Temporal variability and time compression of sediment yield in small Mediterranean catchments: impacts for land and water management

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Abstract

Increased soil erosion, pressure on agricultural land, and climate change highlight the need for new management to mitigate soil loss. Management strategies should utilize comparable datasets of long-term soil erosion monitoring across multiple environments. Adaptive soil erosion management in regions with intense precipitation require an understanding of inter-annual variability in sediment yield (SY) at regional scales. Here, a novel approach is proposed for analysing regional SY. We aim to (i) investigate factors controlling inter- and intra-annual SY, (ii) combine seasonality and time compression analyses to explore SY variability and (iii) discuss management implications for different Mediterranean environments. Continuous SY measurements totalling 104 years for eight small catchments were used to describe SY variability, which ranged from 0 to 271 t/ha/year and 0 to 116 t/ha/month. Maximum SY occurs in spring to summer for catchments with oceanic climates, whilst semi-arid or dry summer climates experience SY minimums. We identified three time compression patterns at each time scale. Time compression was most intense for catchments with minimum SY in spring to summer. Low time compression was linked to very high soil loss, low runoff and sediment production thresholds, and high connectivity. Reforestation, grassland and terracing changed SY magnitudes and time compression, but failed to reduce SY for large storm events. Periods with high probability for high SY were identified using a combination of intra-annual SY variability, seasonality analysis, and time compression analysis. Focusing management practices on monthly flow events, which account for the majority of SYs will optimise returns in Mediterranean catchments.

Key words: sediment yield, controlling factors, time compression, seasonality, Mediterranean, management

Introduction

Soils are a non-renewable and essential resource for the food production and society. Soil erosion occurs as a consequence of anthropic pressure on agricultural land and climate change. It is a major environmental and agricultural threat worldwide (e.g. Vanmaercke *et al.*, 2014; García-Ruiz *et al.*, 2015). Soil erosion in Mediterranean regions is particularly accelerated due to specific environmental conditions (low annual precipitation, high evapotranspiration, intense rainstorms, drought occurrence, and steep slopes) long land management history, and recent tectonic activity, recurrent use of fire, overgrazing, and farming (Verstraeten *et al.*, 2003; González-Hidalgo *et al.*, 2007; de Vente *et al.*, 2011; Prosdocimi *et al.*, 2016a). For mitigating soil loss, effective catchment-specific tailor-made solutions are required (García-Ruiz *et al.*, 2017; Raclot *et al.*, 2017). Several studies have demonstrated that soil erosion and sediment transport are afftected by land use and landscape design (Kosmas *et al.*, 1997; Cerdan *et al.*, 2010; Cerdà *et al.*, 2017). Contemporary erosion management practices in Mediterranean regions include terrace building (Tarolli *et al.*, 2014), no- or reduced-tillage (Kassam *et al.*, 2012), cover crops (Gómez *et al.*, 2009), mulching (Prosdocimi *et al.*, 2016b), planting grass (Marques *et al.*, 2011), using vegetated strips (Mekonnen *et al.*, 2015) and reforestation (Rey *et al.*, 2003). Several constraints may limit their efficiency such as farmers' appropriation, lack of maintenance, or a lack of adaptation to local conditions (Maetens *et al.*, 2012). One of the main scientific and operational challenges is to find the best adapted soil erosion management method to address the temporal scales on which the majority of sediment is delivered in a particular catchment. Larson *et al.* (1997) suggested catchment soil conservation strategies should be designed to account for an exceptional single storm with a 10 or 20-year return period. Analysing annual and decadal mean values of sediment yield (SY) and regional controlling factors (de Vente *et al.*, 2011) provides information on adequate erosion control for years with average SY, but does not properly address the events that contribute to the majority of sediment comprising in annual yields. Time compression refers to phenomenon that major soil losses take place during short periods, typically in a few large events (González-Hidalgo *et al.*, 2007). Large precipitation events and rainfall-runoff responses are highly variable in Mediterranean regions (Merheb *et al.*, 2016). Their effects on SY are often inter-linked to antecedent soil surface conditions set up by previous events (Kim & Ivanov, 2014; Saffarpour *et al.*, 2016), and influenced by land management (Nadal-Romero *et al.*, 2012).

Studies of SY variability and time compression demonstrated that large river systems (Moatar *et al.*, 2013) exhibit lower sensitivity to land cover changes or specific climatic events, relative to smaller catchments (e.g. Walling, 1999; Dearing *et al.*, 2006). Consequently, the impact of land management may be easier to understand when considering small catchments (<100 km^2, Gay *et al.*, 2014). García-Ruiz *et al.* (2015) identified the need for new management guidelines based on comparable datasets from long-term monitoring in variety of environments (Vanmaercke *et al.*, 2012).

Our hypothesis was that adapting management to specific SY temporal distribution is possible at the catchment scale, by considering SY intra-annual variability using monthly datasets (which reflects seasonal interactions between rainfall distribution and agricultural practices), and by combining SY seasonality and time compression analysis.

The objectives of the study were to (i) investigate controlling factors of inter- and intra-annual SY variability, (ii) explore SY variability by combining seasonality and time-compression analyses, and (iii) discuss management implications for different Mediterranean environments. The analyses were based on comparable SY datasets from medium to long-term (3-29 years) continuously monitored small catchments across a wide range of Mediterranean environments.

Material and Methods

Study area

The dataset was compiled from a network of medium to long-term monitored catchments (R-OSMed) across eight small catchments (1.88-130 ha) in five countries (Pellus *et al.*, 2012; Figure 1) spanning four different climate sub regions (Peel *et al.*, 2007), and a range of environments of the Mediterranean region (Table 1). In total, 104 years of continuous environmental and agricultural monitoring and SY measurements from the catchment outlets were available for Roujan, Laval and Brusquet (France), El Cautivo and Can Vila (Spain), Cannata (Italy), Macieira de Alcôba (Portugal), and in Kamech (Tunisia).

Datasets

Monthly (referring to intra-annual variability) and annual (referring to inter-annual variability) datasets of SY, rainfall and runoff were derived from continuous monitoring datasets.

The monthly dataset consisted of monthly SY, calculated from the area-specific SY event data as follows:

$$SY_{i,j} = \sum_{k=0}^{K} SY_{k(i,j)} \tag{1}$$

Where *SY* is the total area specific sediment yield (t/ha), *i* is themonth, *j* is the year, *k* is the event in month *i*, and K is the number of events in month *i*.

Factors influencing SY, such as rainfall, storm runoff and baseflow, were calculated at intra-annual scales from an event-based database similarly to SY (equation 1). The months with unmeasured SY due to equipment failure, were excluded from the database. Additional details of the calculations for these and other controlling factors are in Table 2. The annual dataset was derived from the monthly dataset by aggregating monthly values as a sum or maximum in a hydrological year (Table 2). If one monthly value within a hydrological year was missing, the whole year was excluded from the dataset.

Controlling factors

In order to analyse factors influencing inter-annual variability, we considered SY as a function of labile and stable factors over inter-annual scales:

f (SY) ~ controlling factors (labile + stable influences) (2)

At intra-annual scales, only labile factors were tested:

f (SY) ~ labile influences (3)

The complete list of controlling factors is described in Table 2.

Pearson correlations quantified the relative influence of each factor on SY (similarly to Vanmaercke *et al.*, 2014). Because all inter- and intra-annual variables had non-normal distribution ($p < 0.5$; Lilliefors, 1967), correlations were conducted on log-transformed data (values < 0.01 were set to 0.01) with normal distribution.

SY seasonality

Seasonality of rainfall, runoff, SY and sediment concentration were evaluated from plots of normalized variables for each catchment. For each catchment and month, the mean monthly SY ($mSY_{i,}$) was calculated as follows:

$$mSY_i = \frac{\sum_{j=1}^{J} SY_{i,j}}{J} \tag{4}$$

where $SY_{i,j}$ is the total area specific sediment yield (t/ha) in the i-th month and in j-th year, and J is the total number of records in the annual dataset for the considered catchment.

Secondly, the inter-annual mean SY μSY was calculated as:

$$\mu SY = \frac{\sum_{i=1}^{I} SY_{i,j}}{I} \tag{5}$$

where $SY_{i,j}$ is the sediment yield (t/ha) in *i*-th month and *j*-th year of all *I* considered months.

The normalized SY values for each *i-th* month ($N\,mSY_i$) were than calculated as:

$$NmSY_i = \frac{mSY_i - \mu SY}{\mu SY} \quad (6)$$

Normalized monthly values of rainfall, runoff and sediment concentration were calculated in the same way.

Time compression

Time compression was analysed based on plots of cumulative percentages (Figure 2). To produce the plots, first, the annual SY values were expressed as a percentage of the total SY across the entire measurement period in a catchment (SY-EMP). Each year was expressed as a percentage of the total duration of entire measurement period (DEMP). SY percentages were placed in ascending order, and cumulative SY percentage and cumulative time units' percentages (year in this case) were calculated. This procedure was repeated for annual rainfall and runoff, and for monthly rainfall, runoff and SY. Cumulative percentages of each monthly and annual variable were plotted as the dependent variable (% V-EMP) against cumulative percentage of time units (% DEMP). Three limiting patterns of time compression were described. No time compression occurs when each unit of time (month or year) contributes the same percentage to variable total across the entire measurement period in a catchment (V-EMP, Figure 2A). Extreme time compression is, when the whole V-EMP occurred only within 10% of the entire time (Figure 2B). Generally, steeper slopes on time compression plots indicate bigger contributions of corresponding time units to the independent variable. Low or zero-slope values along portions of the x-axis indicate shorter timescales contribute to the independent variable. A variable (e.g. SY) has low-intensity time compression if the variable value exceeds 25% of the cumulative total within the first-half of the total time (Figure 2C). Medium time compression exists when V-EMP is between 0 and 25% within the first 50% of the total time. When variable values of zero occur after 50% of time, time compression is high. Time compression of rainfall, runoff and SY plotted for each catchment helps distinguish time compression patterns. In order to identify periods with high likelihood of high SY, months contributing more than 5% to V-EMP (in each catchment) were analysed further.

