Brosinsky, A., Förster, S., Segl, K., López-Tarazón, J. A., Pique, G., Bronstert, A. (2014): Spectral fingerprinting: characterizing suspended sediment sources by the use of VNIR-SWIR spectral information. - *Journal of Soils and Sediments*, *14*, 12, pp. 1965—1981.

DOI: http://doi.org/10.1007/s11368-014-0927-z

ANALYSIS AND MODELLING OF SEDIMENT TRANSFER IN MEDITERRANEAN RIVER BASINS

Spectral fingerprinting: Characterising suspended sediment sources by the use of VNIR-SWIR spectral information

Arlena Brosinsky • Saskia Foerster • Karl Segl • José Andrés López-Tarazón • Gemma Piqué • Axel Bronstert

Arlena Brosinsky (□) • A. Bronstert
University of Potsdam, Institute of Earth and Environmental Science, Karl-Liebknecht-Str. 24-25, 14476 Potsdam, Germany
e-mail: arlena.brosinsky@gfz-potsdam.de

A. Brosinsky (□) • S. Foerster • K. Segl
GFZ German Research Centre for Geosciences, Section 1.4 Remote Sensing, Telegrafenberg, 14473 Potsdam, Germany

J. A. López-Tarazón
School of Natural Sciences and Psychology, Liverpool John Moores University, Byrom St, L3 3AF, UK

J. A. López-Tarazón • G. Piqué
Fluvial Dynamics Research Group, Department of Environment and Soil Sciences, University of Lleida, Alcalde Rovira Roure 191, 25198, Spain

G. Piqué
Catalan Institute for Water Research, Emili Grahit 101, 17003 Girona, Spain

(□) **Corresponding author:**
Arlena Brosinsky
Tel +49 (0) 331 288 1195
Fax +49 (0) 331 288 1192
e-mail: arlena.brosinsky@gfz-potsdam.de

Abstract

Purpose: Knowledge of sediment sources is a prerequisite for sustainable management practices and may furthermore improve our understanding of water and sediment fluxes. Investigations have shown that a number of characteristic soil properties can be used as "fingerprints" to trace back the sources of river sediments. Spectral properties have recently been successfully used as such characteristics in fingerprinting studies. Despite being less labour-intensive than geochemical analyses, for example, spectroscopy allows measurements of small amounts of sediment material (>60 mg), thus enabling inexpensive analyses even of intra-event variability. The focus of this study is on the examination of spectral properties of fluvial sediment samples to detect changes in source contributions, both between and within individual flood events.

Materials and methods: Sediment samples from three different origins were collected in the Isábena catchment (445 km²) in the central Spanish Pyrenees: 1) soil samples from the main potential source areas; 2) stored fine sediment from the channel bed once each season in 2011; and 3) suspended sediment samples during four flood events in autumn 2011 and spring 2012 at the catchment outlet as well as at several subcatchment outlets. All samples were dried and measured for spectral properties in the laboratory using an ASD spectroradiometer. Colour parameters and physically based features (e.g. organic carbon, iron oxide and clay content) were calculated from the spectra. Principal component analyses (PCA) were applied to all three types of samples to determine natural clustering of samples, and a mixing model was applied to determine source contributions.

Results and discussion: We found that fine sediment stored in the river bed seems to be mainly influenced by grain size and seasonal variability, while sampling location – and thus the effect of individual tributaries or subcatchments – seem to be of minor importance. Suspended sediment sources were found to vary between, as well as within, flood events; although badlands were always the major source. Forests and grasslands contributed little (<10%) and other sources (not further determinable) contributed up to 40%. The analyses further suggested that sediment sources differ among the subcatchments and that subcatchments comprising relatively large proportions of badlands contributed most to the four flood events analyzed.

Conclusions: Spectral fingerprints provide a rapid and cost-efficient alternative to conventional fingerprint properties. However, a combination of spectral and conventional fingerprint properties could potentially permit discrimination of a larger number of source types.

Keywords Isábena river • Mixing models • Northeast Spain • Sediment fingerprinting • Spectroscopy • Suspended sediment

1 Introduction

In addition to negative impacts that suspended sediments can have on water quality, as described by numerous studies (e.g. Owens et al. 2005; Walling 2005; Davis and Fox 2009; Poulenard et al. 2009), large amounts of suspended sediments also affect water quantity, as is the case in the Isábena catchment (Spain) investigated in this study. Suspended sediment concentrations at the Isábena outlet can exceed 350 g l^{-1} during flood events (López-Tarazón et al. 2009). Such high concentrations result in severe siltation problems in the Barasona reservoir, located at the catchment outlet below the confluence with the River Ésera. The reservoir was built in 1932 and enlarged in the 1970s to a capacity of 92 x 10^6 m^3 (López-Tarazón 2011). Despite sluicing in the late 1990s, the initial capacity has been reduced considerably, adversely affecting the mid-term reliability of water supply (Mamede 2008).

Knowledge of sediment provenance is a key factor in understanding sediment transport and delivery processes and thus a first step in the design of sustainable watershed management strategies (e.g. Walling 2005; Davis and Fox 2009; Navratil et al. 2012). Such strategies must target the primary sources in order to control sediment fluxes within the watershed (Mukundan et al. 2013). In the study catchment, field observations as well as modelling have indicated badlands to be the major sediment source (e.g. Fargas et al. 1997; Francke et al. 2008a; Alatorre et al. 2010; López-Tarazón et al. 2012). Badlands are defined as "areas of unconsolidated sediments or poorly consolidated bedrock, with little or no vegetation […] in an intensely dissected landscape" (Gallart et al. 2002). Lithology is a major factor for badland development and though they are commonly considered characteristic of dryland regions they also occur in more humid climates with high topographic gradients and intense rainstorms (Gallart et al. 2002). Despite badlands being considered as major sediment sources, significant changes in the colour of the suspended sediments have been observed between, and even within, runoff events, suggesting the influence of varying sources.

A direct approach to trace the origin of sediment is a method called fingerprinting. It is founded on the principal assumptions that: (1) potential sediment sources can be discriminated based on a set of characteristic properties ("fingerprints"); and (2) the comparison of these source characteristics with those of (suspended) sediment allow for determination of relative source contribution (Collins and Walling 2004). In the past 30 years, the source fingerprinting approach has been successfully applied as a research tool in many ecoregions around the world (e.g. Walling 2005; Davis and Fox 2009). However, the adaptation of the technique as a management tool is hampered due to several reasons. Most importantly, the choice of successful fingerprint properties is highly site-specific and the lack of general guidelines for pre-selection of parameters capable of tracing back sources can make the approach very time consuming and costly (e.g. Collins and Walling 2002). Thus, recent studies have focused on the testing of robust and inexpensive methods for the derivation of such properties (e.g. Gibbs 2008; Poulenard et al. 2009; Martínez-Carreras et al. 2010b). Consequently, spectroscopy was found to offer considerable potential for time-efficient and cost-effective measurements (Poulenard et al. 2009, 2011; Martínez-Carreras 2010a, 2010b, 2010c; Evrard et al. 2012; Legout et al. 2013; Brosinsky et al., this issue). In addition to being less labour intensive regarding laboratory analyses, spectroscopy offers the advantage of small sample size requirements (Martínez-Carreras et al. 2010a).

The aim of the current study is the interpretation of visible (VIS) to shortwave infrared (SWIR) spectroscopic data (0.35 – 2.5 µm) to examine the relative contributions from different sources and how these contributions change both between and within individual storm events. Therefore, potential source areas (1), as well as suspended sediments (2), and fine sediment stored in the channel bed (3) were collected and spectrally measured. Colour parameters and spectral features with relation to organic carbon, iron oxide and clay content were calculated from spectra and subsequently tested to meet a number of assumptions. Parameters meeting the assumptions were used in principal component analyses (PCA) for all three sample types (1-3) to determine natural clustering, and a mixing model was applied to suspended sediment samples to determine source contributions.

2 Study area

The Isábena River drains a 445 km² basin in the southern Pyrenees (Ebro catchment, NE Spain, just before entering the Barasona reservoir together with the Ésera River (Fig. 1). The Isábena catchment comprises five main subbasins: the Cabecera subbasin in the North (146 km², representing 33 % of the total catchment area), the Villacarli (42 km², 9 %) and Carrasquero (25 km², 6%) subbasins in the NW and Ceguera (28 km², 6 %) and the Lascuarre subbasin (45 km², 10 %) in the SE (Fig. 1). The remaining area drains directly into the Isábena River. Overall, the area is characterized by a rough terrain (450 m a.s.l. in the southern lowlands to 2700 m a.s.l. in the headwaters), resulting in a pronounced climatic and land cover gradient. The climate is of Mediterranean mountainous type with mean annual temperatures ranging between 14 °C (south) to 9 °C (north) and a mean annual precipitation of 450 mm (south) to 1600 mm (north) (Verdú 2003). Precipitation is of high spatial and temporal variability with maxima generally occurring in spring and autumn (López-Tarazón et al. 2010). Despite occasional gravel mining, the Isábena is an entirely unregulated river with a pluvial–nival runoff regime. Valero-Garcés et al. (1999) found that the major floods in the Ésera–Isábena basins are caused by late spring–early summer snow melt in combination with heavy rains, summer thunderstorms, and late autumn heavy rains. Frequent floods keep sediment transport rates at relatively high levels, with instantaneous suspended sediment concentrations occasionally attaining 350 g l^{-1} (López-Tarazón et al. 2009).

While valley bottoms are mainly used for agriculture, higher altitudes are dominated by shrubland (matorral), grassland, woodland (*Quercus* and *Pinus*) and bare soil and rock. Major land use changes that occurred over the past 50 years resulted in the abandonment of cultivated areas and subsequent revegetation, initiated by shrub species and followed by forest regrowth (e.g. Lasanta and Vicente-Serrano 2012).

The catchment is characterized by a heterogeneous lithology. Valero-Garcés et al. (1999) describe several WNW–ESE trending geologic units, i.e.: (1) the Axial Pyrenees composed of Paleozoic rocks (quartzites, limestone) with peaks above 3000 m a.s.l. in the north; (2) the Internal Ranges composed of Cretaceous and Paleocene sediments in the center; and (3) the Intermediate Depression, a relatively lowland area in the south of the catchment that is composed of Miocene continental sediment. The most important soil types developed in this area can be classified as shallow mineral soils (including regosols, leptosols and fluvisols) and soils with a considerable accumulation of organic matter, including kastanosems (Alatorre et al. 2010). There is high variability in soil colour that is most obvious in the agricultural fields, ranging from reddish brown to grayish and dark brown.

