as the most active hydro-sedimentary period. Suspended sediment concentrations observed during events have an intermediate magnitude (i.e. mean flood based SSC_{mean} = 96 mg l⁻¹). The total runoff and sediment transport is around 2.2 hm³ and 572 tonnes respectively, representing the 65.3% and 72.6% of the total transported for the whole period (2005-2008). TL is controlled by the relatively high TR. The Canalda sub-catchment acts as the main source of water (but low sediment), reducing mean SSCs but having a relevant contribution to the total runoff observed in ISTS, as discussed previously. Two

different patterns can be seen in figure 7b. The steeper pattern corresponds to the one dominated by relatively high magnitude events that, according to previous studies (Vericat et al., 2008; Batalla et al., 2010; Vericat and Batalla, 2010), were potentially capable to break-up the surface armour layer of the riverbed thus increasing the availability of fine materials (from the subsurface layer), or generate localised channel erosion. The gentle relationship is represented by the rest of floods recorded during the study period. In general, figure 5 shows that the total sediment load during this period is the highest of all the periods while the range for the TR is considered intermediate. The hysteresis loops observed are mostly counter-clockwise (63%). At the same time, there are also clockwise (27%) hysteresis loops and linear (10%) relationships. Dominant counter-clockwise patterns in this period indicate that sediment sources are relatively far from the outlet, and maximum SSCs are registered after peak flows.

c) Summer-early autumn (July to October). This period shows the largest SSCs although the overall hydrological contribution is rather low. Mean suspended sediment concentrations observed in flood events is 89 mg l⁻¹. A total of 186 tonnes were transported, a value that represents almost ¼ of the total load for the whole study period. The total runoff in this period is around 0.22 hm³ (6.5% of the total), a fact that indicates a modest contribution to TL when compared for instance with spring. However, flood hydrographs are characterised by a rapid increase (i.e. average $Q_p/Q_0 = 4.8$ and an average $FI = 1.32 \text{ m}^3 \text{ s}^{-1} \text{ h}^{-1}$). This phenomenon can be the main cause of the high instantaneous SSCs observed in this period. Figure 7c shows the relationship between flood-based runoff and sediment load. A statistical significant correlation is found between both variables. As it can be seen, figure 7c shows that the range of runoff values is the lowest of all the periods, a fact that suggests a low hydrological activity but a relatively high sedimentary process during this particular time of the year. The dynamics at the flood scale indicate that the majority of the floods have counter-clockwise hysteresis loops (56%), but there are also clockwise (22%), 8-figure (13%) and linear (9%) relationships.

5. SUMMARY AND CONCLUSIONS

In this paper we have presented the relations between rainfall, runoff and sediment transport in a Mediterranean mountainous catchment during three consecutive years. A series of statistical correlations and multivariate analyses between variables have been performed to characterise the hydrosedimentary dynamics in this mesoscale catchment of the Southern Pyrenees. In addition, the use of radar data has been proven to be a useful tool to characterise the spatial distribution of rainfall across multiple spatial scales. These data sets are of special interest in

relatively large catchments where rainfall is typically highly variable in space and time. The main findings of the study are:

1. The Ribera Salada can be divided in two main zones according to the rainfall distribution: (a) the subalpine climate zone (i.e. the top of the basin; headwaters) where the largest values of total rainfall are registered (i.e. > 1000 mm), and (b) the Mediterranean zone (i.e. lowermost reach of the catchment) where the highest rainfall intensities are observed. The hydrological regime of the catchment has a seasonal pattern, with two maxima, one in spring and another, of lesser magnitude, in autumn. Runoff coefficients are overall rather low, reflecting the high interception of the land cover and the high fissuration of the substrate and, consequently, the difficulty to exceed the soil infiltration capacity. Flood-based maximum suspended sediment concentrations were higher than 2 g l^{-1} in six of the analysed floods, reaching a maximum value of around 3 g l^{-1} . The total suspended sediment load was 780 tons (2005-2008), which represents $2.3 \text{ t km}^{-1} \text{ y}^{-1}$, pointing out the low intensity of the geomorphic processes in the catchment. The majority of the load is transported mainly during spring and summer.

2. Most of the runoff variables in the Ribera Salada are highly correlated to the base flow prior to the event. The influence of the base flow decreases during winter and summer months, when the respective low temperatures and high rainfall intensities reduce the high infiltration capacity of the basin. Rainfall in the Canalda sub-catchment is the dominant process that controls the runoff volume of the floods, while in the case of the Fred sub-catchment the rainfall intensity has a direct influence on the magnitude of the peak discharges.

3. Maximum suspended sediment concentrations are positively correlated with the magnitude of the floods. Short but intense rainfall events prompt high suspended sediment concentrations. Contrarily, flood-based total sediment load is strongly correlated with the total direct runoff and, to a lesser extent, with the peak discharge of the event.

4. The multivariate analysis shows that total suspended sediment load is the variable that can be better predicted by a multivariate equation integrating rainfall and runoff variables. A total of 5 variables form the sediment transport equation: (i) base flow, (ii) duration of the rainfall, (iii) total surface runoff, (iv) peak flow and (v) the runoff coefficient. The volume of surface runoff is the variable supplying more weight to the equation. Seasonal relations between total surface runoff and total sediment transport reveals that the magnitude of sedimentary processes presents a clear seasonality that is, in turn, influenced by rainfall intensity and sediment availability.

5. Three intra-annual sediment transport patterns have been found, with each having distinct influence on the total sediment load and water yield. The first period that last from November to February carries less than 4% of the annual sediment load although yields more than ¼ of the total runoff. This period is characterised by low rainfall intensities, low temperatures and a clear reduction of sediment availability. The second period is from March to June and represents almost ¾ of the total sediment load and 2/3 of the water yield. Floods in this period are characterised by having highly variable sediment loads and a moderate runoff volume. Finally, the third period moves encompasses months from July to October, representing around ¼ of the total sediment load but only yielding 6.5% of the total annual runoff. Flood events in this period are characterised by sharp and rapid hydrographs, transporting little runoff but generating high suspended sediment concentrations.