Results

Factors controlling sediment yield

Annual SY values varied greatly over space and time, from 0 t/ha/year in El Cautivo (1998) to 271.13 t/ha/year in Laval (1994; Figure 3). Factors exerting a dominant influence on inter-annual SY values are described in supporting information (S1, S2). Monthly SY varied from 0 to 116 t/ha/month (S1), and was below 100 t/ha/month in 50% of all 1254 monthly measurements across all catchments (S3). Monthly variability of rainfall, runoff, sediment concentration and vegetation cover are described further in S4-S7.
Annual SY values had a strong positive correlation with (log-transformed) maximum annual specific flood-peak discharge, number of erosive events, and sediment concentration, and was negatively correlated with vegetation cover (Table 3). The strength of correlations between SY and controlling factors increased for intra-annual scale data relative to inter-annual data, except for baseflow and vegetation cover. Maximum and median kinetic energy from rainfall were weakly correlated to SY.

SY seasonality and time compression

The seasonality of rainfall, runoff, sediment concentration, SY and vegetation cover are plotted in Figure 4. Kamech, Cannata, Macieira de Alcôba, Roujan and El Cautivo had minimum SY throughout spring and summer (i.e., May to August), while Can Villa, Brusquet and Laval had exhibited maximum SY during this period.

Three different seasonality relational patterns were noted for rainfall, runoff, SY, and sediment concentration: (i) variables had similar trends with different magnitudes, (ii) variables had similar trends but lines were shifted, and (iii) variables had opposing trends.

After classifying time compression intensity (Figure 2C), the results indicated low inter-annual time compression for rainfall across all catchments (Figure 5A), while it was low to medium for runoff and dominantly medium for SY. Intra-annual time compression was medium for rainfall for all catchments (Figure 6A), medium to high for runoff, and mostly high for SY. The time in which ~50% of total measured rainfall, runoff, or SY was collected is enclosed in supporting-information (S8). Three patterns of time compression were identified at both intra-annual and inter-annual scales (Table 4). Laval had the lowest time compression at both time scales. The remainder of the catchments fell into two groups (i) medium compression patterns at inter- and intra-annual scales in Brusquet, Can Villa and Macieira de Alcôba, and (ii) highly compressed patterns at Cannata, El Cautivo, Kamech and Roujan (Figure 5B, Figure 6B, Table 4).

Months contributing to time compression

Months contributing >5% of total sediment yield measured during entire measurement period (SY-EMP, 3 to 29 years long, Table 1) existed in all catchments (Table 5), except in Laval with a maximum monthly contribution of 2.8%. The four-month period from October to January had frequent high contributions to SY-EMP; accounting for 7% of SY-EMP in Can Vila, 14-22% SY-EMP in Brusquet, Roujan and El Cautivo, 36% SY-EMP in Macieira de Alcôba, and >65% SY-EMP in Cannata and Kamech. Amounts of rainfall collected in the months with SY >5% SY-EMP differed between catchments, and was only 6% to 32% of total rainfall measured during entire measurement period (rainfall-EMP). Similarly, the amount of runoff was 10-51% of total runoff measured during entire measurement period (runoff-EMP).

Further, we analysed whether months that contributed >5% SY-EMP differed from months that contributed >5% rainfall-EMP or >5% runoff-EMP. Excluding Kamech and Macieira de Alcôba, months with rainfall contributions >5% of rainfall-EMP produced the highest SY (SY >5% SY-EMP). In Macieira de Alcôba, Kamech and Roujan, months with highest runoff (>5% runoff-EMP) had >70% overlap with months that had >5% contributions to SY-EMP. In Can Vila, Brusquet and Cannata, months with highest SY (>5% SY-EMP) had the highest sediment concentration twice as often as the highest runoff (>5% runoff-EMP). The opposite trend was found in Kamech, Roujan, El Cautivo and Macieira de Alcôba.

Discussion

Variability of SY and correlation between SY and influencing factors

SY inter-catchment variability at inter-annual timescales was similar to that described in de Vente *et al.* (2011) for the Mediterranean region. Monthly analysis showed great intra-annual variability. Significant positive correlations ($p>0.01$) between SY and rainfall, and SY and runoff at annual and monthly scales, were contrary to previous results which had indicated negative or no significant correlations for other catchments (Verstraeten *et al.*, 2003; de Vente *et al.*, 2011; Vanmaercke *et al.*, 2014). Weak correlations between maximum and median monthly rainfall intensity with sediment yield were caused by a combination of factors (such as connectivity, land use, and soil type) and differed between catchments. Thease weak correlations therefore did not relate directly to the extent of splash erosion in each individual catchment, and the role of splash should be investigated in further studies. Annual SY correlations between badlands area (strongly eroded steep slopes with minimal vegetation and high drainage density), mean slope, gully erosion contributions to SY, and sediment reaching the outlet was similar to Verstraeten *et al.* (2003). Negative correlation between annual SY and mean annual vegetation cover occurred because the lowest mean annual vegetation cover was found in catchments with highest sediment yield (Laval, Kamech). Correlation between monthly vegetation cover and monthly SY was weak because of relative inter-annual stability of vegetation in some catchments (e.g. Brusquet, Can Vila, El

Cautivo). In other catchments, e.g. Macieira de Alcôba (Nunes *et al.,* 2016) inter-annual vegetation cover variability influenced sediment production and delivery.

Seasonality and time compression

Observed seasonal patterns in SY followed the trend of rainfall distribution in summer. Catchments with dry summers (Cannata, El Cautivo, Kamech, Macieira de Alcôba, and Roujan) had minimum SY from May to August, while catchments with humid summers (Brusquet, Can Villa, Laval) reached a maximum in SY. Observed rainfall-runoff distributions closely followed patterns common to the northwest Mediterranean region (Merheb *et al.*, 2016). In spite of this, runoff-SY seasonal distribution differed more than rainfall-SY seasonal distribution. Tarolli *et al.* (2012) concluded that increased frequency of flash flood events in autumn contribute to increased runoff in November and winter. In our study >5% runoff-EMP and >5% SY-EMP were most likely to occur in December and January.

Time compression was more intense for semi-arid (El Cautivo) and all the dry summer catchments compared to those with humid summers. Macieira de Alcôba which has dry summers was an exception because of specific winter-pasture management on irrigated terraces with a shallow water table (Nunes *et al.*, 2016). These conditions decreased soil loss, but not runoff, from November to January when most >5% rainfall-EMP and >5% runoff-EMP took place. SY did not occur for all events with runoff, and SY time compression was more intense relative to runoff time compression. Time compression also reflected land-management practices for grasslands (Nadal-Romero *et al.*, 2012). Specific management practices for the dry-summer catchment in Macieira de Alcôba lead to similar time compression to humid-summer catchments in Brusquet and Can Villa, and a winter hydrological response resembling catchments in humid climates (Latron *et al.*, 2008). Neighbouring catchments in Laval and Brusquet with oceanic climates and humid summers had similar characteristics except for vegetation cover and badland area (Table 1). Despite many similarities, the Laval and Brusquet catchments differed in both SY magnitude and time compression. Laval's low time compression was due to the catchment's low runoff and sediment production thresholds that were independent of inter-annual variability in rainfall and runoff, and due to very high soil erosion vulnerability. In contrast, forest management in Brusquet decreased SY and caused time lags in sediment response.

Combining analysis of SY seasonality and time compression for management purposes

Comparing regional annual SY values may assist in identifying regional soil erosion hot-spots (Vanmaercke *et al.,* 2014), but careful selection of controlling factors is crucial due to significant variance in the local sediment responses of individual catchments (e.g. Laval and Brusquet). Our findings confirm our hypothesis that improving management adaptation to specific SY temporal distribution is possible at the small catchment scale, by considering SY intra-annual variability, and by combining SY seasonality and time compression analysis. Inter-annual time compression analysis distinguished well-connected catchments with low erosion thresholds, where management targeting connectivity (e.g. terraces, stripes, water harvesting tillage) and/or surface cover (e.g. reforestation) could decrease SY (Rey, 2003) and cause postponed sediment response represented by higher time compression (e.g. Brusquet catchment). Grassland and forest management in humid catchments (Brusquet, Can Villa, Laval), and Macieira de Alcôba decreased runoff time compression intensity more than SY time compression intensity at inter-annual scales. However, in semi-arid El Cautivo, and in dry-summer catchments with higher proportions of arable land (Roujan, Kamech), runoff and SY time compression intensities were equivalent and high. Despite further management to reduce runoff and soil loss (e.g. autumn tillage, vegetation stripes, and ditches), most of studied catchments experienced significant soil loss and SY time compression. Vegetation cover, soil cover, and sediment trapping measures were effective in reducing runoff, soil loss and SY during single events and over longer timescales (Cerdà *et al.*, 2016; 2017), but the degree of efficiency differs for mean and extreme rainfall conditions (Marques *et al.*, 2011; Biddocu *et al.*, 2017). In catchments with high SY but low or medium time compressions, such as Laval, the permanent vegetation cover is certainly the best option for erosion control. In situations where excessive aridity prevents vegetation from permanently covering the soil, it will be necessary to set up other type of erosion control measures, such as terraces or waterways management. When intra-annual time compression for runoff and/or SY are high (e.g. Kamech), temporary control measures such as mulch, geotextiles, sediment traps, cover crops and water harvesting tillage during months with higher probability of soil loss will increase efficiency of SY management (Sherriff *et al.*, 2016). Prosdocimi *et al.* (2016b) demonstrated that mulching can decrease soil loss and runoff volume by more than 90%, while Mekonnen *et al.* (2015) showed similar reductions for trapping efficiencies with some types of vegetative strips. Applying spatially adjusted management practices (Gumiere *et al.*, 2014; Levavasseur *et al.*, 2016) can be planned best by using combined SY seasonality analyses and intra-annual time compression analyses. The approach used here proposed a synoptic view of sediment yields dynamics, which distinguished periods with a high probability of significant SY more precisely than typical annual SY analyses, and was less sensitive to variability from extreme events than single event analyses. Variability in monthly SY (e.g. Kamech) demonstrates the SY magnitudes to which applied management practices should be adjusted.