Valero-Garcés et al. (1999) describe several internal depressions formed upon highly erodible materials (marls, sandstones, and carbonates) that are located in the central part of the watershed. These areas with relatively high topographic gradients and moderate vegetation cover lead to the development of badlands. Despite representing <1 % of the total basin area (mainly in the Villacarli and Carrasquero subbasins), badlands are considered the most important sediment source in the catchment (e.g. Fargas et al. 1997; Francke et al. 2008a; Alatorre and Beguería 2009; López-Tarazón et al. 2012) with erosion rates estimated to exceed 550 t ha^{-1} yr^{-1} (Appel 2006). Although the topographic gradient is higher in the northern areas, lithology as well as higher vegetation cover (grassland, forest) reduce sediment production. In the southern areas, cultivated land predominates. While Valero-Garcés et al. (1999) suggest that the smaller topographic gradient seems to be reducing erosion, Alatorre et al. (2010) identify dryland crop areas as important contributors of suspended sediment yield.

The catchment has been subject to intensive hydrological studies over the past decade (e.g. Bronstert et al. this issue), resulting in a detailed understanding of hydrological and geomorphological processes and a favorable instrumentation situation, thus making it an ideal test site for innovative techniques.

3 **Material and methods**

3.1 Sampling and data overview

Field campaigns were conducted to collect samples from three different origins: 1) 152 soil samples were collected from the main potential source areas within the Isábena catchment; 2) a total of 48 samples of fine sediment stored in the main channel bed were collected at 14 cross sections once each season in 2011; and 3) suspended sediment samples from the river were collected during four flood events in autumn 2011 and spring 2012 at the catchment outlet (44 samples) as well as at several sub-catchment outlets (46 samples selected for analyses). The spatial location of sampling sites is shown in Fig.1, the temporal allocation of sediment samples (channel bed and suspended) with respect to discharge at the Capella gauge can be seen in Online Supplementary Material 1.

3.1.1 Source material sampling

Source material samples were collected during two campaigns in October 2010 and June 2011. Sampling sites were selected based on previous analyses of land use distribution (Ministerio de Medio Ambiente y Medio Rural y Marino (MARM) 2008), knowledge on erosion susceptibility (Fargas et al. 1997) and accessibility. All major land uses that potentially contribute to erosion in the Isábena catchment were sampled, namely agricultural land (covering 14 % of the catchment), forest (47 %), grassland (8 %) and shrubland (30 %) (Table 1). In addition, potential sources covering only small areas (< 1 %) but possibly contributing a high proportion of material were sampled, including badlands, unpaved roads and open slopes. Thereby, the distribution of sampling locations were considered to be spatially representative of all subcatchments. The number and details of samples collected are listed in Table 2.

Since soils in the study area are shallow with poorly developed diagnostic horizons (López-Tarazón 2011), and lithology is not very distinct and overall rather homogeneous in large parts of the catchment, emphasis was placed on a land use-based sampling strategy. However, care was taken to ensure that the distribution of sampling locations were spatially representative over all lithological units (Ministerio de Agricultura, Alimentación y Medio Ambiente). Sampling sites were chosen in close vicinity (< 100 m) to stream or river reaches to make sure the material will be easily transported to the river. From each site, five grab samples of easily erodible material (top 1-3 cm) were collected from a 5 m x 5 m area and well mixed. The location of sampling sites is shown in Fig. 1.

3.1.2 River sediment sampling

Suspended sediment samples were collected hourly during flood events by an ISCO automatic sampler (ISCO 3700, Teledyne, Lincoln, Nebraska, USA) at the Capella gauging station near the catchment outlet. The sampler was triggered by flow conditions (i.e., start sampling from a certain water level). Four of the events sampled were chosen to be analyzed and discussed in more detail in the present work, namely from (i) 24th/25th September 2011 (event A), (ii) 22nd March 2012 (event B), (iii) 3rd/4th June 2012 (event C) and (iv) 20th June 2012 (event D) (Table 3).

In addition, suspended sediment samples were collected near the outlets of the five main subcatchments described above, by means of ISCO samplers (ISCO 3700C, Teledyne). Again, the samplers were triggered by flow conditions and samples were collected in 15 minute to hourly intervals depending on the runoff behavior prevailing in the individual subcatchment (Table 3).

Furthermore, fine sediment stored within the bed of the Isábena main channel was sampled using the methodology developed by Lambert and Walling (1988). At 14 different cross-sections along the main channel, a metal cylinder of 50 cm in diameter and 60 cm height was carefully placed on the channel bed and slowly rotated to create a seal with the underlying gravel. The sampling area thus created was manually disturbed using a rod, resulting in re-suspension of stored fine sediment (for details see López-Tarazón et al. 2011). This procedure was repeated four times, once per season (namely, 25th February, 24th May, 26th July, and 1st December) in 2011; sampling was performed at exactly the same locations during all campaigns. The number and details of samples analyzed are listed in Table 4, and sampling locations are shown in Fig 1.

Sediment concentration of all samples was determined by settling of known volumes of higher concentration samples (approx. > 2 g l^{-1}) and filtering of lower concentration samples using 1.2 µm FILTER-LAB glass microfiber filters. Loose material was dried at 60 °C for > 24 hours or air dried for over one week and weighed; filters were weighed prior to material application, then dried at 60 °C for two to three hours or air dried for > 24 hours and reweighed.

3.1.3 Water discharge and rainfall measurements

Water stage was recorded in 15 minute intervals at the Capella gauging station by the Ebro Water Authorities (CHE) and later transformed into discharge using the calibrated stage–discharge rating curve developed by López-Tarazón et al. (2010). Rainfall was measured by tipping-bucket gauges operated by the University of Potsdam / GFZ Potsdam. There are one or two rain gauges installed per subcatchment, resulting in a total number of eight rain gauges representing rainfall distribution over the catchment area. Sampling locations are shown in Fig. 1.

3.2 Spectral measurements of source and sediment samples

Spectral reflectance data were collected using an Analytical Spectral Device (ASD) FieldSpec3 High-Res portable spectroradiometer (Analytical Spectral Device, INC., Boulder, Colorado, USA), acquiring 2151 bands in the 0.35 – 2.5 µm range of the electromagnetic spectrum at a true sampling interval of 1.4 nm in the VIS-NIR region (0.35 – 1.0 µm) and 2 nm in the SWIR region (1.0 – 2.5 µm). Relative reflectance was calculated automatically by using a white reference panel as standard (100 %).

Loose material was thoroughly mixed to provide homogeneous samples. Since suspended sediment samples were mainly < 63 µm, source material was sieved to 63 µm to minimize spectral variations resulting from differences in particle size composition between source and suspended sediment material (e.g. Walling 2005). Source and suspended sediment material was placed in shallow 5 cm x 5 cm plastic containers and oven dried at 60 °C for 24 hours prior to spectral measurements. Spectral readings were taken in a dark room facility (for details see Brosinsky et al. (this issue)). Four readings per sample were taken, with the sample rotated 90° after each reading to reduce illumination effects.

We detected spectral differences between loose material and material on filters that can partly be attributed to a loss in fine material (filter pore size 1.2 µm) and partly to alignment of sediment particles resulting in changes in reflectance behaviour. Thus, loose material and material retained on filters can both be used but the measurements should not be compared directly. While all soil and suspended sediment analyses were based on loose samples, there was not always enough material from resuspension samples. Thus, all resuspension samples were applied to glassfiber filters as described above for spectral measurements. In addition, some of the resuspension samples were much coarser than suspended samples collected by ISCOs; the resuspension samples were not sieved prior to spectral measurements.

3.3 Preprocessing and parameter calculation

Spectral readings per sample were averaged and smoothed using a Savitzky-Golay filter (Savitzky and Golay 1964). Then, red, green and blue (RGB) colour parameters were calculated from spectra by averaging values of spectral reflectance ranges corresponding to the blue, green and red Landsat bands (0.45 – 0.52 µm, 0.52 – 0.6 µm, and 0.63 – 0.69 µm, respectively) and multiplication with 255 to get 8-bit colour encoding (Viscarra Rossel et al. 2006). These RGB values were transformed to other colour space models using ColoSol software developed by Viscarra Rossel et al. (2006). All transformation algorithms are described in detail by Viscarra Rossel et al. (2006) and details on colour models are explained by Wyszecki and Stiles (1982).

Following the description by Bayer et al. (2012), features found in the previous literature to be diagnostic of physically based information on soil organic carbon, clay, iron and carbonate content were calculated. The selected spectral parameters can be divided into spectral indices and three feature types, namely curve features, hull features, and absorption features. Details on the calculation of parameters can be found in Chabrillat et al. (2011), Bayer et al. (2012) and Brosinsky et al. (this issue).

In total, a set of 98 colour and physically based soil reflectance parameters was calculated (see Brosinsky et al (this issue)). Since colour coefficients may be easily converted and all spectral features are potentially used in spectroscopy and soil science, they were all considered in subsequent analyses, although some of these parameters may be highly correlated (Viscarra Rossel et al. 2006; Martínez-Carreras et al. 2010c). In the following, the term “spectral parameter(s)” is used as a synonym for spectral fingerprint property, describing colour parameters and/or physically based reflectance features calculated as outlined above.

3.4 Test of assumptions

A number of fundamental assumptions of the fingerprinting procedure were tested in an attempt to limit uncertainty of sediment provenance assessment to a minimum. In recent studies, the potential non-conservativeness of tracer properties has been identified as a major concern, with key issues being particle size selective transport and tracer transformation (e.g. Koiter et al. 2013). For example, Smith and Blake (2014) found the relationships between these processes to be highly complex and discourage the use of correction factors. Thus, the problem of size selective transport was addressed by sieving all soil and suspended sediment material to < 63 µm (e.g. Martínez-Carreras 2010a; Mukundan et al. 2013; Smith and Blake 2014). Grain size analyses of a selection of sieved samples pointed to no enrichment or depletion effects. Secondly, although tracer transformation cannot be entirely excluded, it was addressed by limiting the analyses to spectral parameters whose values calculated from suspended sediment lie wholly in the range of those calculated from potential source samples (92 out of 98) (Smith and Blake 2014). The high number of parameters meeting this prerequisite indicates that any alteration effects may have been relatively small (Walden et al. 1997). Though spectroscopic measurements are sensitive to alterations during transport, such as reduction of iron or decomposition of organic matter, Legout et al. (2013) found changes in VIS spectra and colour parameters to remain < 10% when comparing original samples to samples immersed in a river for a maximum period of 63 days. Linear additivity of spectral properties was explicitly tested by comparing properties calculated from artificial mixture spectra to properties calculated from mixture spectra produced by a linear mixing algorithm (Brosinsky et al. this issue). Only 48 out of 92 parameters met this assumption and were used in subsequent procedures. Following Walling (2005), all remaining parameter values were scaled between 0 and 1 to ensure equal consideration of individual properties. A non-parametric Kruskal-Wallis H-test used to assess the existence of any significant interclass contrasts (Collins and Walling 2002) revealed that all 48 parameters were able to detect contrasts between the seven source types at the 95% confidence level.