This paper corroborates that the relationships between rainfall, runoff and sediment transport are highly in Mediterranean mountainous catchments. This variability is primarily controlled by the general physical characteristics of the basin, but the antecedent conditions and the intensity and distribution of the rainfall shape the final hydrosedimentary response in the river. Land use and climate change may have thus an important role in modifying the cycles of water and sediment yields in this type of highly contrasted environments that will, ultimately, alter the transfer of water and sediments downstream thus the functioning of the overall fluvial ecosystem.

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Figure Captions

Figure 1. (A) Location of the Ribera Salada catchment in the Ebro basin (NE Iberian Peninsula). (B) The Ribera Salada sub-catchments showing the location of the Inglabaga Sediment Transport Station (ISTS), the Canalda Hydrometric Station (HS), the Port del Comte and Lladurs Meteorological Station (MS), and the Cambrils Rainfall Station (R). A total of 3 main sub-catchments have considered in this study: the Canalda sub-catchment, the River Fred sub-catchment and the Inglabaga sub-catchment.

Figure 2. (A) Hydrograph and (B) sedigraph recorded at ISTS during the study period. A summary table is included where Q_{mean} indicates the mean flow discharge for the all study period (November 2005 to November 2008), Q_i shows characteristic percentiles of the flow discharge, where i is the given percentile; SSC_{mean} indicates the mean suspended sediment concentration, and SSC_i shows characteristic i percentiles of the suspended sediment load.

Figure 3. Rainfall map of the Ribera Salada for the event of 12th August 2007. Total daily rainfall in the rain gauges is indicated together with the estimates from the radar data.

Figure. 4. Observed and estimated daily rainfall ($N=47$). Observed values were obtained at the Cambrils rainfall station while the predicted values were estimated from radar data (see methods from more details).

Figure 5. Mean monthly Total Load (TL) and Total Runoff (TR) at ISTS for the whole study period (2005-2008).

Figure 6. Observed and predicted sediment transport values from the multivariate equations presented in table 10: (A) total loads (TL), (B) maximum suspended sediment concentrations (SSC_{max}), and (C) mean suspended sediment concentrations (SSC_{mean}).

Figure 7. Flood-based relationship between Total runoff (TR) and Total suspended sediment load (TL) for the whole study period (2005-2008) segmented by: (A) winter, B) spring and C) summer-early autumn. Note that two different patterns are observed in spring in relation to sediment availability (see text for more discussion). Note the differences in the magnitude of the axes between figures.

Table 1. Selected pre-event conditions, rainfall, runoff and sediment transport variables. These variables were used for the Correlation and Multivariate Regression Analyses (see methods for more details).

Type of variable	Abbreviation	Description	Unit
Pre-event conditions	T°_ISTS	Water temperature at the ISTS	°C
	Q ₀	Base flow at the beginning of the flood event	m ³ s ⁻¹
Rainfall	Pdur	Duration of the rainfall event	hour
	Pd	Total precipitation	mm
	Pd1	Precipitation during the first day of the event	mm
	Pd7	Antecedent precipitation during the 7 days before the event	mm
	I _{max60}	Maximum 60 minute rainfall intensity	mm/h
	EcI ₆₀	Kinetic energy of the I _{max60}	MJ mm ha ⁻¹ h ⁻¹
Runoff	Fdur	Flood duration	hour
	TR	Volume of surface runoff	hm ³
	Qp	Peak discharge	m ³ s ⁻¹
	Qm	Mean discharge	m ³ s ⁻¹
	Qb	Base flow water volume	m ³ s ⁻¹
	RC	Runoff coefficient	%
	Qp/Q ₀	Quotient between Qp and Q ₀	-
	FI	Flashiness index for the first peak flood	m ³ s ⁻¹ h ⁻¹
Sediment Transport	SSC _{mean}	Mean suspended sediment concentration	g l ⁻¹
	SSC _{max}	Maximum suspended sediment concentration	g l ⁻¹
	TL	Total suspended sediment load	t

Table 2. Flood-based pre-event, rainfall, runoff and sediment transport variables. Note: that CA indicates Canalda sub-catchment; FR Fred sub-catchment, and IN Inglabaga sub-catchment. See table 1 for the description of the variables and table 3 for mean monthly and annual values.