Conclusion

This study used a novel approach to improve regional SY studies based exclusively on a dataset from medium to long-term monitoring efforts in multiple catchments. Its originality resided in the combination of analysing both inter- and intra-annual SY variability using SY seasonality and time compression analyses. We conclude, that two contrasting SY seasonal patterns existed for the studied catchments in Mediterranean region, differing in the season where maximum SY ocurred. Catchments with oceanic climate and humid summer had maximum SY from spring to summer, while catchments with Mediterranean dry season or with semi-arid climates had largest SY rates between October and January, and sediment delivery was concentrated into few months or years. Catchments with low inter- annual time compression of rainfall, runoff and SY had very high soil loss, high sediment connectivity, and low runoff and sediment production thresholds, which were independent of rainfall and runoff variability. Long-term grasslands, forests, irrigated winter pastures, and terracing decreased SY volumes and reduce catchment sediment response. Therefore, surface cover (e.g. reforestation) and sediment connectivity management (terraces, sediment traps, water harvesting tillage) are recommended in order to decrease SY and reduce catchment sediment response for catchments with very high soil loss. However, our analysis showed that current management failed to target many of the largest SY events. Successful reduction of SY will require spatially and temporally adjusted management practices. Further experimental and modelling studies on the impact of spatially and temporally adjusted management practices under extreme events conditions would be needed for improving soil conservation strategies. Advantages of combining intra-annual SY, seasonality and time compression analyses include: (i) improved regional erosion hotspot detection, (ii) proper identification of important periods for SY management, and (iii) accurate estimation SY monthly magnitudes to which SY reduction management should be adjusted.

Application of the method proposed here could facilitate the required adjustment of soil conservation techniques (Larson, 1997), and would be especially beneficial in regions with limited financial resources or where agricultural soil protection is most crucial (de la Rosa *et al.*, 2000).

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References

Ben Slimane, A., Raclot, D., Evrard,O., Sanaa, M., Lefèvre, I., Ahmadi, M., Tounsi, M., Rumpel, C., Mammou, A.B., Le Bissonnais, Y. 2013. Fingerprinting sediment sources in the outlet reservoir of a hilly cultivated catchment in Tunisia. *Journal of Soils and Sediments,* **13**, 801–815.

Biddocu, M., Ferraris, S., Pitacco, A., Cavallo, E. 2017. Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy. *Soil & Tillage Research* **165**, 46–58.

Cerdà, A., González-Pelayo, Ó., Giménez-Morera, A., Jordán, A., Pereira, P., Novara, A., Brevik, E.C., Prosdocimi, M., Mahmoodabadi, M., Keesstra, S., García Orenes, F., Ritsema, C.J. 2016. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency–high magnitude simulated rainfall events. *Soil Research*, **54**,154-165.

Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A., Keesstra, S. 2017. An economic, perception and biophysical approach to the use of oat straw as mulch in Mediterranean rainfed agriculture land. *Ecological Engineering*, **108**, 162-171.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca. A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.J.P.M., Raclot, D., Ionita. I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M.J., Dostal, T. 2010. Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. *Geomorphology*, **122**, 167–177.

Chamizo, S., Cantón, Y., Rodríguez-Caballero, E., Domingo, F., Escudero, A. 2012. Runoff at contrasting scales in a semiarid ecosystem: A complex balance between biological soil crust features and rainfall characteristics. *Journal of Hydrology*, **452–453**, 130–138.

David, M., Follain, S., Ciampalini, R., Le Bissonnais, Y., Couturier, A., Walter, C. 2014. Simulation of medium-term soil redistributions for different land use and landscape design scenarios within a vineyard landscape in Mediterranean France. *Geomorphology*, **214**, 10–21.

Dearing, J.A., Battarbee, R.W., Dikau, R., Larocque, I., Oldfield, F. 2006. Human–environment interactions: towards synthesis and simulation. *Regional Environmental Change*, **6**, 115 -123.

de la Rosa, D., Moreno, J.A., Mayol, F., Bonsón, T. 2000. Assessment of soil erosion vulnerability in western Europe and potential impact on crop productivity due to loss of soil depth using the ImpelERO model. Agriculture. *Ecosystems & Environment*, **81**, 179–190.

de Vente, J., Verduyn, R., Verstraeten, G., Vanmaercke, M., Poesen, J. 2011. Factors controlling sediment yield at the catchment scale in NW Mediterranean geoecosystems. *Journal of Soils and Sediments*, **11**, 690–707.

García-Ruiz, J.M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J.C., Lana-Renault, N., Sanjuán, Y. 2015. A meta-analysis of soil erosion rates across the world. *Geomorphology*, **239**, 160–173.

García-Ruiz, J.M., Beguería, S., Lana-Renault, N., Nadal-Romero, E., Cerdà, A. 2017. Ongoing and emerging questions in water erosion studies. *Land Degradation & Development*, **28**, 5-21.

Gay, A., Cerdan, O., Delams, M., Desmet, M. 2014. Variability of suspended sediment yields within the Loire river basin (France). *Journal of Hydrology*, **519**, 1225–1237

Gómez, J.A., Sobrinho, T.A., Giráldez, J.V., Fereres, E. 2009. Soil management effects on runoff, erosion and soil properties in an olive grove of Southern Spain. *Soil & Till*age, **102**, 5-13.

Gonçalves Ferreira, C. 1996. Erosão hídrica em solos florestais. *Rev. Fac. Let. - Geogr., Series I –Porto*, **12-13**, 145–244.

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

Gumiere, S., Bailly, J.-S., Cheviron, B., Raclot, D., Le Bissonnais, Y., Rousseau, A. 2014. Evaluating the Impact of the Spatial Distribution of Land Management Practices on Water Erosion: case study of a Mediterranean catchment. *Journal of Hydrology Engineering*, DOI: 10.1061/(ASCE)HE.1943-5584.0001076, C5014004.

Inoubli, N., Raclot, D., Moussa, R., Habaieb, H., Le Bissonnais, Y. 2016. Soil cracking effects on hydrological and erosive processes in Mediterranean cultivated vertisols. *Hydrological Processes*, **30**, 4154-4167.

IUSS Working Group WRB 2015. World Reference Base for Soil Resources 2014, update 2015

International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Kassam A., Friedrich T., Derpsch R., Lahmar R., Mrabet R., Basch G., González-Sánchez E.J., Serraj R. 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crops Research*, **132**, 7–17.

Kim, J. & Ivanov, V.Y. 2014. On the non-uniqueness of sediment yield at the catchment scale: The effects of soil antecedent conditions and surface shield. *Water Resources Research*, **50**, 1025-1045.

Kosmas, C., Danalatos, N., Cammeraat, L.H., Chabart, M., Diamantopoulos, J., Farand, R., Gutierrez, L., Jacob, A., Marques, H., Martinez-Fernandez, J., Mizara, A., Moustakas, N., Nicolau, J.M., Oliveros, C., Pinna, G., Puddu, R., Puigdefabregas, J., Roxo, M., Simao, A., Stamou, G., Tomasi, N., Usai, D., Vacca, A. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. *Catena*, **29**, 45–59.

Latron, J. & Gallart, F. 2008. Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *Journal of Hydrology*, **358**, 206–220.

Latron, J., Soler, M., Llorens, P., Gallart, F. 2008. Spatial and temporal variability of the hydrological response in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees*). Hydrological Processes*, **22**, 775–787.

Larson, W.E., Lindstrom, M.J., Schumacher, T.E. 1997. The role of severe storms in soil erosion: a problem needing consideration. *Journal of Soil Water Conservation*, **50**, 90–95.

Legout, C., Poulenard, J., Nemery, J., Navratil, O., Grangeon, T., Evrard, O., Esteves, M. 2013. Quantifying suspended sediment sources during runoff events in headwater catchments using spectrocolorimetry. *Journal of Soils and Sediments*, **13**, 1478–1492.

Levavasseur, F., Bailly, J.-S., Lagacherie, P. 2016. Are ditch networks optimised for mitigating rill erosion in cultivated Mediterranean landscapes? A numerical experiment. *Land Use Policy*, **50**, 441-448.

Licciardello, F. 2007. Runoff and soil erosion evaluation by the AnnAGNPS model in a small Mediterranean watershed. *Trans. Asabe*, **50**, 1585–1593.

Lilliefors, H. 1967. On the Kolmogorov–Smirnov test for normality with mean and variance unknown. *Journal of American Statistical Association*, **62**, 399–402.

Maetens, W., Poesen, J., Vanmaercke, M. 2012. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? *Earth-Sciences Review*, **115**, 21 – 36.

Marques, M.J., Garciá-Muñoz, S., Muñoz-Orangero, A., Bienes, R. 2011. Soil conservation beneath grass cover in hillside vineyards under Mediterranean climatic conditions (Madrid, Spain). *Land Degradation & Development*, **21**, 122–131.

Mekonnen, M., Keesstra, S.D., Stroosnijder,L., Baartman, J.E.M., Maroulis, J. 2015. Soil conservation through sediment trapping: A review. *Land Degradation & Development*, **26**, 544–556.

Merheb, M., Moussa, R., Abdallah, C., Collin, F., Perrin, C., Baghdadi, N. 2016. Hydrological response characteristics of Mediterranean catchments at different time scales: a meta-analysis. *Hydrological Sciences Journal*, **61**, 2520-2539.

Moatar, F., Meybeck, M., Raymond, S., Birgand, F. 2013. River flux uncertainties predicted by hydrological variability and riverine material behaviour. *Hydrological Processes*, **27**, 3535-3546.

IN TEXT FIGURES

Figure 1 Location of the catchments of the R-OSMed network.

The size of the symbol refers to the measurement period in years used to build the database in each catchment: BRU (Brusquet, 11 years), CAN (Cannata, 9 years), CAU (El Cautivo, 18 years), KAM (Kamech, 7 years), LAV (Laval, 29 years), MAC (Macieira de Alcôba, 3 years), ROU (Roujan, 17 years), VIL (Can Vila, 10 years). Brusquet and Laval are neighbouring catchments.

Figure 2 Conceptual framework for time compression analysis

A - no time compression of a variable. All units of time contribute with the same portion to the total value of a variable measured during entire measurement period (V-EMP), B - high time compression of a variable. V-EMP is created during only one unit of time, C – threshold values to define intensity of time compression: L (low) - variable value > 25 % of V-EMP during < 50 % total duration of measurement period (DEMP); M (medium) – variable value non-zero and maximum 25 % of V-EMP during < 50 % DEMP; H (high) - variable value 0 % of V-EMP during < 50 % DEMP.