3.5 Statistical analyses to assess natural clustering of samples

Principal component analyses (PCA) were performed on the 48 parameter source and sediment datasets to determine natural clustering of samples and to evaluate overall variability and potential overlap between classes (Poulenard et al. 2009). The PCA was applied on source and suspended sediment samples (Capella) together, providing an indication of how successful subsequent quantitative mixing modelling is likely to be (Walden et al. 1997). In addition, PCA was applied on suspended sediment from river samples only (Capella and subcatchments) in order to get an impression of sample clustering between and within individual runoff events.

Furthermore, a PCA was performed on the resuspended material data only, since, unlike all other samples, the resuspended material was retained on glassfiber filters. Therefore these data could not be directly compared to the suspended sediment or source samples which were not filtered. Thus, this analysis will provide only qualitative results on general changes or resemblances within the stored sediment and will not allow us to draw conclusions on source contributions or similarities with the suspended load collected during individual flood events. All PCA analyses were performed using The Unscrambler® X 10.2 software (CAMO Software AS., Oslo, Norway).

3.6 Mixing model analyses

Since previous PCA and discriminant function analyses (DFA) results calculated from source samples suggested confusion between forest and grassland samples, as well as between shrubland and arable land, road and open slopes (Brosinsky et al., this issue), the seven source types were aggregated into three source types for input to the mixing model; namely: badland; forest/grassland;

and others. Only 45 parameters passed the Kruskal-Wallis H-test for the three groups and were used for subsequent unmixing analyses.

Relative contributions of potential sources were estimated by comparing the fingerprint properties of the sediment samples with those of the potential sources using a multivariate mixing model; a detailed description of the model can be found in Brosinsky et al. (this issue). Errors between measured and estimated values were approximated using the non-negative least squares algorithm introduced by Lawson and Hanson (1974), where the best approximation is defined as the one minimizing the sum of squared differences between the measured data values and their corresponding modelled values. The model was restricted by the constraints that the source type contributions must all be non-negative and sum to 100%. Uncertainty associated with modelling results due to source heterogeneity was assessed by producing Gaussian distribution functions from the mean and standard deviation of each tracer property per source type (Martínez-Carreras et al. 2010a). The mixing model was run 10,000 times, choosing source information randomly from the Gaussian distribution functions, thus allowing source describing properties to vary in each solution. This replicate random sampling provides confidence estimates for the modelled contribution results by permitting the calculation of percentiles. The model was implemented using in-house software (ANSI-C).

4 Results

4.1 Principal component analyses – natural clustering of samples

4.1.1 Resuspension samples

Figure 2 shows PCA score plots of all samples of resuspended channel bed sediment (first three components). Generally, the heterogeneity of the samples reflected in the first three components is rather high. The first three components together explain 88 % of the variance (44 %, 35 % and 9 %, respectively), and seven components explain 98 % of the total variance.

A scatterplot of the first two components (Fig. 2a), in general, seems mainly influenced by grain size. Though grain size distribution was not analyzed in particular, visual inspection revealed that some filters contained very fine material while other filters contained coarser material and/or sand grains. The majority of finer samples cluster in the upper right corner of the scatter plot while the coarser samples are mainly distributed to the lower left. Samples from February (I) and July (III) seem generally finer than samples from May (II) and December (IV) but this is inconsistent and not true for all sections sampled (Fig. 2b).

Fig. 2c again depicts the first two components, where the samples are identified by the 14 sections they were collected from. Both samples S1 and two of the three S2 samples cluster well away from the other samples and rather close together. Then, a rough zonation trend can be observed for the upstream sections with samples from S3 situated to the right of the plot and samples from S4, S5, and S6 distributed further to the left. Samples from S7 and S8 are again distributed further to the right. With the exception of S13, samples S9 to S14 are very heterogeneous. The observed "zonation trend" is not consistent with either season or grain size variation.

Figure 2d shows the second and third PC, that mainly seem to reflect seasonal variation. Thus, samples collected in May (II) cluster between the samples from February (I) and December (IV) while samples collected in July (III) are separate. As in the first two component plots, samples from S1 and S2 are somewhat separate. Apart from that, the sampling section does not seem to have a detectable influence on any of the first seven components.

4.1.2 Suspended sediment samples

Figure 3 shows several PCA score plots of source and suspended sediment samples (first two components). Overlap between samples from different land use classes is evident from Fig. 3a, whereas badland and forest/meadow samples form somewhat separate clusters and all other land uses seem not to differentiate. The Capella suspended sediment samples plot within the catchment source materials, between badland and road, agricultural and shrubland samples. Compared to source material samples, sediment material is very homogeneous. However, a distinction between individual events is clearly evident.

No grouping is visible with respect to the source samples' subcatchment of origin (see Fig. 3b), with the exception of the northernmost subcatchment (Cabecera), which is underlain by different substrates than the more southern subcatchments. However, no grouping by lithology is evident from the PCA scatter plots (results not shown).

Although Fig. 3b does not reveal clustering of source samples by subcatchment, Fig. 3c shows a clear distinction of all suspended sediment samples by subcatchment (Capella and subcatchment samples). A distinct clustering of most samples into the four subcatchments of their origin is evident. Due to a lack of sampling material, the northernmost subcatchment (Cabecera) is missing from this analysis. Samples collected near the basin outlet (Capella) plot completely in the center, with a shift towards the Villacarli and Carrasquero subcatchments.

Figure 3d shows the first and second PC of a PCA performed on Capella sediment samples only. Despite being generally much more homogeneous than source samples, the distinction between individual events evident from Fig. 3a is even more pronounced when looking at the sediment samples separately. While events B and C plot closely together, most samples from event D are clearly different. Intra-event variability is mainly visible from PC-2. Event A contains most samples and is most heterogeneous, with large variability along both first PCs, with some samples resembling events B, C and D and other samples being obviously of different composition. Therefore, it is the early (samples A1-A4) and later (samples A15-A22) stages of the event that more closely resemble the other events sampled at Capella while, the middle (samples A7-A14) and end (samples A23 and A24) stages seem most different.

4.2 Application of mixing model to suspended sediment samples

Source tracing results of four events sampled at Capella from September 2011 to June 2012 including information on runoff and suspended sediment concentration (SSC) are shown in Fig. 4 to Fig. 7. Details on precipitation (sum, average, intensity, duration) and a rough characterization of distribution over the subcatchments can be found in Table 5. Figure 4 provides evidence of the high intra-event variability from 24th to 25th September 2011. Runoff shows a pronounced peak with steep rising and falling limbs and a much smaller second peak about 12 hours after the first peak. The peak runoff was 33 $m^3\ s^{-1,}$ and maximum SSC was 35 $g\ l^{-1}$ at the peak and decreased quickly. Precipitation during the event was of short duration (< 3 hours) and high intensity (up to 40 $mm\ h^{-1}$) while the average amount of rainfall was moderate (40 mm). Overall, the samples comprise high proportions of badland material (mean 58 to 80 %). During the fallings limbs, other sources became more dominant (on average up to mean 42 %) while the contribution of forest/grassland was generally low (mean 0 to 11 %).

For the three events sampled in 2012, sample availability as well as intra-event variability, were lower (Fig. 5-7). The event from 22nd March 2012 is characterized by a much broader runoff peak with a steep rising and a shallow falling limb (Fig. 5). Peak runoff was 28 $m^3 s^{-1}$ and maximum SSC was 19 g l^{-1} at the peak and decreased quickly. Precipitation during the event was of longer duration (> 15 hours) and of lower intensity (< 20 mm h^{-1}) than the September event while the average amount of rainfall was higher (70 mm). The contribution of badland material to suspended sediment was estimated to exceed 80 % for all but the first sample and forest/grassland contribution was low (< 4 %) for all samples.

The event from 3rd to 4th June, 2012 is again characterized by a steep runoff peak (Fig. 6) yielding a maximum of only 19 $m^3 s^{-1}$. However, SSC was high, with a maximum of 68 g l^{-1} during the peak. Precipitation during the event was again of short duration (< 3 hours) and partly of very high intensity (10-40 mm h^{-1}, in the Villacarli subcatchment up to 105 mm h^{-1}) while the average amount of rainfall was low (25 mm). Mean estimated contribution of badland material to suspended sediment varied between 78 and 85 %, and forest/grassland contribution was again low (< 5 %) for all samples.

As for the event sampled in March 2012, the event from 20th June 2012 was characterized by a broad runoff peak with shallow rising and falling limbs (Fig. 7). Runoff and SSC were low yielding maxima of 15 $m^3 s^{-1}$ and 5.5 g l^{-1}, respectively. Precipitation during the event was characterized by several short low intensity – low amount events followed by a longer (> 12 hours) event of low intensity (< 20 mm h^{-1}), while the average amount of rainfall was moderate (40 mm). The mean estimated contribution of badland material to suspended sediment varies between 68 and 81 %, and the contribution increased with the rising and decreased with the falling limb. The forest/grassland contribution was estimated to below (< 5 %) for all but the last sample, where this source was estimated to account for 20 %. Other sources were estimated to contribute 12 to 26 %.

5 Discussion

5.1 Principal components analyses – natural clustering of samples

5.1.1 Resuspension samples

The PCA performed on resuspended sediment samples indicates that spectral reflectance of the samples was mainly influenced by variations in grain size as well as seasonal variations. Since seasonal variations are not completely identical with grain size variations there must be other/further influencing factors such as source contribution variations or variations in storage and transition behaviour of the River Isábena (Piqué et al. this issue). Samples collected at sections S1 and S2, upstream of the Cabecera outlet, were found to differ from most other samples. Apart from that, a lot of heterogeneity was found in the samples within, as well as between, sampling sections, indicating that if there is a pattern at all it is superimposed on other factors. This is consistent with results of López-Tarazón et al. (2011) and Piqué et al. (this issue) who analyzed the amount of stored sediment in the lower Isábena reaches (S11 – S14) for the periods 2007-2008 and 2011-2012, respectively. They found considerable variations in sediment storage along the main channel, identifying an annual cycle of sediment production and transfer downstream. However, it is difficult to capture this pattern since sediment accumulation is not linear in time and space, but is largely influenced by spatial and temporal (i.e. seasonal) heterogeneity in the catchment's hydrology and sediment production in the badlands.

5.1.2 Suspended sediment samples

Results of the source and suspended sediment PCAs can be interpreted as indicators of the feasibility of the spectral fingerprinting approach (Walden et al. 1997). The fact that all suspended sediment samples plot within the margins of potential source samples may be seen as an indicator that all major sources have been sampled and that changes in suspended sediments which may have occurred during transport and storage have been relatively small (Walden et al. 1997).