Flood Date	T°-ISTS	Q ₀	Pdur	Pd	Pd1-CA	Pd1-IN	Pd1-RF	Pd7-CA	Pd7-IN	Pd7-RF	Imax ₆₀ -CA	Imax ₆₀ -IN	Imax ₆₀ -RF	EcI ₆₀ -CA	EcI ₆₀ -IN	EcI ₆₀ -RF	Fdur	TR	Qp	Qm	Qb	RC	Qp/Q ₀	FI	SSCmean	SSCmax	TL
09/11/2005	8.9	0.42	3	12.7	13.2	14.6	11.5	0.5	0.5	0.6	5.4	10.2	-	5.8	21.8	-	17.3	0.01	1.17	0.61	0.03	0.67	2.8	0.227	0.006	0.008	0.22
12/11/2005	8.8	0.45	78	19.2	6	13.6	10.4	25.9	27.6	25.7	3.4	1.4	-	11.9	2.7	-	129.6	0.142	1.43	0.82	0.24	16.04	3.2	0.018	0.006	0.01	2.3
02/12/2005	6.4	0.24	31	20.2	22	19.5	17.3	0.9	0.2	0.5	6.4	2.6	-	80.5	6.5	-	126.7	0.13	1.11	0.56	0.13	5.51	4.6	0.065	0.013	0.044	3.65
29/01/2006	3.4	0.1	13	8.2	8.8	17	5.2	2.1	4.1	0.4	6.1	4	-	7.2	5.1	-	19.4	0.066	1.36	1.06	0.01	6.71	13	0.252	0.109	0.375	8.71
30/01/2006	4.8	0.91	56	16.2	11.6	18.7	14.4	10.7	21	5.5	1.1	4	-	0.7	9.4	-	197.3	0.426	1.6	0.91	0.22	28.88	1.8	0.065	0.008	0.06	6.52
20/03/2006	8.5	0.43	8	5.9	4.6	6.4	8	3.2	4.6	5.4	5.6	2	6.6	8.2	0.7	10.8	9.5	0.007	0.94	0.63	0.01	1.04	2.2	0.306	0.014	0.052	0.32
22/03/2006	7.8	0.66	4	2.7	3.5	1.9	1.5	8.5	11.1	17.4	5	1.4	1.8	6.6	0.6	0.6	17.3	0.01	1.06	0.67	0.03	3.08	1.6	0.436	0.01	0.03	0.45
06/04/2006	9.7	0.65	8	22.8	21.3	21.3	25.8	2.4	0.7	0.2	8.4	14.7	4.4	13.7	66.5	4.6	4.7	0.005	1.81	0.93	0.01	0.19	2.8	1.001	0.15	0.353	2.93
07/04/2006	9	0.68	6	10.6	12.4	12.4	7.3	23.2	22	26	1.2	8	2.8	0.2	20.6	1.5	10.3	0.008	2.29	0.89	0.03	0.6	3.4	0.605	0.156	0.785	6.65
16/06/2006	14	0.24	4	7.1	2.8	1.9	7.3	0.7	0.8	0.4	3.1	2.2	9	1.2	0.5	13.2	1.2	0	0.35	0.3	0	0.06	1.5	0.212	0.233	1.068	0.003
16/06/2006	14	0.31	4	10.4	14.2	12.4	11	3.5	2.6	7.8	17.7	15.9	5.2	89.8	49.6	4.5	4.4	0.003	1.37	0.51	0	0.23	4.4	4.230	0.17	0.538	1.65
11/07/2006	19.9	0.18	2	15.5	19.9	12.7	8.8	4.4	0.7	1	30	21.9	0	277.9	107.6	0	12.3	0.008	2.93	0.41	0.01	0.42	16.2	2.063	0.038	0.316	1.63
14/07/2006	17.9	0.26	5	12.2	11.9	8.1	13.6	27.5	13.8	10.6	4.3	5.2	17.8	3.8	5	107.5	10.9	0.004	0.69	0.37	0.01	0.26	2.6	0.176	0.014	0.097	0.24
15/07/2006	18.2	0.27	6	25.4	23.1	30.6	28	38.8	21.5	24.2	3	28.5	2.6	2.5	226.2	1.2	12.6	0.004	0.75	0.38	0.01	0.15	2.8	0.479	0.119	1.602	3.14
16/07/2006	18	0.29	5	4.4	4.9	3.9	3.5	61.8	51.9	52.1	4.1	2.4	9.6	2.6	0.9	15.3	7.3	0.011	2.83	0.79	0.01	2.09	9.9	30.550	0.213	1.283	8.47
15/08/2006	15.9	0.21	4	2.9	13.8	17.5	14.4	0.5	2.4	1.6	4.6	20.5	0.2	9.4	100.5	0.1	2.8	0.002	0.75	0.43	0	0.12	3.5	0.310	0.018	0.064	0.1
15/08/2006	15.9	0.52	5	26.4	13.5	4.7	12.4	14.3	20	16	16.8	5	5.8	82.9	4.1	6.4	5.1	0.005	0.9	0.53	0.01	0.32	1.7	0.223	0.021	0.053	0.22
15/08/2006	15.9	0.35	3	23	18.7	23	37.3	27.9	24.6	28.4	11.6	30.8	20.4	28.8	242	92.5	13.5	0.032	5.85	1.08	0.02	1.19	16.7	2.128	0.673	2.8	62.58
13/09/2006	17.2	0.19	6	21	22.8	26.1	16.8	14.1	18.5	18.4	8	9.3	6.2	27.6	26.7	14.7	13.5	0.006	0.71	0.33	0.01	0.23	3.8	0.144	0.028	0.182	0.6
14/09/2006	15.5	0.28	8	15.8	13.5	19.4	18.8	36.4	44.6	35.1	4.1	4.6	3.4	7.2	5.3	3.5	11.7	0.003	0.57	0.38	0.01	0.16	2.1	0.065	0.012	0.032	0.21
23/09/2006	14.7	0.25	9	20.6	24	18.9	15.4	2.2	1	2.8	5.8	4.8	3.4	23.7	9.2	4.7	35.4	0.01	0.59	0.37	0.04	0.41	2.4	0.050	0.011	0.024	0.52
11/10/2006	14.6	0.24	6	19.3	22.8	12.9	15	2	2.6	5.8	7.7	13.3	6.6	15.4	42.2	10.7	14.4	0.005	0.75	0.35	0.01	0.23	3.1	0.760	0.229	2.827	5.74
16/11/2006	10	0.22	31	16.8	16.6	11.9	14.7	0.3	0.1	0.2	0.5	0.2	0.4	0.1	0	0	122.4	0.04	0.45	0.37	0.12	2.2	2.1	0.011	0.011	0.018	1.78
22/01/2007	7.1	0.19	12	13.5	14.3	13.3	11.4	0.4	0.5	0.4	5.7	4.8	2.8	13.7	8	3.3	42.1	0.013	0.43	0.27	0.03	0.82	2.3	0.065	0.015	0.026	0.66
12/02/2007	8.1	0.18	4	5.4	6.9	2.5	3.6	9.6	6.9	5.2	9.5	3.2	2.2	22	1.4	0.6	94.5	0.024	0.34	0.27	0.07	3.71	1.9	0.004	0.011	0.015	1.05
25/02/2007	7.8	0.21	3	3.4	3.4	2.8	3.6	2	2	0.5	3.7	2.8	2.2	2.9	1	0.8	20.3	0.002	0.37	0.25	0.02	0.62	1.8	0.029	0.011	0.013	0.2
07/03/2007	7.1	0.23	8	9.4	10.2	10.9	7.9	0.3	0	0	7.6	5	2.8	14.7	6.1	1.3	24.8	0.004	0.58	0.3	0.02	0.4	2.5	0.040	0.011	0.011	0.29
01/04/2007	8.7	0.34	17	8.1	10.1	10.8	4.2	23.7	19.7	16.6	4.2	3	1.4	9.9	3	1	27.8	0.022	0.81	0.61	0.04	2.23	2.4	0.068	0.051	0.354	3.57
02/04/2007	8.7	0.59	8	10.8	9.7	18.7	10.8	33.7	30.5	20.8	2.2	4.6	3.4	1.7	9.6	4.2	3.9	0.007	1.3	0.95	0.01	0.61	2.2	0.328	0.124	0.322	1.98