Figure 3 Inter-annual variability of (A) rainfall (mm), (B) runoff (mm), (C) sediment yield (10^2 t/ha) and (D) sediment concentration (g/l). 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Inter-annual means are plotted as red dot. The values of runoff, sediment yield and sediment concentration < 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the differences in the scale of y axis. Catchments abbrev. in Figure 1.

Figure 4 Seasonality of rainfall (RL, mm), runoff (RF, mm), sediment yield (SY, t/ha), sediment concentration (SC, g/l) and vegetation cover (VC, % area). The variability of mean monthly values from the inter-annual mean was calculated using eq. 2-4. Mean values for each variable are noted in the bottom left corner. The values greater than the scale maximum: *1 (SC=4.8), *2 (SY=4.98), *3 (SY=6.24), *4 (SY=6.28).

Figure 5 Inter-annual time compression of rainfall, runoff and sediment yield in all catchments (A) and time compression patterns in each catchment (B). V-EMP - total value of variable measured during entire measurement period, DEMP – duration of entire measurement period. If any portion of a line is not visible it equals the superposed line. The patterns are classified according rules in Figure 2C. Thresholds are shown by dark dashed rectangle.

Figure 6 Intra-annual time compression of rainfall, runoff and sediment yield in all catchments (A) and time compression patterns in each catchment (B). V-EMP - total value of variable measured during entire measurement period, DEMP – duration of entire measurement period. If any portion of a line is not visible it equals the superposed line. The patterns are classified according rules in Figure 2C. Thresholds are shown by dark dashed rectangle.

Nadal-Romero, E., Lasanta Martínez, T., González-Hidalgo, J.C., de Luis, M., García-Ruiz, J.M. 2012. The effect of intense rainstorm events on the suspended sediment response under various land uses: the Aísa Valley experimental station. *Cuadernos de Investigación Geográfica*, **38**, 27–47.

Nunes, J.P., Bernard-Jannin, L., Rodríguez Blanco, M.L., Santos, J.M., Coelho, C.O.A., Keizer, J.J. 2016. Hydrological and erosion processes in terraced fields: observations from a humid Mediterranean region in northern Portugal. *Land Degradation & Development*, DOI: 10.1002/ldr.2550

Peel, M.C., Finlayson, B.L., McMahon, T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology & Earth System Sciences*, **11**, 1633–1644.

Pellus, J., Le Bissonnais, Y., Gob, F., Smetanová, A. 2012. Network of catchments research on soil erosion in the Mediterranean region [WWW Document]. R-OSMed Netw. Catchments Res. Soil Eros. Mediterr. Reg. Available at: https://sites.google.com/site/rosmedsicmed/; accessed 19/10/2016.

Prosdocimi, M., Cerdà, A., Tarolli, P. 2016a. Soil water erosion on Mediterranean vineyards: A review. *Catena*, **141**, 1–21.

Prosdocimi, M., Tarolli, P., Cerdà, A. 2016b. Mulching practices for reducing soil water erosion: A review. *Earth-Science Reviews*, **11**, 191–203.

Raclot, D., Le Bissonnais, Y., Annabi, M., Sabir, M., Smetanová, A. 2017. Main issues for preserving mediterranean soil resources from water erosion under global change. *Land Degradation & Development*. DOI: 10.1002/ldr.2774

Rey, F. 2003. Influence of vegetation distribution on sediment yield in forested marly gullies. *Catena*, **50**, 549–562.

Rodríguez-Caballero, E., Cantón, Y., Chamizo, S., Lázaro, R., Escudero, A. 2013. Soil Loss and Runoff in Semiarid Ecosystems: A complex Interaction between biological soil crusts, micro-topography, and hydrological drivers. *Ecosystems*, **16**, 529–546.

Saffarpour, S., Western, A.W., Adams, R., McDonnell, J.J. 2016. Multiple runoff processes and multiple thresholds control agricultural runoff generation. *Hydrology & Earth System Sciences*, **20**, 4525-4545.

Sherriff, S.C., Rowan, J.C., Fenton, O., Jordan, P., Melland, A.R., Mellander, P.-E., Ó hUallacháin, D. 2016. Storm Event Suspended Sediment-Discharge Hysteresis and Controls in Agricultural Watersheds: Implications for Watershed Scale Sediment Management. *Environmental Sciences & Technology*, **50**, 1769-1778.

Tarolli, P., Borga, M., Morin, E., Delrieu, G. 2012. Analysis of flash flood regimes in the North-Western and South-Eastern Mediterranean regions. *Natural Hazards and Earth System Sciences*, **12**, 1255–1265.

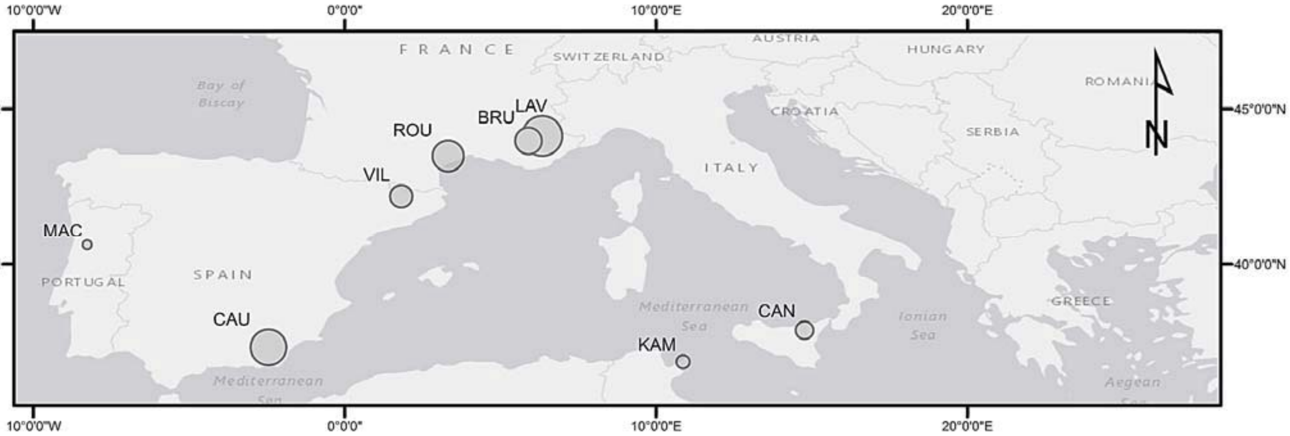
Tarolli, P., Preti, F., Romano, N. 2014. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene*, **6**, 10-25.

Vanmaercke, M., Poesen, J., Radoane, M., Govers, G., Ocakoglu, F., Arabkhedri, M. 2012. How long should we measure? An exploration of factors controlling the inter-annual variation. *Journal of Soils & Sediments*, **12**, 603-619.

Vanmaercke, M., Poesen, J., Broeckx, J., Nyssen, J. 2014. Sediment yield in Africa. *Earth-Sciences Review*, **136**, 350 – 368.

Verstraeten, G., Poesen, J., de Vente, J., Koninckx, X. 2003. Sediment yield variability in Spain: a quantitative and semiqualitative analysis using reservoir sedimentation rates. *Geomorphology*, **50**, 327–34.

Walling DE. 1999. Linking land use, erosion and sediment yields in river basins. *Hydrobiologia*, **410**, 223–240.