A distinct pattern of source samples by land use was found, however, no clustering was evident by lithological units, indicating that (in this catchment) land use practices may supercede soil type or lithological differences. The plotting of suspended sediment samples close to badland and unpaved road, agricultural and shrubland source samples, and further away from forest and grassland source samples, confirm the mixing model results, which suggest: a high contribution of badland materials in all samples; a medium to high contribution of other materials; and a low contribution from forest/grassland materials. Compared to source material samples, the heterogeneity of sediment material is very limited. However, a distinction between individual events is evident, confirming changes in source contributions between the events as suggested by the mixing model. Samples estimated to contain a higher proportion of badland materials (events B and C, some samples of events A and D) plot closer to badland source samples, while samples containing higher shares of other materials (event A) plot closer to unpaved road, open slope, agricultural and shrubland source samples.

There is no clustering of source samples by subcatchment but there is a clear distinction in the suspended sediment samples from the subcatchments by origin, indicating major differences of source contributions in individual subcatchments. Unfortunately, the number of source samples per subcatchment is limited, constraining a subcatchment-based fingerprinting approach. Samples collected near the basin outlet (Capella) plot in the center of the subcatchment sediment samples and thus seem to represent mixtures of the subcatchment's materials, with higher contributions from the Villacarli and Carrasquero subcatchments. This is consistent with the results of other studies undertaken in the area, which identified Villacarli as a major contributor for the same (Francke et al. this issue) and other study periods (Francke et al. 2008a, 2008b; Lopéz-Tarazón et al. 2012). However, Lopéz-Tarazón et al. (2012) identified Lascuarre as the second most important sediment source, indicating that there may be major changes in spatial source contribution between different years/study periods. In addition, analyses of resuspension samples indicate that tributaries not attributed to any subcatchment (i.e. S6, S7, S9, S11-S14) may cause substantial heterogeneity and thus contribute to sediment collected at the catchment outlet.

5.2 Mixing model

The mixing model results are consistent with the PCA results in terms of source ascription, suggesting that contribution estimates are reliable (Walden et al. 1997). Previous experiments on artificial laboratory mixtures where source contributions were known revealed high levels of uncertainty (Brosinsky et al. this issue), thus suggesting reliance on the general ascription of source contributions but not on exact values. However, when comparing the suspended sediment mixing model results to artificial laboratory unmixing results it is evident that unmixing results obtained in the present study fall within the ranges that seemed reliable in the previous, controlled study (i.e. Brosinsky et al. this issue) using artificial mixtures (> 60 % badland, < 40 % others, < 20 % forest/grassland).

Overall, although badlands were found to be the major contributing sources to all samples analyzed, there are differences between, as well as within, events. Rainfall is distributed irregularly over the catchment and runoff response was found to be highly variable (e.g. López-Tarazón et al. 2010), resulting in differences in the occurrence of floods at the subcatchment level and in the production of secondary SSC peaks (López-Tarazón et al. 2012). Differences in precipitation (short duration/high intensity around 24th/25th September and 3rd/4th June vs. long duration/low intensity around 22nd March and 20th June) caused differences in runoff behavior. Whereas the runoff peak was very pronounced with steep limbs in September and early June, it was a lot broader in March and late June. The SSC was found to be generally lower in the two broad peak events, whereas it was found to be extremely low in the 20th June event. This is likely due to material depletion after the event from 3rd/4th June, where SSC exceeded 60 g l^{-1}. Material availability may also be the explanation for the differences between events B and D which, due to similar rainfall and runoff characteristics, were expected to be of more similar composition. However, mixing model as well as PCA analyses suggest a greater similarity between events B and C, whereas samples from event D resemble first peak/early falling limb and the later samples of event A. No concurrent explanation was found on the changes within the very long event A. Samples from the late stages of the first falling limb of event A are unique in their low badland/high other sources contribution as compared to the other events sampled, which again may be due to the long duration of the event and thus sediment exhaustion. Samples taken during the second, smaller peak largely resemble events B and C. Together with the occurrence of the second runoff and SSC peak, this indicates that a local rainburst may have led to the delayed contribution of a source, tributary or subcatchment.

This leads to the limitations of the fingerprinting technique, which is capable only of providing information on the ultimate sediment source and not the proximal one; sediment stored from previous events will be identical to sediment arriving at the sampling location at the same time from the ultimate source (Parsons 2012). Furthermore, mixing models do not consider the travel time of sediment from source to sampling point. Thus, differences in travel time arising, for example, from differences in particle size or source distance in larger catchments, can invalidate the analysis of spatial origin (Parsons 2012) and impede interpretation of changes in source type contribution.

However, the overall suggestion of badland sources being the main contributors meets the general expectation for this catchment (e.g. Valéro-Garcés et al. 1999; Alatorre et al. 2010). There are no analyses specifying the proportion of badland material in suspended sediment. Nevertheless, previous studies found badland erosion rates to be very high with specific sediment yields exceeding

6200 t km^{-2} for a three month study period (Francke et al. 2008a). In addition, Francke et al. (2008a, 2008b) calculated suspended sediment yield of the Villacarli subcatchment – the subcatchment with highest portion in badlands (6 % of the area) – to account for about 45 % of the yield measured at the catchment outlet from September to December 2006. López-Tarazón et al. (2012) estimated Villacarlis' suspended sediment contributions to vary between 61 % and 27 % for the study periods 2007-2008 and 2008-2009, respectively. Forest and grassland sources contributed little to the samples analyzed in the current study, which was also expected since the soil is predominantly well protected by high vegetation cover. Unfortunately, the aggregated "other" sources could not be analyzed in more detail. Mukundan et al. (2012) discuss a catchment size of < 250 km² as the maximum scale at which fingerprinting is likely to be meaningful. Collins et al. (1998) state < 500 km² appropriate for source type fingerprinting, while increasing source heterogeneity in larger catchments could make source type fingerprinting less successful. A combination of spectral with classic fingerprinting properties such as geochemistry, mineral magnetism or radionuclides, as proposed by Martínez-Carreras et al. (2010a), could potentially provide a deeper understanding of the contribution of sources classified as "others" in this study.

Though differences between source contributions to different events were detected, no obvious seasonal variation was found. Instead, sediment availability seems to play a major role in the Isábena catchment. This is consistent with findings of López-Tarazón et al. (2010), who found that while there was no correlation between rainfall intensity and SSC, sediment availability in badlands and sediment storage in the channels influence the river's sedimentary response. López-Tarazón et al. (2012) found sediment delivery ratios of 90 %, indicating that large parts of the sediment mobilized in the catchment is easily transported to the outlet. However, sediment storage values in the Isábena main channel were estimated by López-Tarazón et al. (2011, 2012) to range from an average of 5 % of the annual total load to up to 55 % during certain periods Thus, they conclude that the fine-grained sediment stored in the channel can represent an important factor in controlling the suspended sediment dynamics.

6 Conclusions

The focus of this study was on the examination of spectral parameters for changes in sediment storage over the seasons and in suspended sediment, both within and between flood events. Results suggest that variability in stored fine sediment is most likely due to grain size and seasonal variation. Apart from the two uppermost sampling sections, no clear trends by sampling location were observed. Overall, the influence of inter-storm and/or seasonal variation on storage and transition behaviour of the Isábena seems to be much greater than the influence of sampling location and thus, for example, the influence of individual tributaries or subcatchments.

However, regarding suspended sediment, considerable variability was detected between subcatchments as well as in source type contribution, both between and within individual runoff events. Badlands, with a total aerial fraction cover of <1%, were found to be the major contributing sources with values of 60 – 80 %. Other sources, covering 45% of the study catchment, contributed up to ~40 % and forest/grasslands usually contributed < 10 % despite covering 54% of the study area. This is consistent with expectations based on field observations and previous studies. Unfortunately, it was not feasible to trace the aggregated “other sources” in more detail by this spectral approach. The PCA further suggest that the Villacarli and Carrasquero subcatchments contribute most material to the flood events sampled, and that suspended sediment sources are very different in the subwatersheds.

The results of this study point to badlands as the major sources of suspended sediment, thus management actions should focus on controlling sediment production from these areas. While García-Ruiz et al. (2013) think that more studies are needed to understand the evolution and functioning of badland ecosystems and that little can be done to prevent sediment export, Lee et al. (2013) demonstrate successful application of erosion control measures on previously bare badland structures developed on steep mudstone slopes in Taiwan. On studying Italian badlands that have become overgrown in recent years, Bierbaß et al. (2014) found that vegetation plays a key role in altering soil properties, resulting in more stable slope conditions. However, considering that reservoir siltation rather than loss of surface soil is the main problem in the study catchment, trapping material in or near the outlet of badlands, at the place of production, might be a more economically feasible option. Morgan (2005) describes measures such as siltation fences and artificial sedimentation ponds – capturing suspended sediment and allowing clearer runoff to flow – as suitable (temporary) measures. These might be adapted for use in badland areas. Nevertheless, for sustainable management, other sources of suspended sediment – which were found to contribute up to 40% – should not be neglected.

Overall, spectral fingerprints were found to provide a rapid, cost-efficient and non-destructive alternative to classic fingerprint properties. In the future, it is planned to compare the results of this spectral fingerprinting approach with “classic” fingerprinting based on geochemistry/radionuclides using the same samples. Thereby, a composite of spectral and classic properties may enable discrimination of other sources which could not be determined in this study. In addition, it would be of interest to study in more detail the sediment sources within the various subcatchments.

Acknowledgments This research was carried out within the project “Generation, transport and retention of water and suspended sediments in large dryland catchments: Monitoring and integrated modeling of fluxes and connectivity phenomena” funded by the Deutsche Forschungsgemeinschaft (DFG). The 4th and 5th authors were supported by the SCARCE-CONSOLIDER project (ref. CSD2009-00065) funded by the Spanish Ministry of Economy and Competitiveness. The authors would like to thank Arne Brauer, Benjamin Kayatz, Iris Kleine and Charlotte Wilczok from the University of Potsdam for their support of field work and Stefan Lips and Heide Kraudelt for their support of laboratory measurements. The authors also wish to thank the Ebro Water Authorities for permission to install the measuring equipment at the Capella gauging station and for providing hydrological data.