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02/04/2007	9	0.9	19	11.4	9	21.5	13.2	59.4	46.2	25.4	2.6	5.8	2	2.2	14	2.3	87.9	0.175	2.07	1.12	0.18	13.77	2.3	0.227	0.058	0.667	27.18
06/04/2007	9.2	0.88	3	3.7	3.2	5	4.2	79.9	94.5	65	0.3	2	2.8	0	0.9	2.4	41.6	0.03	1.38	0.95	0.11	7.35	1.6	0.058	0.014	0.036	2.07
20/04/2007	11.2	0.85	6	0.9	1.1	2.7	0.2	13.8	20	17	2.6	2.6	4.4	1.2	0.7	2.7	13.5	0.005	1.23	0.96	0.04	4.29	1.5	0.184	0.027	0.056	1.32
21/04/2007	11.1	0.92	4	10.8	12.1	12.9	8.2	12.8	17.2	11.8	1.2	11.3	8.2	0.2	33.5	10.9	9.6	0.012	2.48	1.31	0.03	0.91	2.7	2.084	0.093	0.456	5.48
01/05/2007	10.3	0.78	16	19.6	21.1	18.9	17.2	9.2	9.6	6.8	3.5	7	5.4	5	16.4	9.7	4.2	0.008	1.77	1.32	0.01	0.34	2.3	0.475	0.064	0.126	1.48
01/05/2007	10.3	1.36	19	12.2	13.6	12.6	9.9	30.3	28.5	23.9	3.6	3.2	2.4	3.4	4	1.9	38.6	0.091	2.27	1.7	0.14	6.33	1.7	0.576	0.05	0.334	12.95
04/06/2007	13.5	0.6	5	16.2	19.4	16	11	1	1	0.6	16	15.3	5.8	72.6	55.7	9.9	22.9	0.015	1.9	0.85	0.06	0.76	3.2	0.202	0.042	0.158	3.48
05/06/2007	13.2	0.83	4	15.6	15.4	18.7	15.1	20.4	17	11.7	0.8	19.7	4.2	0.1	95.8	2.7	8.5	0.006	1.39	0.99	0.02	0.31	1.7	0.554	0.12	1.088	4.22
12/08/2007	16.9	0.6	3	12.6	10.8	18.7	14.3	17.2	4.2	15.4	4.1	9.7	7.4	3.4	27.1	8	3.2	0.012	2.73	1.62	0.01	0.84	4.6	1.404	0.185	0.457	4.55
12/08/2007	16.9	1.45	4	16.6	13.5	9.3	23.3	28	22.9	29.7	7.1	5.2	17.2	15.3	5.8	28.4	16.2	0.048	2.26	1.11	0.02	2.7	1.6	0.976	0.063	0.278	5.27
08/10/2007	14.7	0.29	4	4	6.9	0	0	26.5	15.2	18.8	14.4	0.4	0.4	44.7	0	0	18.3	0.018	2.32	0.59	0.02	3.49	7.9	8.125	0.341	3.000	27.51
10/10/2007	12.8	0.29	4	9.7	10.8	5.5	8.8	33.9	15.3	18.8	6.7	4.6	6	10.4	4.3	7.7	9.6	0.003	0.58	0.38	0.01	0.24	2	0.094	0.017	0.028	0.24
20/11/2007	5.5	0.17	28	26.2	28.4	17.4	17.4	0.1	0	0	8.2	2.4	1.6	74.1	3.3	1.5	132.8	0.044	0.47	0.31	0.1	1.56	2.8	0.014	0.014	0.02	2.11
03/01/2008	3.8	0.16	9	8.8	8.3	11.5	9.1	0.1	0	0	3.2	3.6	1	3.6	3.8	0.3	38.8	0.007	0.35	0.22	0.02	0.71	2.2	0.018	0.016	0.022	0.5
11/01/2008	7.9	0.23	7	8.3	8.7	8.1	7.6	1.2	0.9	0.5	6	3.2	1.8	9.8	2.6	0.8	16.3	0.002	0.41	0.27	0.01	0.26	1.8	0.050	0.018	0.038	0.29
03/02/2008	4.9	0.2	10	10.5	6.4	7	6.2	1.6	0.4	0.6	4.3	3.8	2.4	12.9	4.4	2.1	37.3	0.01	0.44	0.28	0.03	1.38	2.2	0.058	0.021	0.029	0.81
30/03/2008	9.3	0.36	5	10.2	10.4	9.3	10	4.7	1.9	2.5	5.5	4.2	8	9.8	4.1	11.8	24.6	0.004	0.59	0.43	0.03	0.33	1.6	0.011	0.013	0.029	0.49
09/04/2008	10.7	0.48	10	14.3	15.6	14.4	12.1	9.1	8.2	7.7	10.7	0	6	53.9	0	12.6	4	0.003	0.85	0.66	0.01	0.15	1.8	0.158	0.049	0.128	0.54
10/04/2008	10.7	0.89	6	13.9	14.9	21.3	10.8	24.7	22.6	19.8	9.1	18.9	5	22.1	77.2	3.8	11.1	0.023	1.99	1.19	0.02	1.41	2.2	1.015	0.113	0.571	6.38
18/04/2008	8.9	0.65	19	18.4	20.6	18.4	14.8	17.9	15.6	17.1	6.5	8.6	3.2	45.5	20.3	4	28.3	0.036	2.01	1.22	0.09	1.67	3.1	0.072	0.051	0.353	7.58
20/04/2008	9.5	0.96	18	37	41.3	42.7	28.5	37.2	30.9	30.9	5.6	9.3	5.8	32.2	50	16.1	54	0.225	5.42	2.3	0.22	5.15	5.7	0.306	0.121	0.915	93.71
10/05/2008	10.9	1.45	20	14.5	11.8	23.9	16.8	17.5	22.1	19.7	0	3.8	2.2	0	6.4	1.8	33.3	0.112	2.74	2.04	0.13	6.93	1.9	0.216	0.034	0.077	8.65
12/05/2008	10.9	1.59	8	7.7	8.7	17.7	3.8	29.8	47.4	36.7	4.2	4.8	4	5.1	10.1	3.3	26.4	0.085	2.71	2.12	0.12	9.05	1.7	0.425	0.023	0.058	4.85
14/05/2008	11.4	1.68	4	9.5	7.9	11.7	11.7	38.5	65	40.4	5.5	7	3	6.3	10.9	2.1	2.7	0.017	5.8	3.08	0.01	1.64	3.5	2.603	0.318	1.255	14.76
14/05/2008	11.4	3.67	7	7.5	7.1	3.7	8.9	46.4	76.7	52.1	8.1	2.6	3.4	18.8	1	2.9	49.3	0.307	5.63	3.14	0.25	36.69	1.5	1.303	0.059	0.439	43.05
16/05/2008	11.5	2.08	3	6	6.8	6.9	4.6	59.6	82.4	56	5.7	2.4	3	6.9	1	1.4	2.8	0.011	3.02	2.56	0.02	1.57	1.5	0.868	0.06	0.387	1.7
17/05/2008	11.6	2.43	2	0.6	0.9	0	0.2	49.2	67.5	41.4	3.1	0	0.8	1.5	0	0.1	1	0.007	3.77	3.26	0.01	9.08	1.6	2.693	0.071	0.118	0.96
17/05/2008	11.6	3.16	5	4.6	3.9	8	4.9	50.1	67.5	41.6	2	4.8	7.8	1.4	4.3	15.1	25.5	0.195	5.01	3.7	0.15	37.53	1.6	1.382	0.064	0.219	23.71
24/05/2008	11.9	2.41	16	10.1	9.8	8.3	10.8	20.6	21.7	13.9	8	2.8	7.2	16.9	1.5	8.5	19.3	0.102	4.74	3.37	0.13	8.92	2	1.472	0.048	0.219	11.78
25/05/2008	11.6	3.06	19	29.7	33.9	21.7	24.6	25.3	22	19.9	7.1	4.6	5	52.8	10.9	13.7	45.8	0.461	9.27	5.12	0.38	13.15	3	0.778	0.172	1.01	188.89
01/06/2008	11.8	2.44	6	5.6	5.2	10.1	5.1	50.1	37.9	36.4	5.7	11.5	8.6	9.1	23	36.4	12.8	0.053	6.35	3.84	0.13	8.28	2.6	5.868	0.289	1.373	59.73
05/06/2008	12	2.13	9	11.2	13.4	8.2	8.4	14	19.4	12	10.4	4	11.6	44.1	4.4	54.6	40.2	0.128	4.35	3.3	0.35	9.58	2	2.052	0.048	0.333	24.34
26/06/2008	15	1.19	6	12.9	8.7	8.5	8.6	0	0	0	22.5	7.2	10	132.4	16.3	23	14.8	0.008	1.74	1.37	0.07	0.78	1.5	0.331	0.046	0.279	3.54
30/06/2008	15.3	1.2	5	11	13.6	8	7.5	12.8	17.5	12.1	7.7	4.4	2	12.1	5	0.8	7.8	0.006	2.89	1.45	0.04	0.47	2.4	0.922	0.049	0.134	2.26