10°0'0"W
0°0'0"
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45°0'0"N
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FRANCE
SWITZERLAND
AUSTRIA
HUNGARY
ROMANIA
CROATIA
SERBIA
ITALY
SPAIN
PORTUGAL
GREECE
Bay of Biscay
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Ionian Sea
Aegean Sea
LAV
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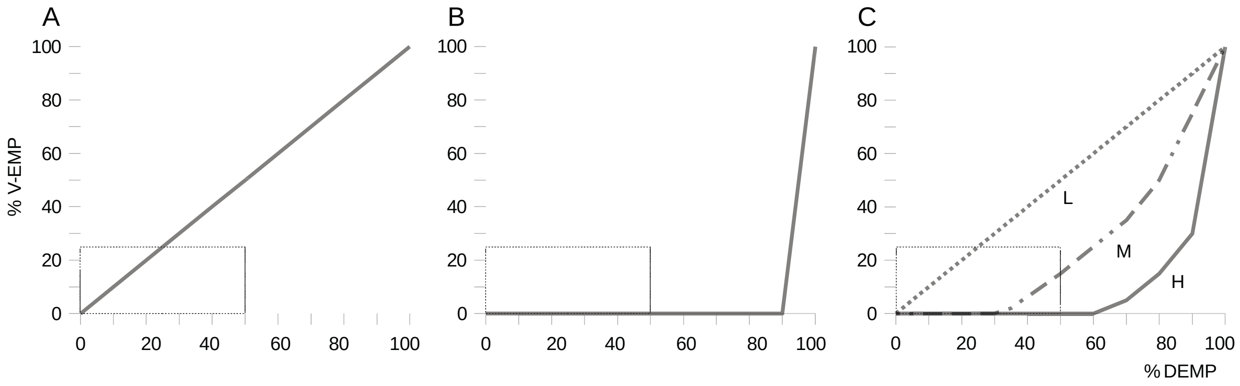
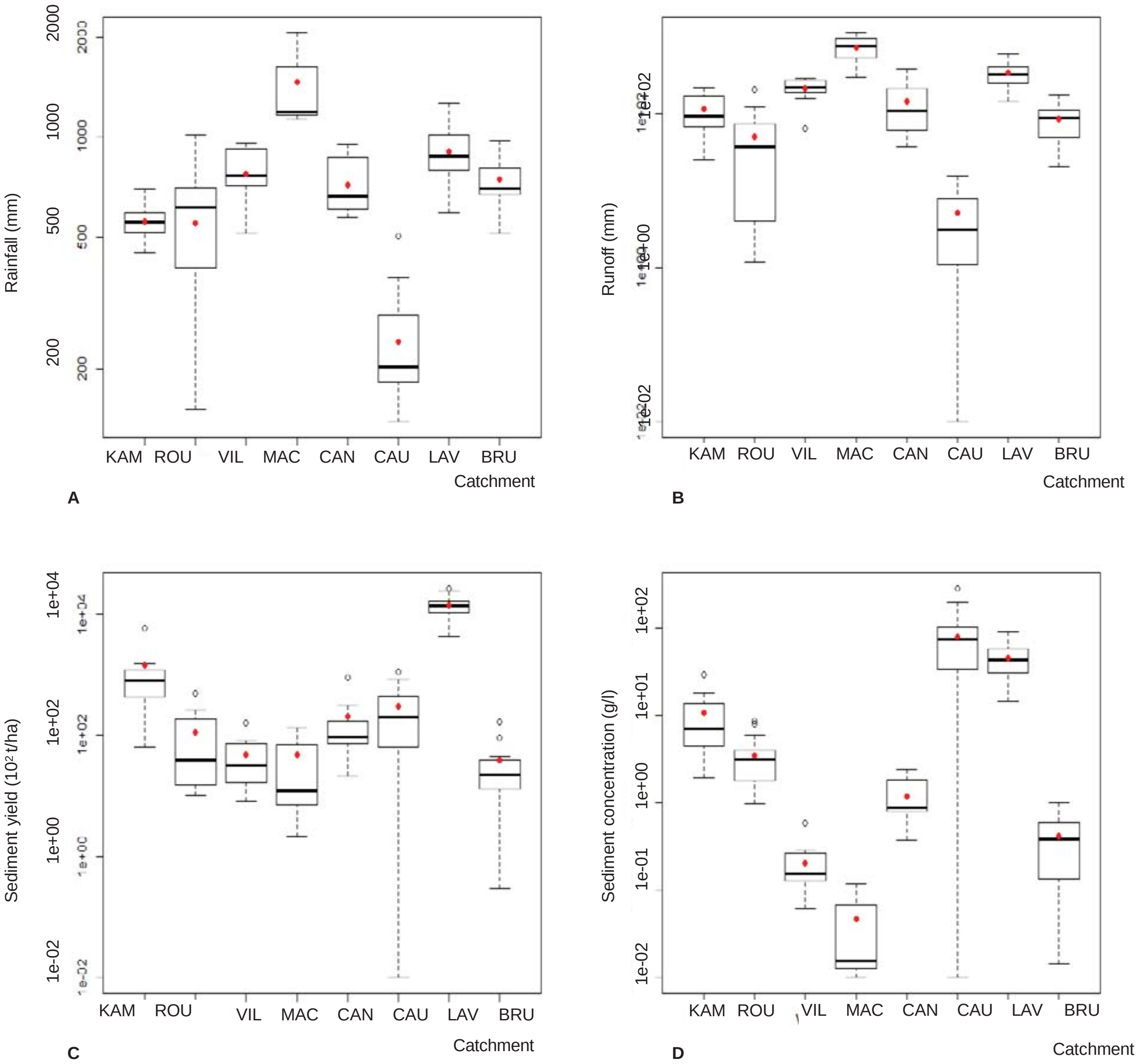
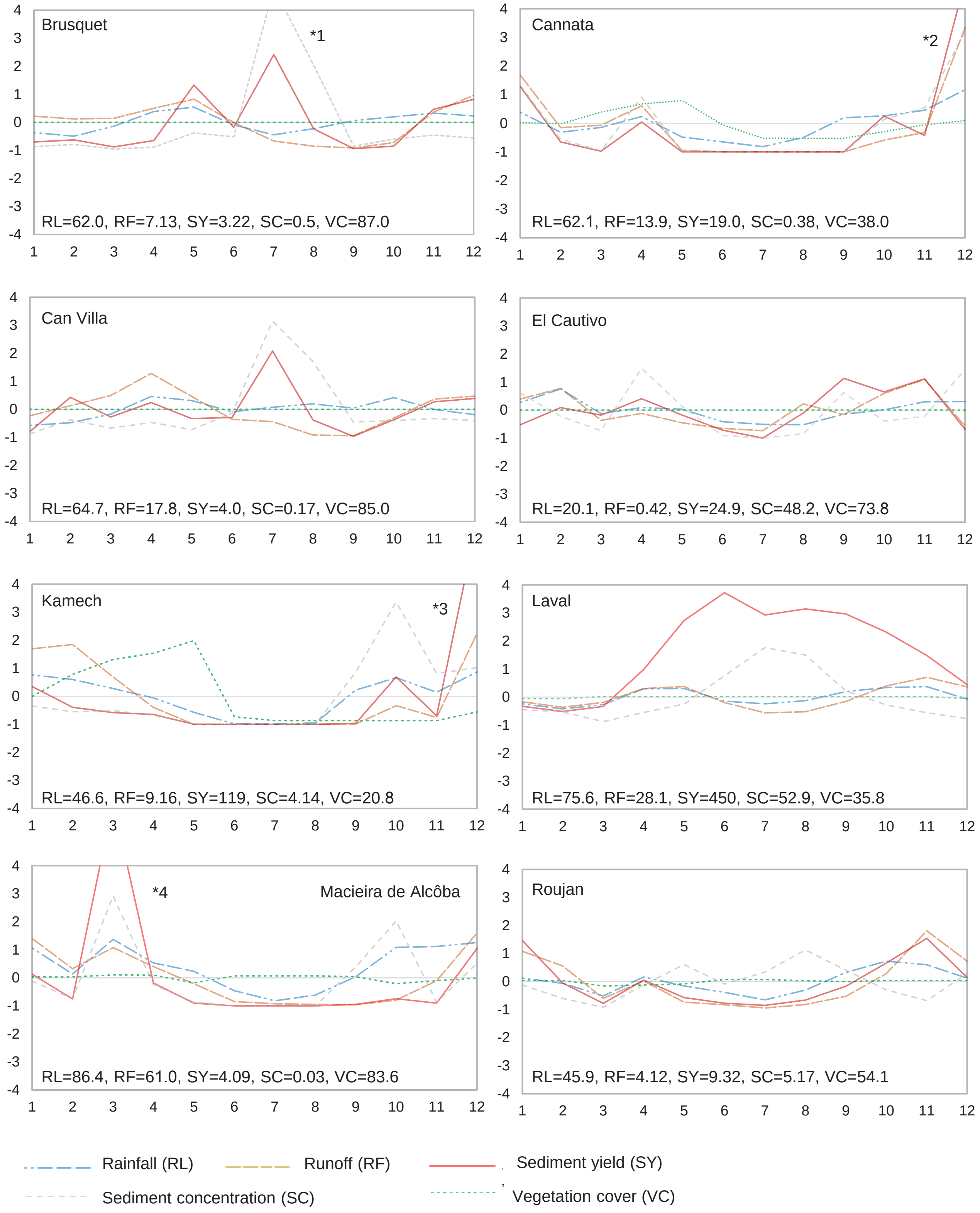

A
B
C
% V-EMP
% DEMP
0
20
40
60
80
100
L
M
H


A
Rainfall (mm)
2000
1000
500
200
KAM
ROU
VIL
MAC
CAN
CAU
LAV
BRU
Catchment
B
Runoff (mm)
1e+02
1e+00
1e-02
KAM
ROU
VIL
MAC
CAN
CAU
LAV
BRU
Catchment
C
Sediment yield (10² t/ha)
1e+04
1e+02
1e+00
1e-02
KAM
ROU
VIL
MAC
CAN
CAU
LAV
BRU
Catchment
D
Sediment concentration (g/l)
1e+02
1e+01
1e+00
1e-01
1e-02
KAM
ROU
VIL
MAC
CAN
CAU
LAV
BRU
Catchment