References

Alatorre LC, Beguería S (2009) Identification of eroded areas using remote sensing in a badlands landscape on marls in the central Spanish Pyrenees. Catena 76:182–19

Alatorre LC, Beguería S, García-Ruiz JM (2010) Regional scale modeling of hillslope sediment delivery: A case study in the Barasona Reservoir watershed (Spain) using WATEM/SEDEM. J Hydrol 391:109–123

Appel K (2006) Characterisation of badlands and modelling of soil erosion in the Isábena watershed, NE Spain. Diploma Thesis, University of Marburg, Germany

Bayer A, Bachmann M, Müller A, Kaufmann H (2012) A comparison of feature-based MLR and PLS regression techniques for the prediction of three soil constituents in a degraded South African ecosystem. Appl Environ Soil Sci Article ID 971252

Beven K, Binley A (1992) The future of distributed models: model calibration and uncertainty prediction. Hydrol Process 6:279-298

Bierbaß P, Wündsch M, Michalzik B (2014): The impact of vegetation on the stability of dispersive material forming biancane badlands in Val d'Orcia, Tuscany, Central Italy. Catena 113: 260-266

Bronstert A, de Araújo JC, Batalla RJ, Cunha Costa A, Francke T, Foerster S, Guentner A, López-Tarazón JA, Mamede GL, Medeiros PH, Mueller EN, Vericat D (this issue) Process-based modelling of erosion, sediment transport and reservoir siltation in mesoscale semi-arid catchments (this issue)

Brosinsky A, Foerster S, Segl K, Kaufmann C, Bronstert A (this issue) Spectral sediment fingerprinting: Source discrimination and contribution modelling of artificial mixtures based on VNIR-SWIR spectral properties. J Soils Sediments (this issue)

Chabrillat S, Eisele, A, Guillaso S, Rogaß C, Ben-Dor E, Kaufmann H (2011) HYSOMA: An easy-to-use software interface for soil mapping applications of hyperspectral imagery. 7th EARSeL SIG Imaging Spectroscopy workshop, Edinburgh, Scotland

Collins AL, Walling DE, Leeks GJL (1998): Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. Earth Surf Process Landforms 23:31-52

Collins AL, Walling DE (2002) Selecting fingerprint properties for discriminating potential suspended sediment sources in river basins. J Hydrol 261:218-244

Collins AL, Walling DE (2004) Documenting catchment suspended sediment sources: problems, approaches and prospects. Prog Phys Geogr 28:159-196

Davis CM, Fox JF (2009) Sediment fingerprinting: review of the method and future improvements for allocating nonpoint source pollution. J Environ Eng 135:490-504

Evrard O, Poulenard J, Némery J, Ayrault S, Gratiot N, Duvert C, Prat C, Lefèvre I, Bonté P, Esteves M (2013) Tracing sediment sources in a tropical highland catchment of central Mexico by using conventional and alternative fingerprinting methods. Hydrol Process 27:911-922

Fargas D, Martinez-Casasnovas J, Poch R (1997) Identification of critical sediment source areas at a regional level. Phys Chem Earth 22:355-359

Francke T, López-Tarazón JA, Vericat D, Bronstert A, Batalla RJ (2008a) Flood-based analysis of high-magnitude sediment transport using a non-parametric method. Earth Surf Process Landforms 33:2064-2077

Francke T, López-Tarazón JA, Schröder B (2008b): Estimation of suspended sediment concentration and yield using linear models, random forests and quantile regression forests. Hydrol Process 22:4892–4904

Francke T et al (this issue) Analysis of runoff, sediment dynamics and sediment yield of subcatchments in the highly erodible Isábena catchment, Central Pyrenees. J Soils Sediments (this issue)

Franks SW, Rowan JS (2000) Multi-parameter fingerprinting of sediment sources: Uncertainty estimation and tracer selection. In: Bentley LR et al (eds) Computational Methods in Water Resources. Balkema, Rotterdam, The Netherlands, pp 1067-1074

Gallart F, Solé A, Puigdefábregas J, Lázaro R (2002) Badland Systems in the Mediterranean. In: Bull LJ, Kirkby MJ (eds) Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels. John Wiley and Sons, Ltd, Chichester, UK

García-Ruiz JM, Nadal-Romero E, Lana-Renault N, Beguería S (2013) Erosion in Mediterranean landscapes: Changes and future challenges. Geomorphology198: 20-36

Gibbs MM (2008) Identifying source soils in contemporary estuarine sediments: a new compound-specific isotope method. Estuar Coast 31:344–359

Koiter AJ, Owens PN, Petticrew EL, Lobb DA (2013) The bahavioural characteristics of sediment properties and their implications for sediment fingerprinting as an approach for identifying sediment sources in river basins. Earth Sci Reviews 125:24-42

Lambert CP, Walling DE (1988) Measurements of channel storage of suspended sediment in a gravel-bed river. Catena 15:65–80

Lasanta T, Vicente-Serrano SM (2012) Complex land cover change processes in semiarid Mediterranean regions: An approach using Landsat images in northeast Spain. Remote Sens Environ 124:1-14

Lawson CL, Hanson RJ (1974) Solving Least Squares Problems. Englewood Cliffs, Prentice-Hall, 340 pp

Lee D-H, Chen P-Y, WU J-H, Chen H-L, Yang Y-E (2013): Method of mitigating the surface erosion of a high-gradient mudstone slope in southwest Taiwan. Bull Eng Geol Environ 72: 533-545

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. J Soils Sediments 13:1478-1492

López-Tarazón JA, Batalla RJ, Vericat D, Francke T (2009) Suspended sediment transport in a highly erodible catchment: The River Isábena (Southern Pyrenees). Geomorphology 109:201-22

López-Tarazón JA, Batalla RJ, Vericat D, Balasch JC (2010) Rainfall, runoff and sediment transport relations in a mesoscale mountainous catchment: the River Isábena (Ebro basin). Catena 82:23-3

López-Tarazón JA (2011) The sediment budget of a highly erodible catchment. The river Isábena (Ebro basin, Central Pyrenees). Dissertation, University of Lleida, Spain

López-Tarazón JA, Batalla RJ, Vericat D (2011) In-channel sediment storage in a highly erodible catchment: the River Isábena (Ebro Basin, Southern Pyrenees). Geomorphology 55:365-382

López-Tarazón JA, Batalla RJ, Vericat D, Francke T (2012) The sediment budget of a highly dynamic mesoscale catchment: The River Isábena. Geomorphology 138:15–2

Mamede GL (2008) Reservoir Sedimentation in Dryland Catchments: Modelling and Management. Dissertation, University of Potsdam, Germany

Martínez-Carreras N, Udelhoven T, Krein A, Gallart F, Iffly J, Ziebel J, Hoffmann L, Pfister L, Walling DE (2010a) The use of sediment colour measured by diffuse reflectance spectrometry to determine sediment sources: Application to the Attert river catchment (Luxembourg). J Hydrol 382:49-63

Martínez-Carreras N, Krein A, Udelhoven T, Gallart F, Iffly JF, Hoffman L, Pfister L, Walling DE (2010b) A rapid spectral-reflectance based fingerprinting approach for documenting suspended sediment sources during storm runoff events. J Soil Sediments 10:400-413

Martínez-Carreras N, Krein A, Gallart F, Iffly JF, Pfister L, Hoffmann L, Owens PN (2010c) Assessment of different colour parameters for discriminating potential suspended sediment sources and provenance: A multi-scale study in Luxembourg. Geomorphology 118:118-129

Ministerio de Agricultura, Alimentación y Medio Ambiente/Confederación hidrográfica del Ebro (no date): Geología Dominio Sinclinal de Tremp 1:50,000

Ministerio de Medio Ambiente y Medio Rural y Marino (MARM) (2008) Mapa de cultivos y aprovechamientos 1:50,000

Morgan RPC (2005) Soil Erosion and Conservation. Third Edition. Blackwell Publishing Ltd, Oxford, UK, 304 pp

Motha JA, Wallbrink PJ, Hairsine PB, Grayson RB (2003) Determining the sources of suspended sediment in a forested catchment in southeastern Australia. Water Resour Res 39:1056

Mukundan R, Walling DE, Gellis AC, Slattery MC, Radcliffe DE (2012) Sediment source fingerprinting: transforming from a research tool to a management tool. J Amer Water Resour Assoc 48:1241-1257

Navratil O, Evrard O, Esteves M, Legout C, Ayrault S, Némery J, Mate-Marin A, Ahmadi M, Lefèvre I, Poirel A, Bonté P (2012) Temporal variability of suspended sediment sources in an alpine catchment combining river/rainfall monitoring and sediment fingerprinting. Earth Surf Process Landforms 37:828-846

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA (2005) Fine-grained sediment in river systems: Environmental significance and management issues. River Res Applications 21:693–717

Parsons A (2012) Interactive comment on "Influence of basin connectivity on sediment source, transport, and storage within the Mkabela Basin, South Africa" by J. R. Miller. Hydrol. Earth Syst Sci Discuss 9:C4345–C4347

Piqué G, López-Tarazón JA, Batalla RJ (this issue) Variability of in-channel sediment storage in a river draining highly erodible areas (the Isábena, Ebro Basin). J Soils Sediments (this issue)

Poulenard J, Perrette Y, Fanget B, Quetin P, Trevisan D, Dorioz JM (2009) Infrared spectroscopy tracing sediment sources in a small rural watershed (French Alps). Sci Total Environ 407:2808-2819

Poulenard J, Legout C, Némery J, Bramorski J, Navratil O, Douchin A, Fanget B, Perrette Y, Evrard O, Esteves M (2012) Tracing sediment sources during floods using Diffuse Reflectance Infrared Fourier Transformed Spectrometry (DRIFTS): A case study in a highly erosive mountainous catchment (Southern French Alps). J Hydrol 414-415:452-462

Rowan JS, Goodwill P, Franks SW (2000) Uncertainty estimation in fingerprinting suspended sediment sources. In: Foster IDL (ed) Tracers in Geomorphology. John Wiley & Sons Ltd., Chichester, UK, pp 279-290

Savitzky A, Golay MJ (1964) Smoothing and differentiation of data by simplified least square procedures. Anal Chem 36:1627–1639

Small IF, Rowan JS, Franks SW, Wyatt A, Duck RW (2004) Bayesian sediment fingerprinting provides a robust tool for environmental forensic geoscience applications. Geological Society of London, Special Publications 232:207-213

Smith HG, Blake WH (2014) Sediment fingerprinting in agricultural catchments: A critical re-examination of source discrimination and data corrections. Geomorphology 204:177-191

Valero-Garcés BL, Navas A, Machin J, Walling D (1999) Sediment sources and siltation in mountain reservoirs: a case study from the Central Spanish Pyrenees. Geomorphology 28:23-41

Verdú JM (2003) Análisis y modelización de la respuesta hidrológica y fluvial de una extensa cuenca de montaña mediterránea (río Isábena, Pre-Pirineo). Dissertation, University of Lleida, Spain

Viscarra Rossel RA, Minasny B, Roudier P, McBratney AB (2006) Colour space models for soil science. Geoderma 133:320-337

Walden J, Slattery MC, Burt TP (1997) Use of mineral magnetic measurements to fingerprint suspended sediment sources: approaches and techniques for data analyses. J Hydrol 202:353-372

Walling DE (2005) Tracing suspended sediment sources in catchments and river systems. Sci Total Environ 344:159-184

Wyszecki G, Stiles WS (1982) Color Science: Concepts and Methods, Quantitative data and Formulae. Second Edition, Wiley, New York, USA

Tables

Table 1: Main physical characteristics of the study catchments, Isábena basin, Spain