11/07/2008	16.4	0.65	2	9.7	9.1	17.7	8.8	0.7	0	0.2	7.8	16.5	5.2	9	54.3	3.8	6.5	0.003	1.02	0.76	0.02	0.23	1.6	0.302	0.037	0.502	0.68
22/08/2008	17.5	0.41	3	7.1	6.2	41.6	0.8	0.3	1.1	0.6	0.3	28.3	3.2	0.1	200	1.2	9.3	0.005	1.27	0.57	0.01	0.59	3.1	0.130	0.099	0.364	2.11
26/08/2008	17.7	0.44	2	6.3	1.1	72.9	0	6.2	41.6	0.8	0.4	14.5	0	0	100.3	0	2.8	0.005	1.56	0.92	0	0.63	3.6	1.123	0.309	0.758	3.32
27/08/2008	17.1	0.49	7	16	12.4	51.9	13.9	13.9	114.5	1.9	4.8	25.9	16.6	5.4	293.3	61.3	8.5	0.027	5.25	1.43	0.02	1.46	10.6	3.002	0.341	2.396	35.08
02/09/2008	15.1	0.38	3	0.4	0.6	0.5	0.2	24.1	137.1	19.9	0.4	0.6	7	0	0	7	6.5	0.003	1.03	0.52	0.01	5.68	2.7	4.489	0.018	0.05	0.24
18/09/2008	15.1	0.35	3	5.1	2.6	24.4	4.9	6.4	9.2	6.6	0.5	24.1	1.2	0	132.9	0.1	5.2	0.004	1.03	0.56	0.01	0.66	3	0.565	0.137	0.438	1.66
18/09/2008	14	0.44	3	9.6	7	20.4	11.4	9	33.7	11.5	2.5	15.3	3.6	3.1	55.4	2.9	12.3	0.011	1.79	0.65	0.02	1.05	4.1	1.541	0.27	2.837	13.52
24/09/2008	14	0.39	11	5.2	5.1	5	5.4	20.8	58.1	12.3	3.1	1.2	2.6	4	0.6	2.8	20.7	0.006	0.63	0.5	0.03	1.04	1.6	0.058	0.013	0.022	0.49
Average	11.8	0.79	9.9	12.1	11.9	14.8	10.7	18.4	23.5	15.3	6	7.9	5	21.5	32.9	10.4	28	0.047	2.01	1.13	0.06	4.06	3.3	1.320	0.091	0.499	10.98
SD	3.9	0.79	12	7.3	7.7	11.9	7.2	18.3	28.4	15.6	5.2	7.6	4.3	40.3	59.7	19.6	36.9	0.09	1.79	1.04	0.08	7.39	3.1	3.797	0.115	0.734	26.86