Brusquet
*1
RL=62.0, RF=7.13, SY=3.22, SC=0.5, VC=87.0
Cannata
*2
RL=62.1, RF=13.9, SY=19.0, SC=0.38, VC=38.0
Can Villa
RL=64.7, RF=17.8, SY=4.0, SC=0.17, VC=85.0
El Cautivo
RL=20.1, RF=0.42, SY=24.9, SC=48.2, VC=73.8
Kamech
*3
RL=46.6, RF=9.16, SY=119, SC=4.14, VC=20.8
Laval
RL=75.6, RF=28.1, SY=450, SC=52.9, VC=35.8
*4
Macieira de Alcôba
RL=86.4, RF=61.0, SY=4.09, SC=0.03, VC=83.6
Roujan
RL=45.9, RF=4.12, SY=9.32, SC=5.17, VC=54.1
4
3
2
1
0
-1
-2
-3
-4
1
2
3
4
5
6
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9
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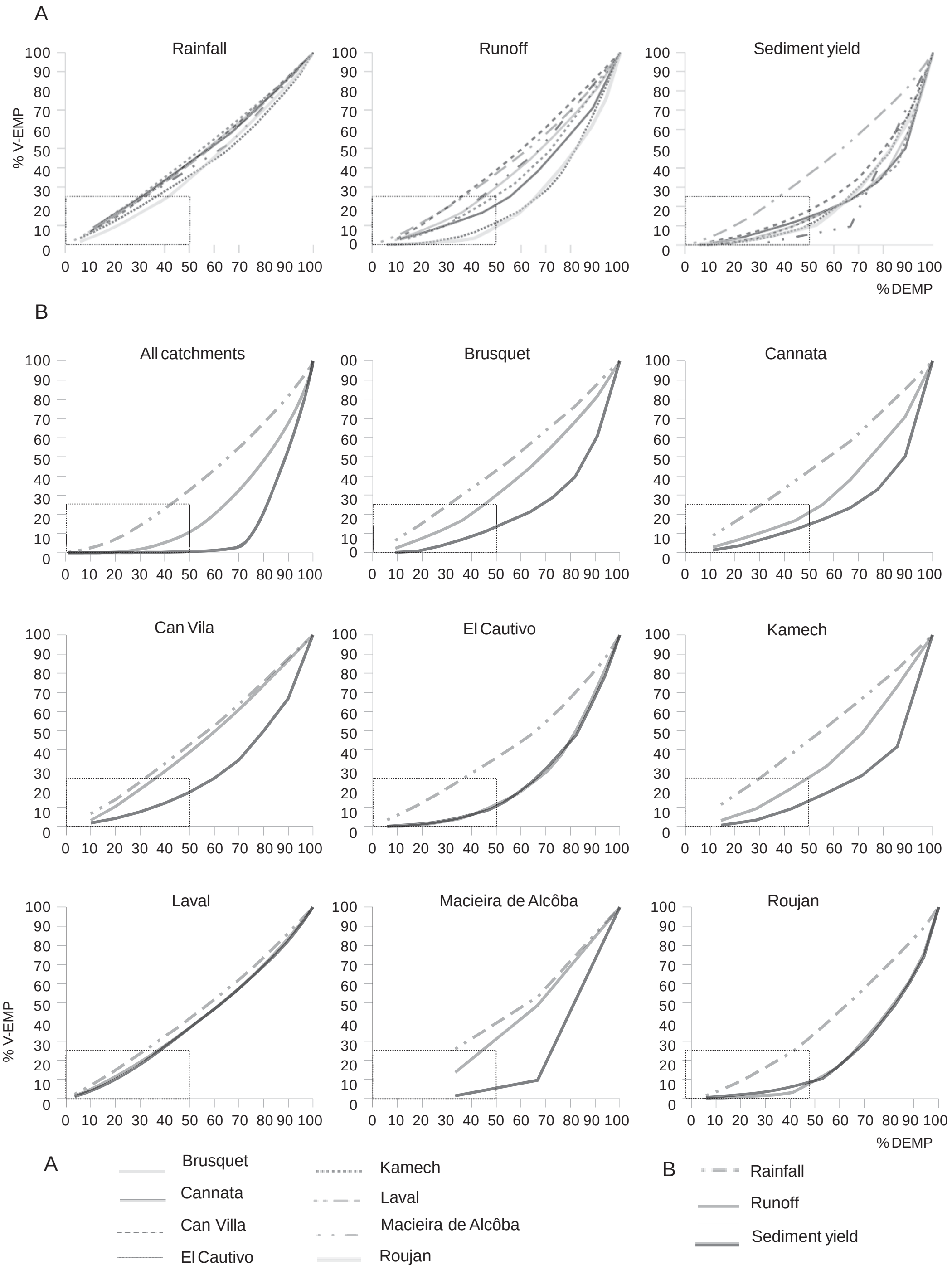
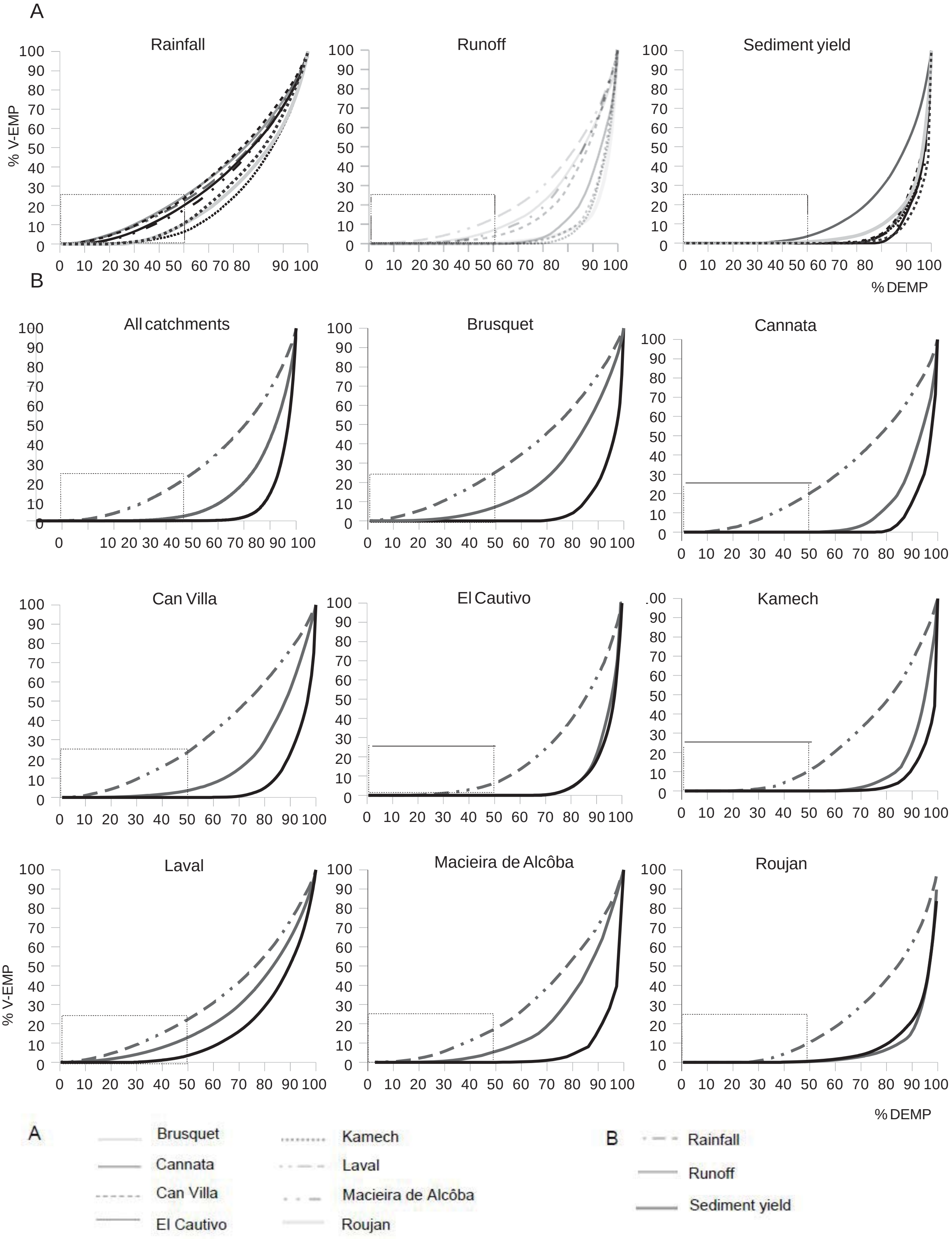
11
12
Rainfall (RL)
Runoff (RF)
Sediment yield (SY)
Sediment concentration (SC)
Vegetation cover (VC)


A
Rainfall
Runoff
Sediment yield
% V-EMP
% DEMP
0 10 20 30 40 50 60 70 80 90 100
B
All catchments
Brusquet
Cannata
Can Vila
El Cautivo
Kamech
Laval
Macieira de Alcôba
Roujan
A
Brusquet
Cannata
Can Villa
El Cautivo
Kamech
Laval
Macieira de Alcôba
Roujan
B
Rainfall
Runoff
Sediment yield


A
Rainfall
Runoff
Sediment yield
% V-EMP
0 10 20 30 40 50 60 70 80 90 100
% DEMP
B
All catchments
Brusquet
Cannata
Can Villa
El Cautivo
Kamech
Laval
Macieira de Alcôba
Roujan
% V-EMP
0 10 20 30 40 50 60 70 80 90 100
% DEMP
A
Brusquet
Cannata
Can Villa
El Cautivo
Kamech
Laval
Macieira de Alcôba
Roujan
B
Rainfall
Runoff
Sediment yield

S1 Minimum and maximum inter-annual and intra-annual values

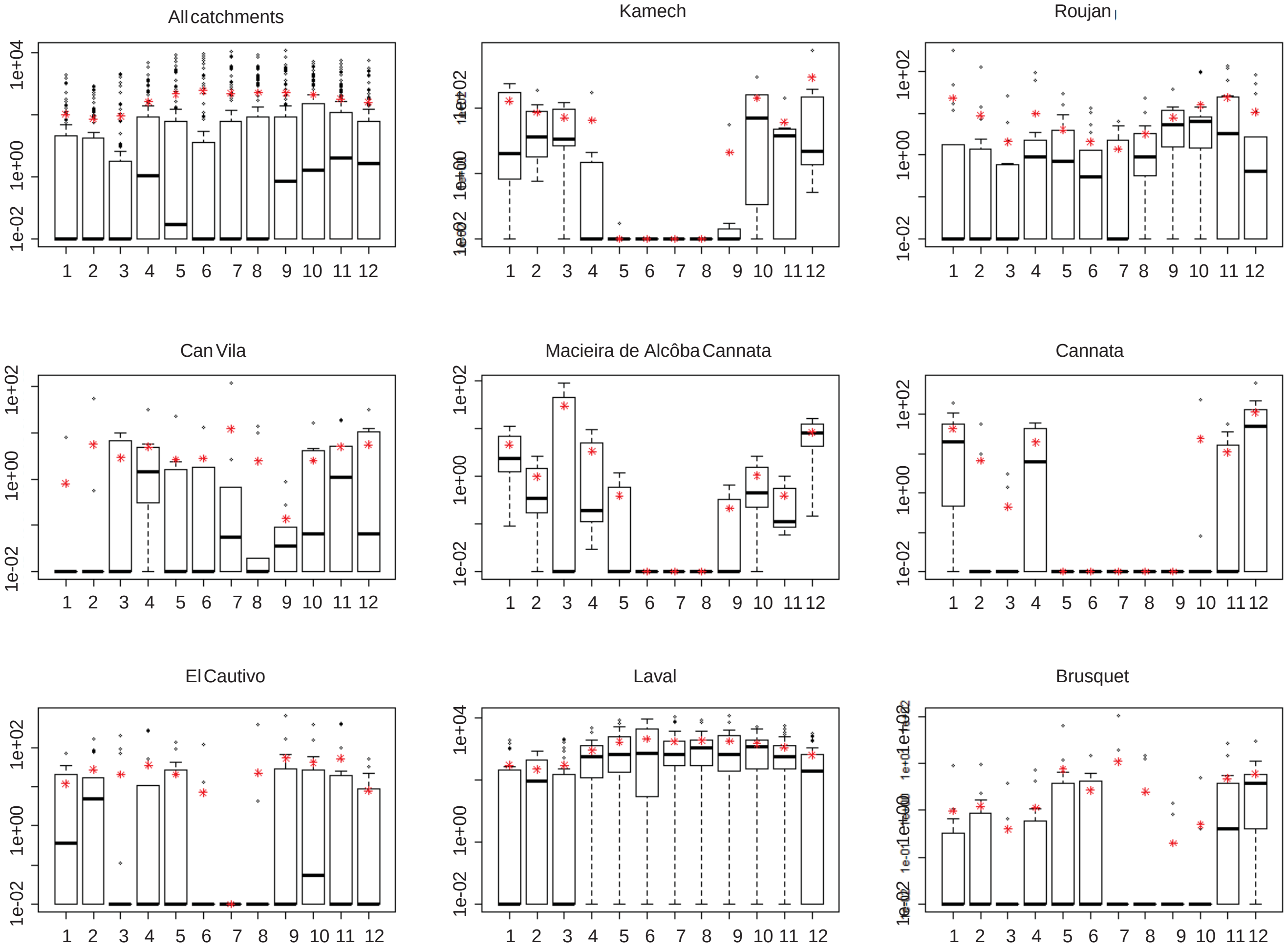
Variable	Inter-annual variability		Intra-annual variability	
	Minimum	Maximum	Minimum	Maximum
	Cat (Y)	Cat (Y)	Cat (M/Y)	Cat (M/Y)
Sediment yield (t/ha)	0 CAU (1998)	271 LAV (1994)	0 ***	116 LAV (09/1994)
Rainfall (mm)	139 CAU (2005)	2061 MAC (2013)	0 ***	459 MAC (03/2013)
Runoff (mm)	16 CAU (1992)	1127 MAC (2013)	0 ***	284 MAC (03/2013)
Sediment concentration (g/l)	0 CAU (1998)	284 CAU (1998)	0 ***	747 CAU (04/2006)
Baseflow* (mm)	0 CAN (2001)	693 MAC (2013)	0 ***	156 MAC (12/2010)
Specific flood-peak discharge (m^3/s/km^2)	0 CAU (1998)	27 LAV (2013)	0 ***	26.5 LAV (06/2013)
Number of runoff events with maximum discharge > 1 l/s/ha	0 BRU (2007) CAU (1998)	44 LAV (1992)	0 ***	15 LAV (06/1992)