Catchment	Area (km²)	Min. altitude (m)	Max. altitude (m)	Main lithology	Land use			
					cultivated	grassland	shrubland	forest
Cabecera	145	827	2745	limestones, conglomerates, quartzite	< 1	20	33	45
Villacarli	41	836	2366	marls, limestones	5	12	28	44
Carrasquero	25	728	1539	marls, limestones, sandstones	13	2	36	49
Ceguera	29	606	1314	sandstones	13	< 1	32	54
Lascuarre	44	552	1139	sandstones	30	< 1	15	55
Con-Isábena	160	450	1739	sandstones	24	< 1	31	44

Table 2: Number of samples collected from potential suspended sediment sources per subcatchment

Catchment	Area [km²]	Number of samples							
		cultivated	grassland	shrubland	forest	badland	open slope	road	total
Cabecera	145	1	10	7	6	-	-	3	**27**
Villacarli	41	3	1	5	4	6	1	1	**21**
Carrasquero	25	3	1	4	2	4	1		**15**
Ceguera	29	4		3	6	1	4	2	**20**
Lascuarre	44	8	1	10	5	-	8	3	**35**
Con-Isábena	160	8	3	7	7	3	5	1	**34**
Total		**27**	**16**	**36**	**30**	**14**	**19**	**10**	**152**

Table 3: Number of suspended sediment samples collected during different events at the outlet of the main channel and at four subcatchment outlets, along with information on suspended sediment concentration (SSC). Vaues are number of samples measured with the spectrometer, with the total number of samples collected during the event in paretheneses

		SSC [g l-1]			
Date	Catchment	number of samples	min	mean	max
24 Sept 2011	Villacarli	5 (16)	11.08	151.08	332.62
24 Oct 2011	Villacarli	5 (15)	4.55	63.09	215.33
27 Oct 2011	Villacarli	5 (16)	2.13	32.54	99.94
03 Nov 2011	Villacarli	3 (12)	3.68	22.57	101.60
24 Sept 2011	Carrasquero	3 (03)	40.20	71.00	116.57
24 Oct 2011	Carrasquero	5 (16)	1.06	6.19	22.05
27 Oct 2011	Carrasquero	3 (11)	2.03	5.72	10.81
03 Nov 2011	Carrasquero	4 (10)	3.02	8.23	40.22
24 Sept 2011	Ceguera	3 (16)	9.87	25.86	54.25
03 Nov 2011	Ceguera	3 (24)	3.09	12.48	30.79
24 Sept 2011	Lascuarre	3 (14)	3.55	7.00	11.32
03 Nov 2011	Lascuarre	4 (23)	0.98	11.82	42.25
24-25 Sep 2011	Capella	24 (24)	3.28	10.36	35.72
22 Mar 2012	Capella	5 (05)	4.71	11.73	19.88
03-04 Jun 2012	Capella	8 (08)	2.54	34.23	65.25
20 Jun 2012	Capella	7 (07)	1.78	3.60	5.47

Table 4: Number of channel bed resuspension samples collected on four dates, once each season, in 2011. Sampling site location can be seen in Fig. 1. * indicates that the amount of material was not enough for measurement or that filters were damaged

25.02.2011 (I)	24.05.2011 (II)	26.07.2011 (III)	01.12.2011 (IV)
*	*	S01	S01
*	S02	S02	S02
S03	S03	S03	S03
*	*	S04	S04
S05	S05	S05	S05
*	S06	*	S06
S07	S07	S07	S07
S08	S08	S08	S08
S09	S09	S09	S09
S10	S10	S10	S10
S11	S11	S11	S11
S12	S12	S12	S12
S13	S13	S13	S13
*	S14	S14	S14

Table 5: Characterization of precipitation events that caused the runoff sampled for suspended sediment at Capella. Av gives the average amount of precipitation interpolated over the study area from information measured at the subcatchment gauges. Events per subcatchment are summaries of events that occurred in the period given in column date, whereas an event was defined as continuous rainfall with interruptions < 1 hr. The numbers in brackets represent the number of rain gauges per subcatchment. Maximum intensity was calculated for 15 minute intervals

		Precipitation (mm)		Duration (h)			Max. intensity
Date	Catchment	mean	sum	min	mean	max	(mm h^{-1})
18-24 Sep 2011	Cabecera (2)	7.28	118.30	1.40	2.24	3.37	20.27
Av 39.86 mm	Villacarli (2)	5.93	63.98	0.23	1.74	2.82	31.79
	Carrasquero (1)	10.55	57.96	2.68	2.75	2.82	68.04
	Ceguera (1)	4.86	28.14	0.35	1.13	3.15	9.22
	Lascuarre (2)	5.46	31.36	0.43	1.78	2.88	40.37
18-22 Mar 2012	Cabecera (2)	2.45	162.45	0.20	8.48	19.85	12.00
Av 67.99 mm	Villacarli (2)	1.93	142.42	0.22	4.77	19.13	20.95
	Carrasquero (1)	2.57	72.66	0.68	5.55	19.38	16.38
	Ceguera (1)	2.65	91.01	1.43	6.41	19.25	20.09
	Lascuarre (2)	2.26	110.03	0.43	3.18	10.08	16.46
28 May 2012 -	Cabecera (2)	5.34	58.10	0.27	1.17	2.10	28.80
03 Jun 2012	Villacarli (2)	10.24	170.32	0.73	1.99	6.02	102.51
Av 25.46 mm	Carrasquero (1)	9.37	44.46	1.25	1.70	2.20	37.62
	Ceguera (1)	4.20	16.94	0.25	0.92	1.63	8.27
	Lascuarre (2)	8.61	38.40	0.63	1.23	1.70	42.55
18 - 23 Jun 2012	Cabecera (2)	1.90	40.48	0.62	4.25	12.97	18.48
Av 40.22 mm	Villacarli (2)	2.62	99.48	0.40	4.50	13.73	15.68
	Carrasquero (1)	2.53	92.04	0.50	4.35	12.42	15.96
	Ceguera (1)	2.29	44.13	1.00	4.19	12.32	13.97
	Lascuarre (2)	1.62	45.92	0.47	2.98	12.30	9.21

Figures

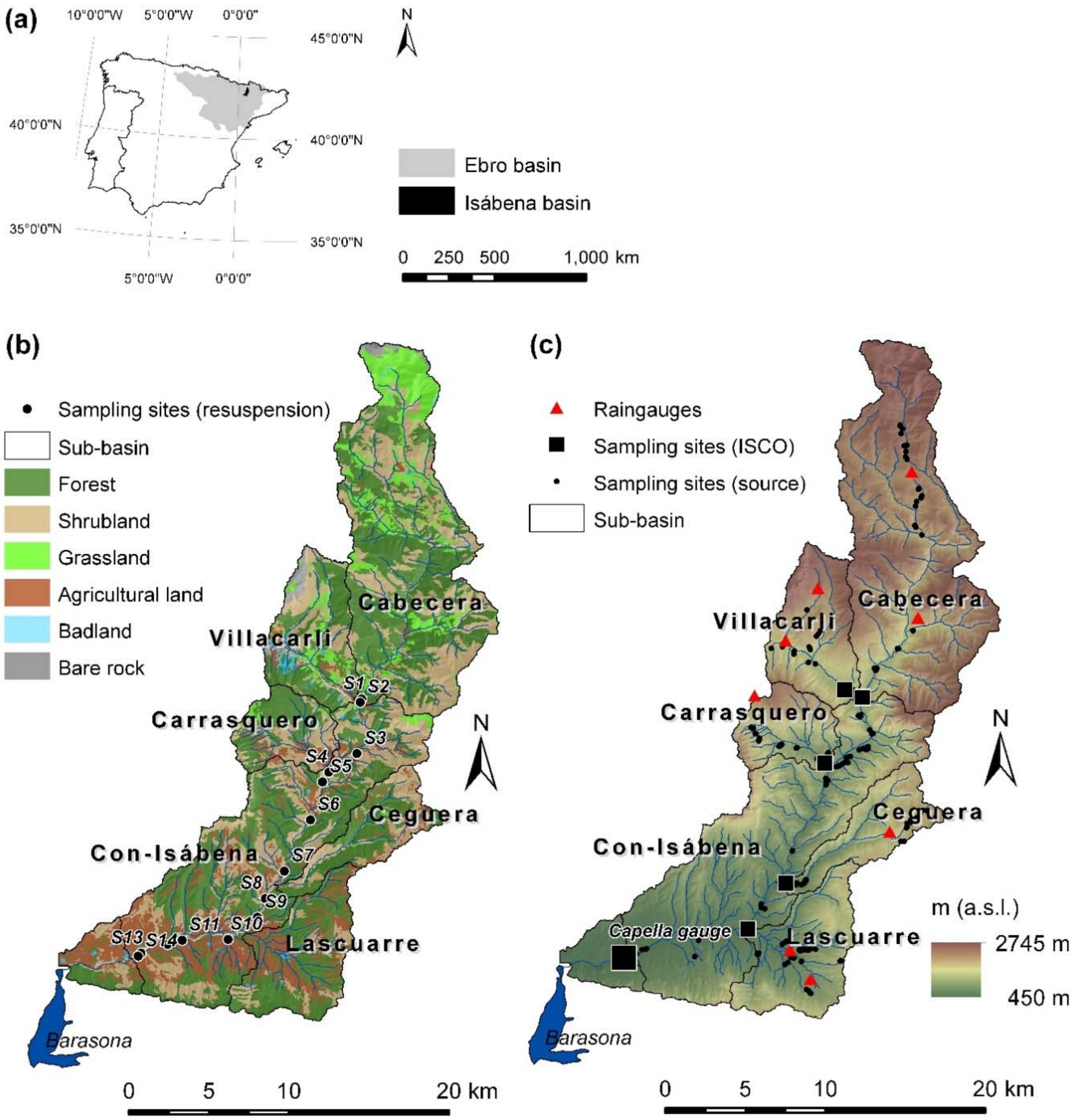


Fig. 1: Study area (Isábena basin) including location in Spain, land use, topography, main river network, subcatchments, and sampling locations (source sampling, ISCOs for suspended sediment, channel bed resuspension sampling, rain gauges)