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1177 3 Table 3. Mean monthly and annual values of pre-event, and flood-based rainfall, runoff and sediment transport variables.
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Month	Pre-event		Rainfall															Runoff								Sediment Transport		
	T°-ISTS	Q ₀	Pdur	Pd	Pd1-CA	Pd1-IN	Pd1-RF	Pd7-CA	Pd7-IN	Pd7-RF	Imax ₆₀ -CA	Imax ₆₀ -IN	Imax ₆₀ -RF	EcI ₆₀ -CA	EcI ₆₀ -IN	EcI ₆₀ -RF	Fdur	TR	Qp	Qm	Qb	RC	Qp/Q ₀	FI	SSCmean	SSCmax	TL	
Jan	5.4	0.3	19.4	11.0	2.9	5.3	1.4	10.3	13.7	9.5	4.4	3.9	1.9	7.0	5.8	1.5	62.8	0.103	0.8	0.5	0.1	7.5	4.2	0.09	0.033	0.104	3.3	
Feb	6.9	0.2	5.7	6.4	4.4	3.1	2.1	5.6	4.1	4.5	5.8	3.3	2.3	12.6	2.3	1.2	50.7	0.012	0.4	0.3	0.0	1.9	2.0	0.03	0.014	0.019	0.7	
Mar	8.1	0.4	5.7	7.4	4.2	4.4	6.3	7.2	7.1	6.9	6.0	3.5	4.2	10.4	3.6	4.6	22.2	0.006	0.7	0.5	0.0	1.3	1.9	0.20	0.011	0.023	0.4	
Apr	9.7	0.7	10.3	13.6	28.2	27.3	21.5	14.3	16.8	11.7	4.6	7.4	4.1	15.2	24.7	5.5	24.7	0.046	2.0	1.1	0.1	3.2	2.6	0.51	0.084	0.416	13.3	
May	11.2	2.2	10.8	11.1	34.2	46.4	32.0	11.4	12.1	10.3	4.6	3.9	4.0	10.7	6.0	5.5	22.6	0.127	4.2	2.9	0.1	11.9	2.0	1.16	0.088	0.386	28.4	
Jun	13.6	1.1	5.4	11.3	12.8	12.0	10.1	11.6	10.5	9.3	10.5	10.0	7.1	45.2	31.3	18.1	14.1	0.027	2.5	1.6	0.1	2.6	2.4	1.80	0.125	0.621	12.4	
Jul	18.1	0.3	4.0	13.4	26.6	17.6	17.6	13.8	14.6	12.5	9.8	14.9	7.0	59.2	78.8	25.6	9.9	0.006	1.6	0.5	0.0	0.6	6.6	6.71	0.084	0.760	2.8	
Aug	16.7	0.6	3.9	13.9	13.5	28.9	11.8	11.3	30.0	14.6	6.2	17.5	8.9	18.2	121.6	24.7	7.7	0.017	2.6	1.0	0.0	1.0	5.7	1.16	0.214	0.896	14.2	
Sep	15.1	0.3	6.1	11.1	16.1	43.2	15.2	10.8	16.4	10.4	3.5	8.6	3.9	9.4	32.9	5.1	15.0	0.006	0.9	0.5	0.0	1.3	2.8	0.99	0.070	0.512	2.5	
Oct	14.0	0.3	4.7	11.0	20.8	11.0	14.5	13.5	6.1	7.9	9.6	6.1	4.3	23.5	15.5	6.1	14.1	0.009	1.2	0.4	0.0	1.3	4.3	2.99	0.196	1.952	11.2	
Nov	8.3	0.3	35.0	18.7	6.7	7.1	6.6	16.1	14.4	13.5	4.4	3.6	1.0	23.0	7.0	0.8	100.5	0.059	0.9	0.5	0.1	5.1	2.7	0.07	0.009	0.014	1.6	
Dec	6.4	0.2	31.0	20.2	0.9	0.2	0.5	22.0	19.5	17.3	6.4	2.6		80.5	6.5		126.7	0.130	1.1	0.6	0.1	5.5	4.6	0.07	0.013	0.044	3.7	
2005-06	12.6	0.4	12.8	14.4	14.7	14.0	13.3	13.6	14.5	13.7	7.4	9.5	6.2	33.0	43.4	17.6	31.6	0.042	1.5	0.6	0.0	3.3	4.9	2.08	0.096	0.466	5.3	
2006-07	10.8	0.6	9.6	11.5	19.1	18.0	14.3	11.8	12.2	10.4	4.6	6.6	4.5	10.2	18.1	5.6	33.1	0.029	1.4	0.9	0.1	2.7	2.3	0.45	0.066	0.402	4.6	
2007-08	12.0	1.1	8.3	11.0	20.4	32.9	17.3	10.9	16.5	9.0	5.9	7.7	4.7	20.3	34.4	9.5	22.8	0.060	2.7	1.6	0.1	5.4	2.8	1.31	0.103	0.575	18.3	

1182 Table 4. Pearson correlation matrix between pre-event conditions and rainfall, with runoff variables (see Table 1 for the abbreviations of the variables).