Cat - catchment, (Y) - year of observation, (M/Y) - month and year of observation, * - measured in ROU - Roujan, MAC - Macieira de Alcôba, and CAN -Cannata; BRU-Brusquet, CAU- El Cautivo, LAV-Laval

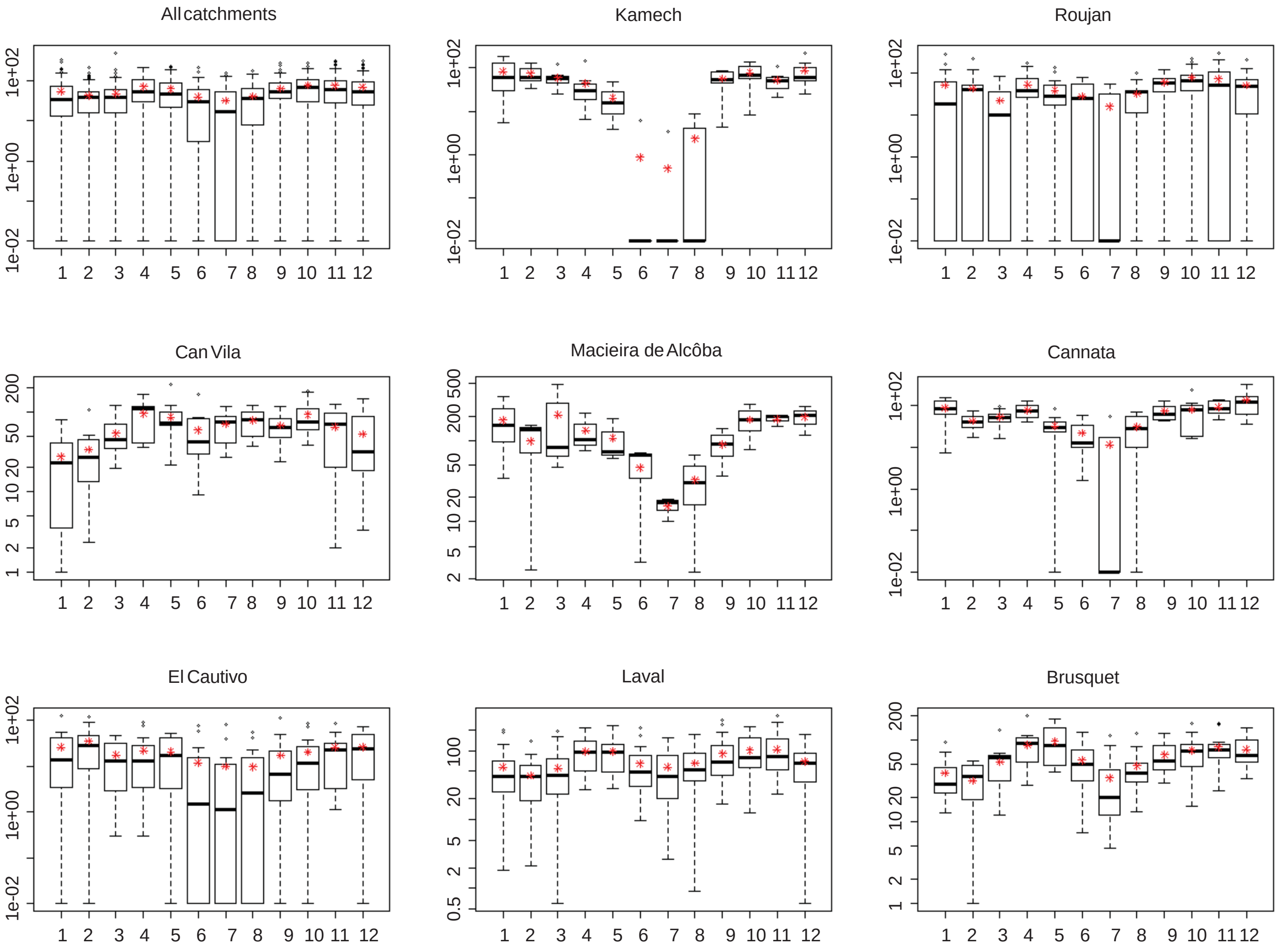
S2 Values of relatively stable controlling factors

Name	Badlands (%)	Contributing erosion process (%)			Portion of sediment reaching outlet (%)	Hypsometric integral	Mean slope (%)
		Sheet & Rill	Gully	Bank &Fluvial			
Brusquet	5	80	20	0	NA	0.7	55.8
Cannata	0	70	0	20	50	0.5	20.5
Can Villa	0.9	0	90	5	100	0.4	26.9
El Cautivo	29.5	80	5	5	80	0.3	52.1
Kamech	0	75	25	0	100	0.5	11.0
Laval	59	50	50	0	100	0.4	77.0
Macieira de Alcôba	0	100	0	0	10	0.3	18.8
Roujan	0	100	0	0	5	0.5	8.5

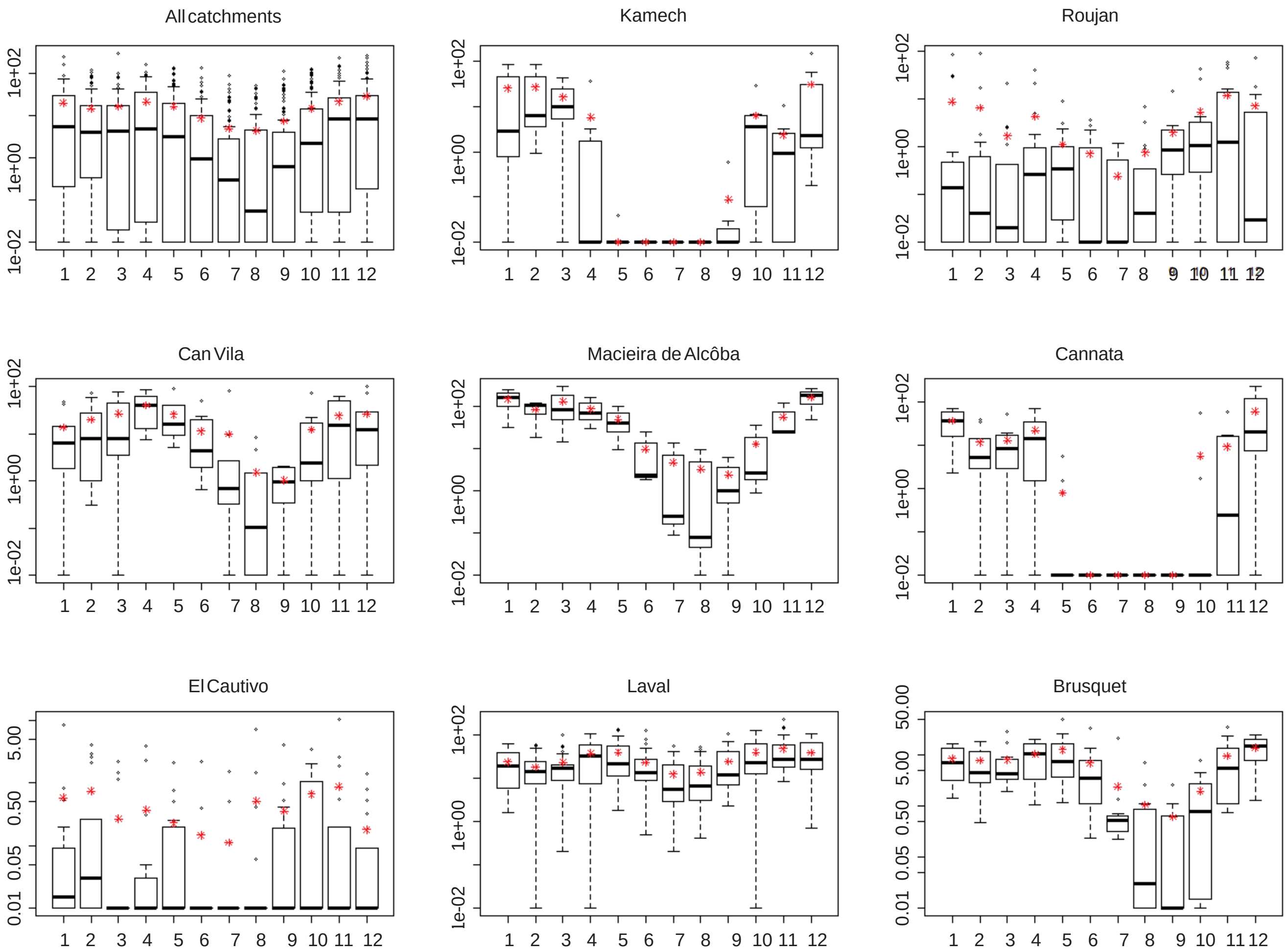
Methods to calculate controlling factors in Table 2



S3 Intra-annual variability of sediment yield (10²t/ha/month, y-axis). Months (1-January to 12-December) are on x-axis. 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Asterisk represents the monthly mean in each month and catchment. The values of sediment yield < 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the difference in y-axis scale.