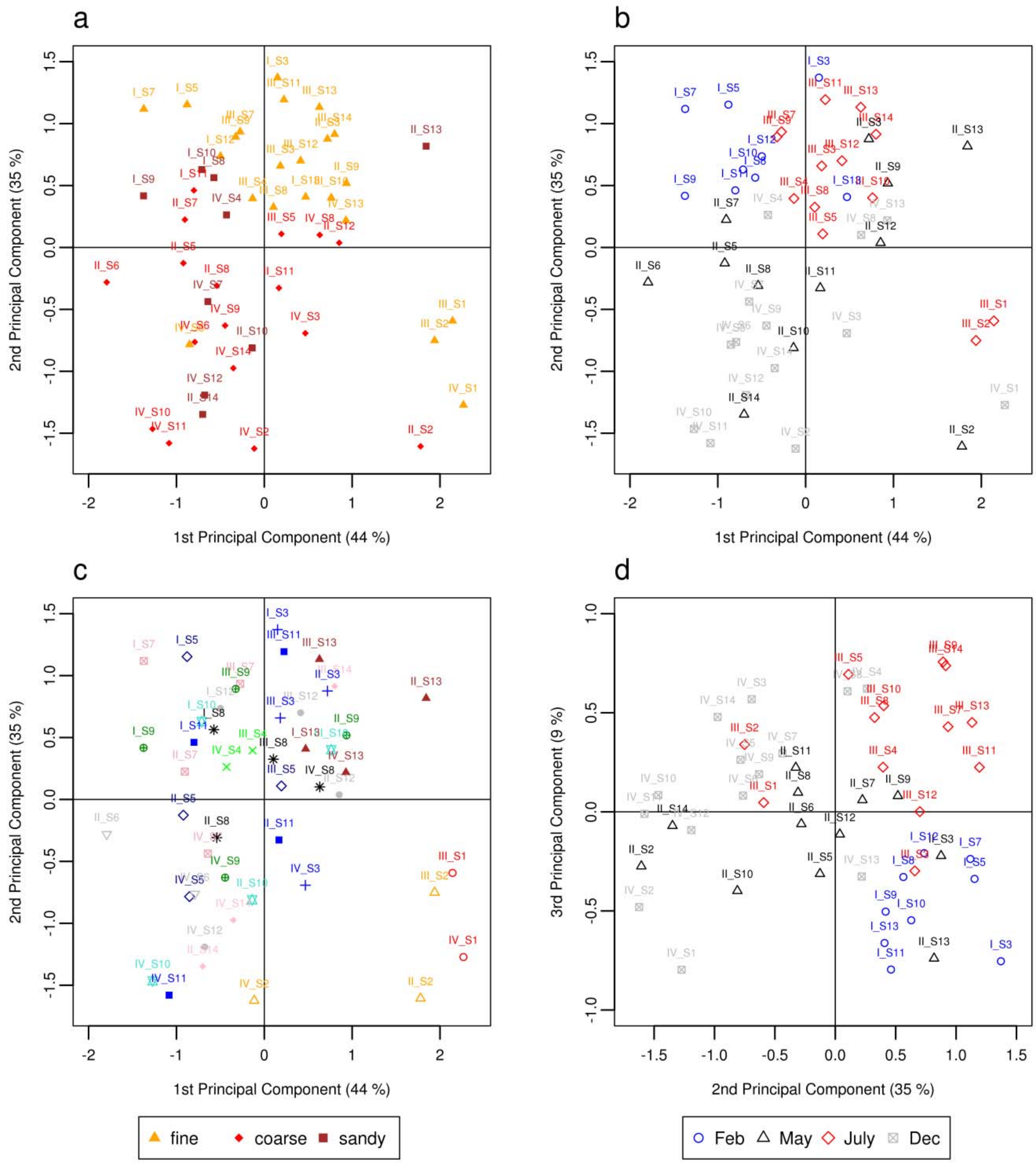


Fig. 2: Two-dimensional scatter plot of scores for the first three principal components (PC) from the PCA fo rchannel bed resuspension samples: a) first two PCs by grain size; b) first two PCs by season; c) first two PCs by sampling location; and d) second and third PC by season

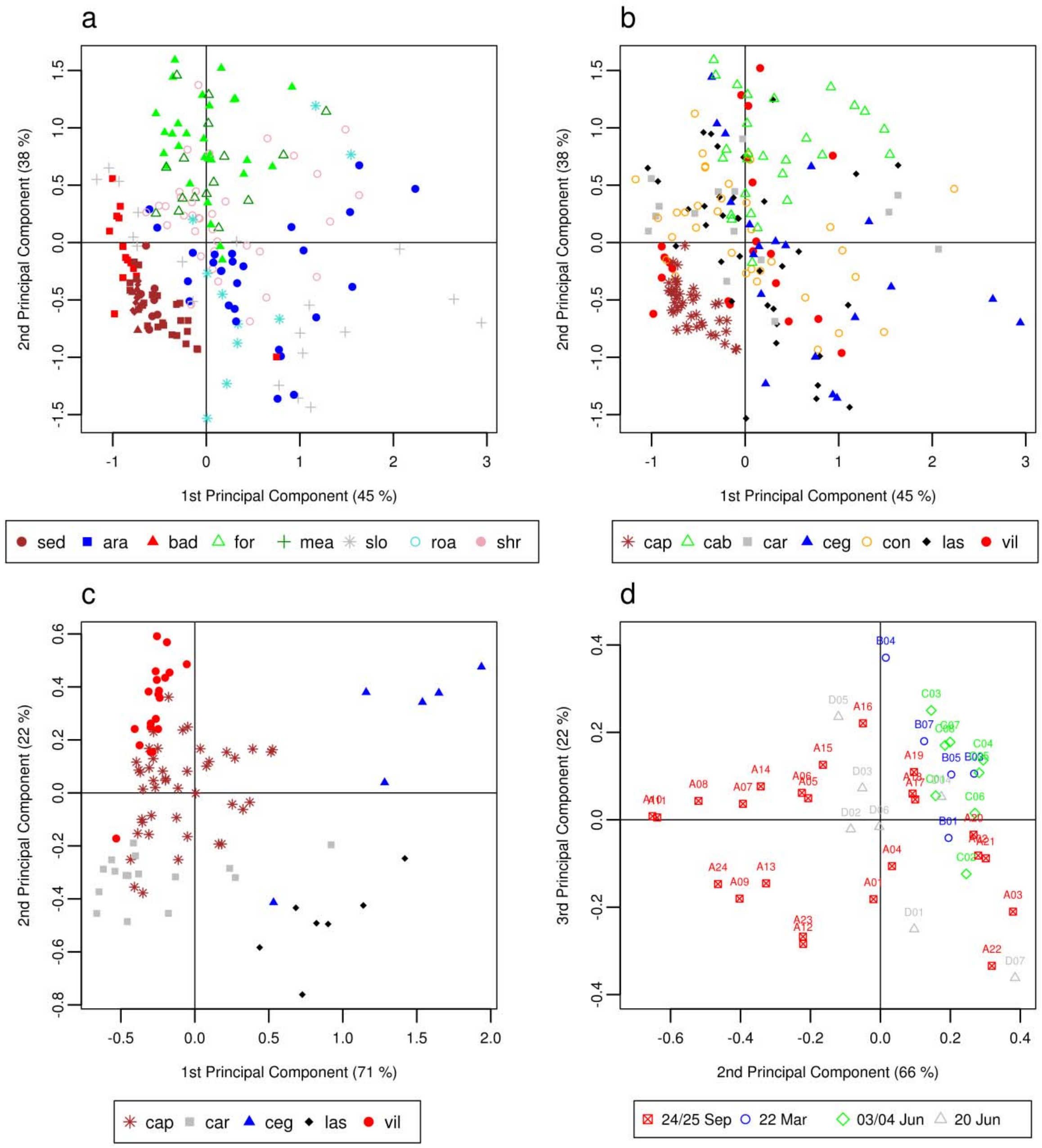


Fig. 3: Two-dimensional scatter plot of scores for the first and second principal component (PC) from the PCA for: a) source data by land use with suspended sediment sampled at the basin outlet (Capella); b) source data by subcatchment with suspended sediment sampled at the basin outlet (Capella); c) suspended sediment samples from the basin outlet (cap) and four subcatchments; and d) suspended sediment samples from the basin outlet by flood event. Acronyms describe Capella suspended sediment (sed) and source sample land use classes (ara = agricultural land, bad = badland, for = forest, mea = grassland, slo = open slope, roa = unpaved road, shr = shrubland) and subcatchment/location of ISCO sampler (cap = Capella, Cab = Cabecera, car = Carrasquero, ceg = Ceguera, las = Lascuarre, vil = Villacarli)

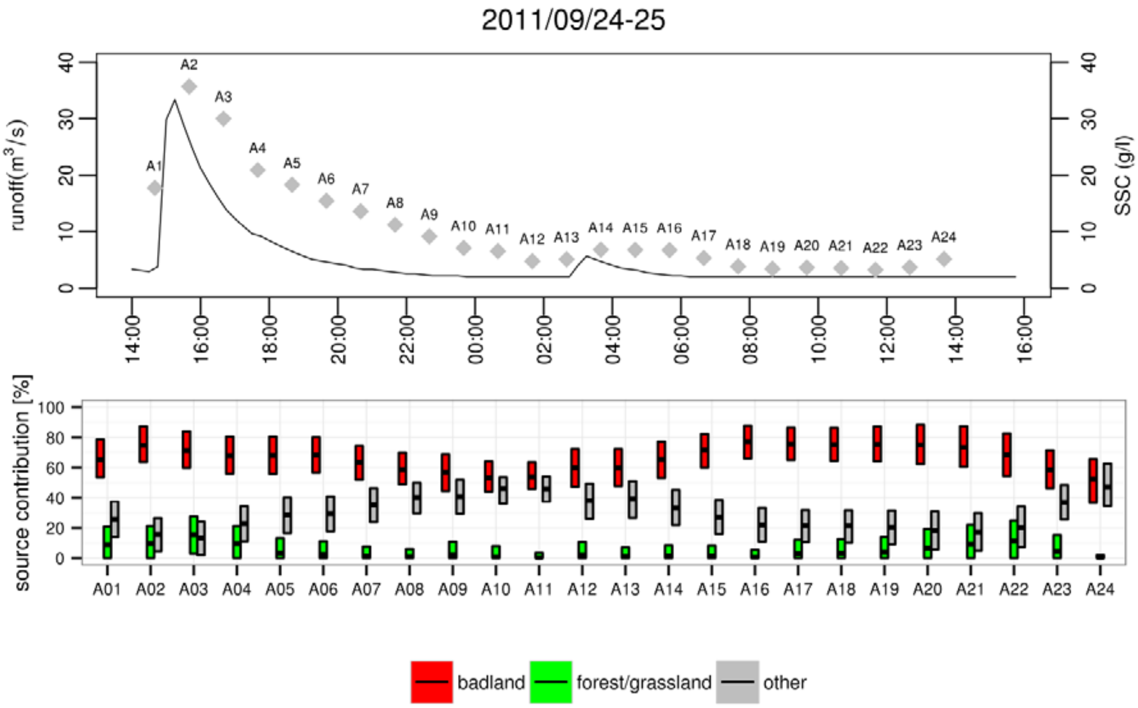


Fig. 4: Discharge, suspended sediment concentration (SSC) and estimated suspended sediment source contribution for the event that occurred on 24th/25th September 2011. Black bars indicate mean estimates, confidence intervals are at the 90 % level