Runoff	Pre-event		Rainfall													
	T°_ ISTS	Q ₀	Pdur	Pd	Imax ₆₀ -CA	Imax ₆₀ - IN	Imax ₆₀ -FR	EcI ₆₀ -CA	EcI ₆₀ -IN	EcI ₆₀ -FR	Pd7-CA	Pd7- IN	Pd7- FR	Pd1- CA	Pd1- IN	Pd1- FR
Fdur	-0.47	0.01	0.71	0.25	-0.05	-0.30	-0.23	0.05	-0.23	-0.11	-0.01	-0.11	-0.07	0.28	-0.04	0.13
TR	-0.14	0.70	0.40	0.30	-0.03	-0.15	0.04	0.03	-0.12	0.06	0.33	0.21	0.33	0.34	0.09	0.26
Qp	0.12	0.77	0.07	0.20	0.10	0.12	0.31	0.09	0.17	0.32	0.44	0.39	0.47	0.21	0.15	0.25
Qm	-0.04	0.94	0.13	0.05	-0.04	-0.12	0.14	-0.04	-0.11	0.14	0.48	0.38	0.51	0.07	0.00	0.05
Qb	-0.24	0.67	0.49	0.25	0.00	-0.23	0.03	0.06	-0.21	0.11	0.28	0.14	0.27	0.30	0.01	0.16
RC	-0.13	0.78	0.11	-0.15	-0.10	-0.23	0.01	-0.08	-0.19	0.01	0.47	0.42	0.50	-0.14	-0.15	-0.11
Qp/Q ₀	0.42	-0.22	-0.16	0.21	0.42	0.50	0.30	0.47	0.56	0.39	0.03	0.07	0.01	0.22	0.25	0.28
FI	0.28	0.01	-0.15	-0.20	0.04	-0.05	0.18	-0.00	-0.02	0.09	0.34	0.23	0.34	-0.17	-0.13	-0.18

Bold marked correlations are significant at $p < 0.01$; $N=66$ (Casewise deletion of missing data)

Table 5. Multivariate statistical analysis between pre-event conditions, rainfall and runoff variables. Variables that do not statistically explain the variability of the equation are not included in this table (see Table 1 for the abbreviations of the variables).

Runoff variables	βeta coefficients									
	Pre-event variables		Rainfall variables							
	T°-ISTS	Q ₀	Pdur	Pd	EcI ₆₀ -CA	EcI ₆₀ -IN	Pd7- FR	Pd1- CA	Pd1- IN	Pd1- FR
Fdur	-0.213		0.619							
TR		0.696	0.221					0.241		
Qp		0.715				0.412	0.176	0.253		
Qm		0.945						0.101	0.12	
Qb		0.618	0.452							
RC		0.798								
Qp/Q ₀		-0.291		-0.414	0.525	0.545	0.345			0.465
FI	0.288	-0.304					0.487			

Variable	Equation	R ²
Fdur =	21.9993-1.6356×T°-ISTS+3.0364×Pdur	0.54
TR =	-0.0671+0.070×Q ₀ +0.0028×Pdur+0.0024×Pd1-CA	0.68
Qp =	-0.6014+1.6170×Q ₀ +0.0130×EcI ₆₀ -IN+0.0200×Pd7-FR+0.0559×Pd1-CA	0.79
Qm =	-0.1308+1.2350×Q ₀ +0.0129×Pd1-CA+0.010×Pd1-IN	0.91
Qb =	-0.0392+0.0619×Q ₀ +0.0057×Pdur	0.64
RC =	-1.9215+6.9121×Q ₀	0.64
Qp/Q₀ =	1.4229-1.1052×Q ₀ -0.1747×Pd-0.0376×EcI ₆₀ -CA+0.0289×EcI ₆₀ -IN+0.0662×Pd7-FR+0.1894×Pd1-FR	0.72
FI =	-3.1717+0.3319×T°-ISTS -1.5368×Q ₀ +0.12419×Pd7-FR	0.27

1195
1196 Table 6. Pearson correlation matrix between rainfall and sediment transport variables (see Table 1 for the meaning of the abbreviations).

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Sediment transport variables	Rainfall variables													
	Pdur	Pd	Pd7-CA	Pd7-IN	Pd7-FR	Pd1-CA	Pd1-IN	Pd1-FR	Imax ₆₀ -CA	Imax ₆₀ -IN	Imax ₆₀ -FR	EcI ₆₀ -CA	EcI ₆₀ -IN	EcI ₆₀ -FR
TL	0.25	0.42	0.26	0.15	0.23	0.45	0.21	0.40	0.05	0.07	0.20	0.07	0.12	0.26
SSCmax	-0.18	0.17	0.14	0.15	0.11	0.13	0.25	0.26	0.06	0.45	0.29	-0.03	0.49	0.30
SSCmean	-0.24	0.13	0.14	0.16	0.14	0.04	0.35	0.28	0.04	0.49	0.39	-0.06	0.53	0.41

Marked correlations are significant at $p < 0.010$; $N=66$ (Casewise deletion of missing data)

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Table 7. Multivariate statistical analysis between rainfall and sediment transport variables. Variables that do not statistically explain the variability of the equation are not included in this table (see Table 1 for the abbreviations of the variables)

Sediment transport variables	βeta coefficients for rainfall variables				
	Pd7-CA	Pd7-FR	Pd1-CA	Pd1-FR	EcI ₆₀ - IN
TL		0.289	0.514		
SSCmax	0.236				0.558
SSCmean			-0.500	0.603	0.462
Variable	Equation				R ²
TL =	-16.972+0.5152×PD7-RF+1.773×Pd1-CA				0.30
SSCmax =	0.087391+0.0068×EcI ₆₀ -IN+0.0090×Pd7-CA				0.33
SSCmean =	0.0481+0.0009×EcI ₆₀ -IN-0.0072×Pd1-CA+0.0095×Pd1-RF				0.51

Table 8. Pearson correlation matrix between runoff and sediment transport variables (see Table 1 for the meaning of the abbreviations).