S4 Intra-annual variability of rainfall (mm, y-axis). Months (1-January to 12-December) are on x-axis. 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Asterisk represents represents the monthly mean in each month (1-January to 12-December) and catchment. The values of rainfall < 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the difference in y-axis scale.



All catchments

Kamech

Roujan

Can Vila

Macieira de Alcôba

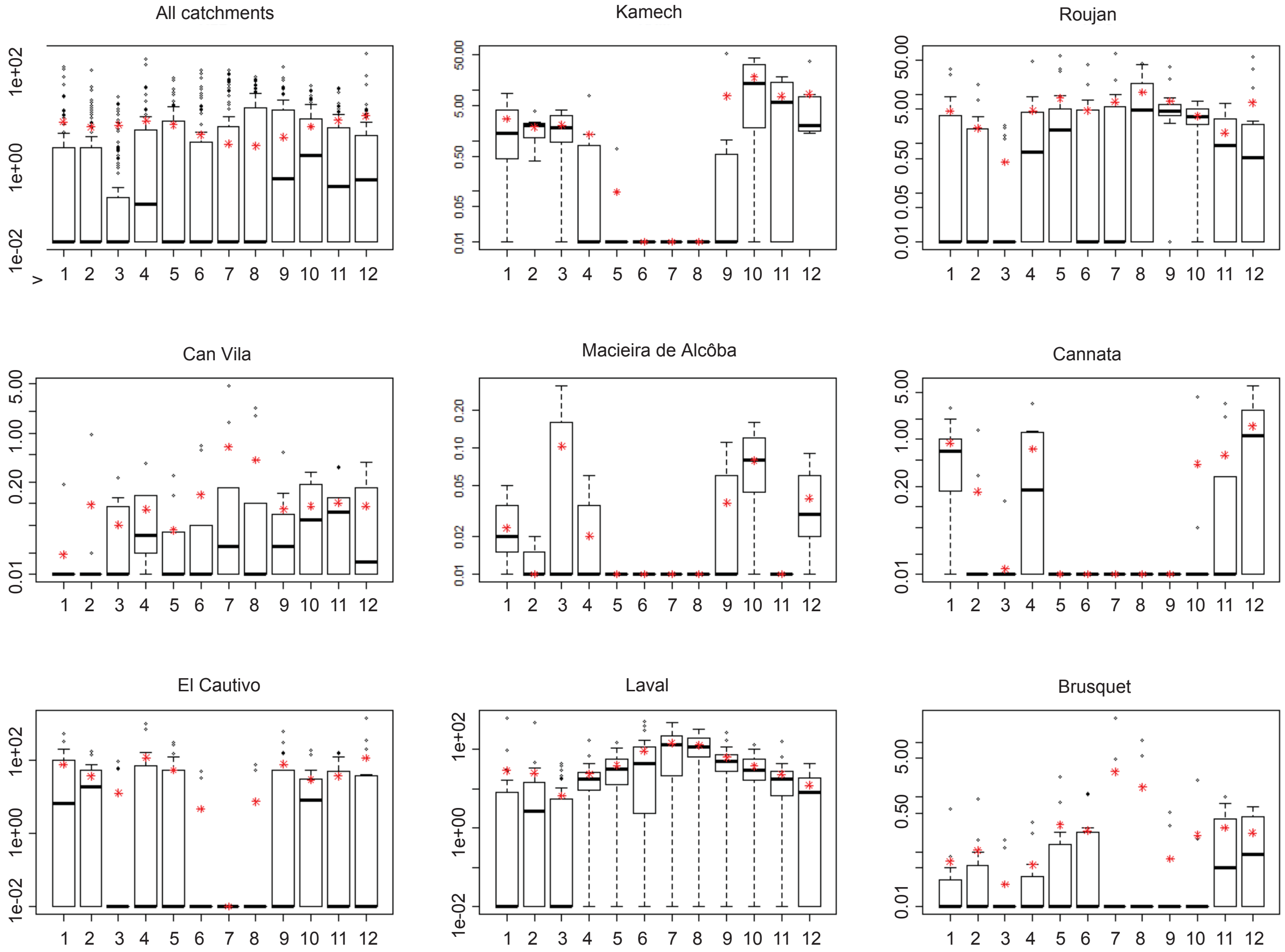
Cannata

El Cautivo

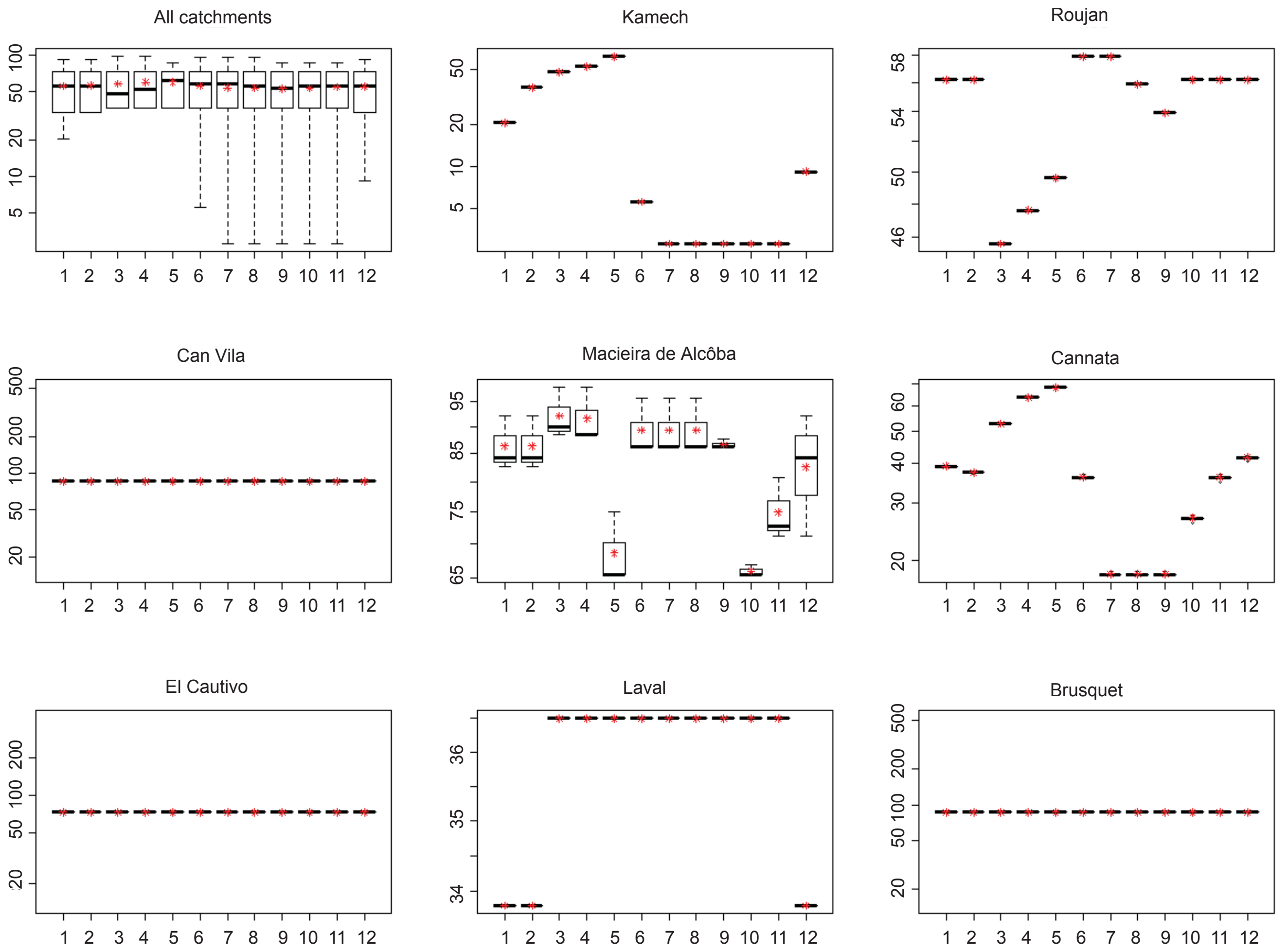
Laval

Brusquet

S5 Intra-annual variability of runoff (mm, y-axis). Months (1-January to 12-December) are on x-axis. 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Asterisk represents the monthly mean in each month (1-January to 12-December) and catchment. The values of runoff< 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the difference in y-axis scale.



S6 Intra-annual variability of sediment concentration (g/l, y-axis). Months (1-January to 12-December) are on x-axis. 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Asterisk represents the monthly mean in each month (1-January to 12-December) and catchment. The values of sediment concentration < 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the difference in y-axis scale.



S7 Intra-annual variability of vegetation cover (% area, y-axis). Months (1-January to 12-December) are on x-axis. 1st quartiles, medians and 3rd quartiles are plotted, whiskers represent 1.5 x interquartile range. Asterisk represents the monthly mean in each month (1-January to 12-December) and catchment. The values of vegetation cover < 0.01 were transformed to = 0.01 and were plotted using logarithmic scale. Please note the difference in y-axis scale.

S8 Inter-annual and intra-annual time compression: time in which ~ 50 % of total measured variable value was collected

	Percentages (%) of total duration of measurement period in which ~ 50 % of total measured variable value was collected Inter-annual / Intra-annual scale							
	Brusquet	Cannata	Can Villa	El Cautivo	Kamech	Laval	Macieira de Alcôba	Roujan
Rainfall	45 / 14	44 / 22	40 / 27	33 / 14	43 / 17	48 / 23	33 / 22	41 / 16
Runoff	18 / 26	22 / 7	40 / 13	17 / 4	29 / 5	41 / 17	33 / 22	24 / 3
Sediment yield	36 / 3	11 / 3	20 / 3	17 / 3	14 / 1	41 / 10	33 / 3	18 / 3
DEMP (Y/M)	11 / 132	9 114	10 / 120	18 / 216	7 / 84	29 / 348	3 /36	17 / 205

DEMP – duration of entire measurement period, Y-year, M-months