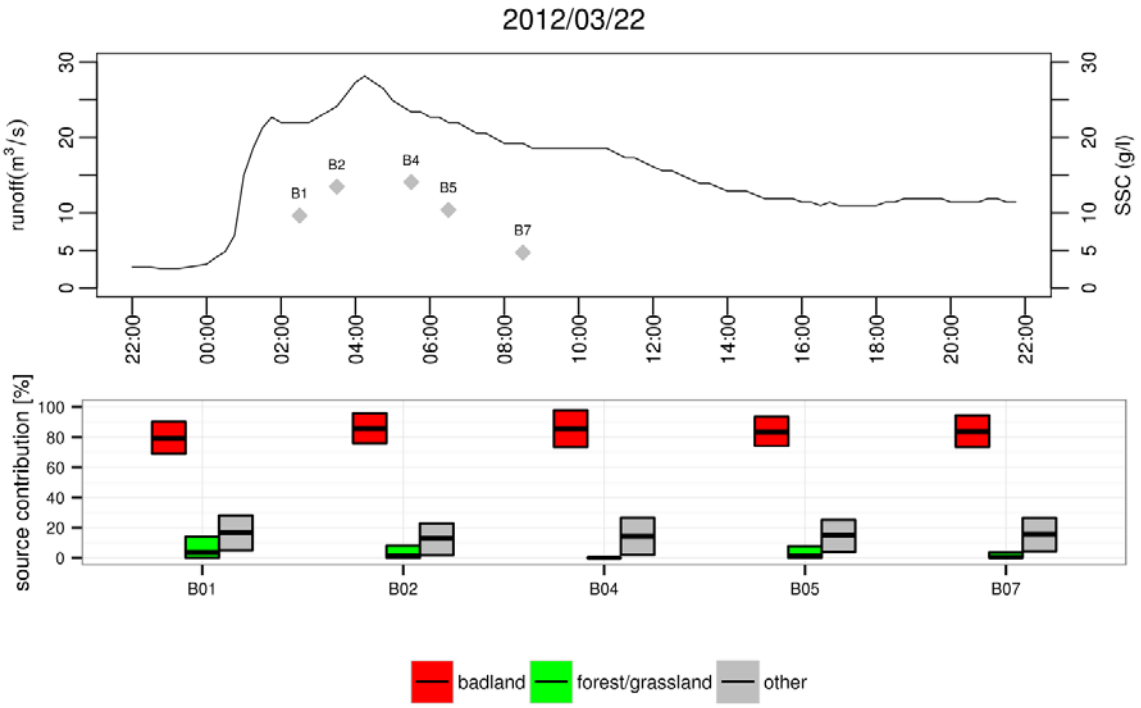


Fig. 5: Discharge, suspended sediment concentration (SSC) and estimated suspended sediment source contribution for the event that occurred on 22th March 2012. Black bars indicate mean estimates, confidence intervals are at the 90 % level

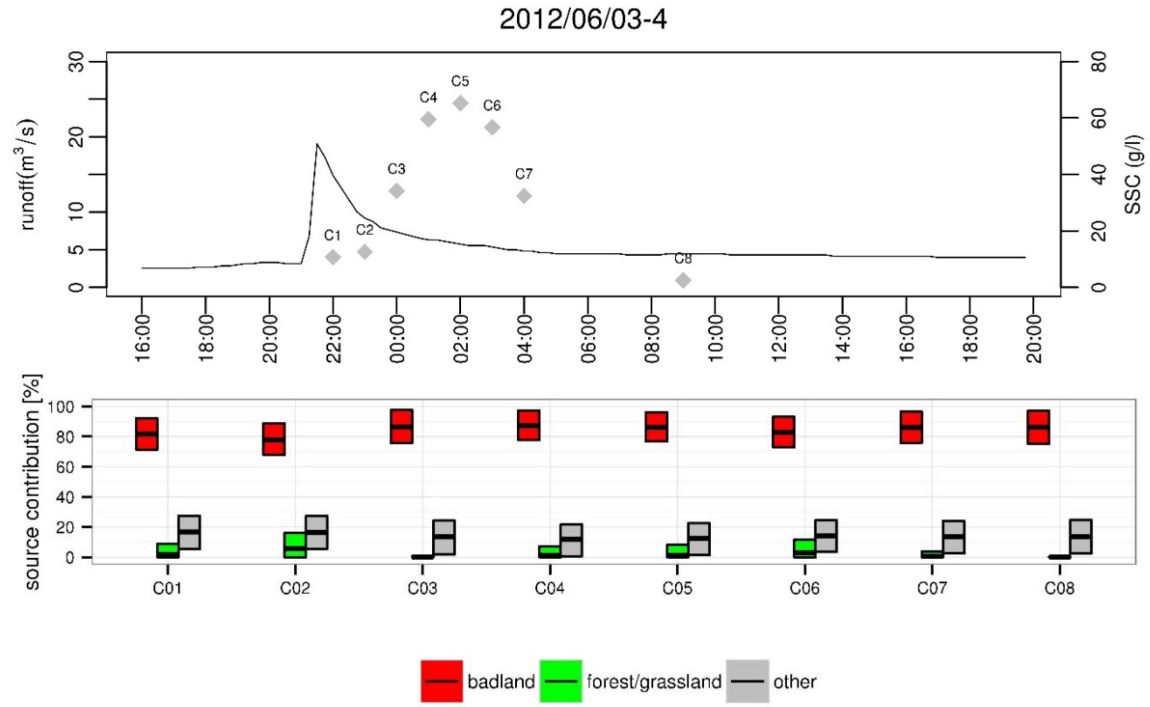


Fig. 6: Discharge, suspended sediment concentration (SSC) and estimated suspended sediment source contribution for the event that occurred on 3rd/4th June 2012. Black bars indicate mean estimates, confidence intervals are at the 90 % level

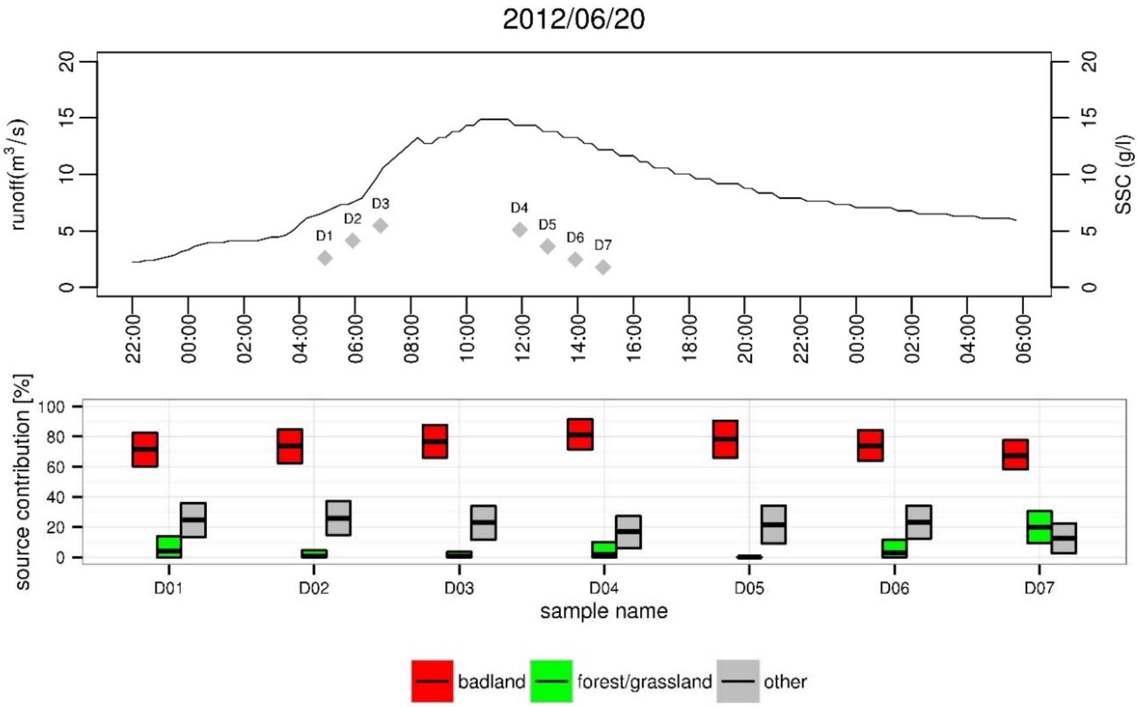
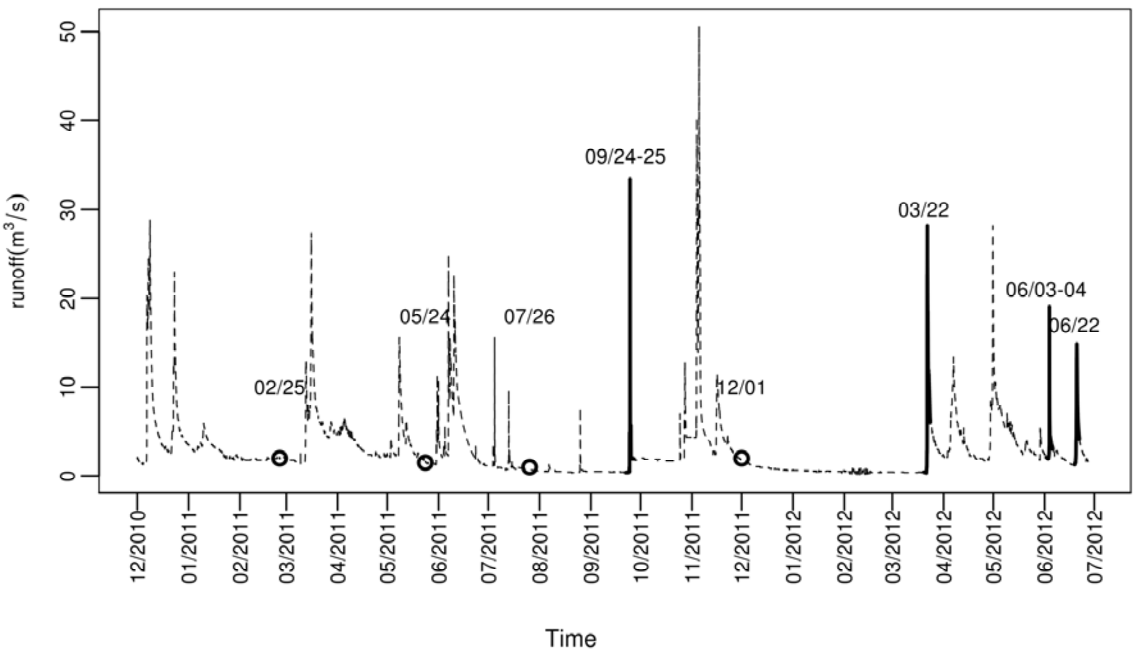


Fig. 7: Discharge, suspended sediment concentration (SSC) and estimated suspended sediment source contribution for the event that occurred on 20th June 2012. Black bars indicate mean estimates, confidence intervals are at the 90 % level

Online Resources



Online Resource 1: Discharge at Capella weir over the study period including sampling dates for resuspension samples (circle) and suspended sediments during storms (thick lines)