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Sediment transport variables	Runoff variables							
	Fdur	TR	Qp	Qm	Qb	RC	Qp/Q ₀	FI
TL	0.08	0.67	0.79	0.64	0.62	0.31	0.21	0.07
SSCmax	-0.21	-0.01	0.37	0.10	-0.08	-0.09	0.48	0.32
SSCmean	-0.28	-0.05	0.49	0.20	-0.14	-0.10	0.57	0.32

Marked correlations are significant at $p < 0.0100$; $N=71$ (Casewise deletion of missing data)

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Table 9. Multivariate statistical analysis between runoff and sediment transport variables. Variables that do not statistically explain the variability of the equation are not included in this table (see Table 1 for the abbreviations of the variables).

Sediment transport variables	βeta coefficients for runoff variables						
	Fdur	TR	Qp	Qm	Qb	RC	
TL	-0.354	0.819	0.681	-0.392	0.259	-0.417	
SSCmax			1.419	-0.975	-0.229		
SSCmean			1.453	-0.867	-0.4014		
Variable	Equation						R ²
TL =	-1.757-0.254×Fdur-241.02×TR+10.58×Qp-10.56×Qm+87.69×Qb-1.599×RC						0.84
SSCmax =	0.1879+0.552×Qp-0.657×Qm-1.874×Qb						0.53
SSCmean =	0.0416+0.095×Qp-0.098×Qm-0.552×Qb						0.63

Table 10. Multivariate analysis between pre-event, rainfall, runoff and sediment transport variables (see Table 1 for abbreviations). Variables that do not statistically explain the variability of the equation are not included in this table.

Sediment transport variables	βeta Coefficients								
	Pre-event variable	Rainfall variables				Runoff variables			
	Q ₀	Pdur	Pd	Pd1-CA	EcI60-CA	TR	Qp	Qm	RC
TL	-0.347	-0.141				1.089	0.455		-0.376
SSC _{max}					-0.221		1.555	-1.256	
SSC _{mean}			1.013	-1.11		-0.369	1.431	-0.806	

Variable	Equation	R ²
TL =	1.905-12.244×Qo-0.63×Pdur+379.544×TR+7.094×Qp-1.53×RC	0.94
SSCmax =	0.283-0.004×EcI60-CA-0.602×Qp-0.842×Qm	0.54
SSCmean =	0.020+0.016×Pd-0.016×Pd1-CA-0.535×TR+0.093×Qp-0.09×Qm	0.75

Table 11. Observed (Obs) *vs* estimated (Est) values for the sediment transport multivariate equations. The upper and lower 95% confidence intervals (CI) of the equations are presented. The residual and the percentage of error provide a test of the predictive power of the equations. Results in bold indicate the residuals are higher or lower than the values of the confidence intervals. Note that the percentage the % error is calculated based on the observed and residual values (i.e. Res/Obs, expressed in %).

Floods	Total Sediment Transport (TL in t)						Maximum flood-based Suspended Sediment Transport (SSCmax in g l ⁻¹)						Mean flood-based Suspended Sediment Transport (SSCmean in g l ⁻¹)					
	Obs.	Est.	Lower 95% CI	Upper 95% CI	Residual	% error	Obs.	Est.	Lower 95% CI	Upper 95% CI	Residual	% error	Obs.	Est.	Lower 95% CI	Upper 95% CI	Residual	% error
07/04/2006	6.6	8	5.4	10.5	-1.4	21	0.79	0.91	0.71	1.11	-0.13	16	0.16	0.13	0.1	0.16	0.03	19
15/07/2006	3.1	1.5	-1.3	4.3	1.6	52	1.6	0.41	0.23	0.59	1.19	74	0.12	0.11	0.05	0.16	0.01	11
13/09/2006	0.6	2.7	-0.2	5.6	-2.1	346	0.18	0.33	0.16	0.51	-0.15	83	0.03	0.04	0	0.07	-0.01	31
11/10/2006	5.7	2.1	-0.7	4.9	3.6	63	2.83	0.38	0.21	0.55	2.45	87	0.23	0.01	-0.03	0.05	0.22	95
01/04/2007	3.6	-2.6	-6.6	1.5	6.2	172	0.35	0.22	0.06	0.39	0.13	37	0.05	0	-0.02	0.03	0.05	97
12/08/2007	5.3	12	7.4	16.6	-6.7	126	0.28	0.65	0.51	0.8	-0.38	135	0.06	0.18	0.14	0.21	-0.11	179
01/06/2008	59.7	20.7	13	28.4	39	65	1.37	0.84	0.48	1.2	0.53	39	0.29	0.24	0.18	0.31	0.05	16
11/07/2008	0.7	0.6	-3.1	4.3	0.1	17	0.5	0.22	0.06	0.38	0.28	55	0.04	0.06	0.04	0.08	-0.02	61
18/09/2008	1.7	3.5	0.4	6.6	-1.8	105	0.44	0.43	0.26	0.6	0.01	2	0.14	0.11	0.08	0.13	0.03	23

Figure 1.

Figure 2.

A)

B)

Figure 3.

Figure 4.

Figure 5.

Figure 6

Figure 7.

A)

B)