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FINGERPRINTING SEDIMENT CONTRIBUTION FROM ALPINE SOILS TO MOUNTAIN RESERVOIRS

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ABSTRACT

Soil in alpine environments plays a key role in the development of ecosystem services and information is required on processes that lead to soil erosion to maintain and preserve this important resource. In common with other mountain alpine environments, the Benasque catchment is characterized by temperatures below freezing that can last from November to April, intense rainfall events, and rugged topography which makes assessment of erosion challenging. Indirect approaches to soil erosion assessment offer opportunity to evaluate soil erosion in such areas. In this study sediment fingerprinting procedures were used to evaluate soil sources in the area of the Posets-Maladeta National Park (Central Spanish Pyrenees). Sediment contributions of potential sediment sources defined by soil type (Kastanozems/Phaeozems; Fluvisols and Cambisols) were assessed by different characterizations of sources and identified Fluvisols, which dominate the riparian zone, as the main sediment source at the time of sampling indicating the importance of connectivity and also potential differences in the source dynamic of material in storage versus that transported efficiently from the system during high flows. The approach enabled us to better understand soil erosion processes in the Benasque alpine catchment wherein identified areas that, due to high connectivity, contribute more to sediment deposits.

KEYWORDS

alpine soils; fingerprinting procedure; erosion;

INTRODUCTION

Mountain systems all over the world are unique in their ecology and diversity. However, extreme topography and intense climate result in high instability, fragility and sensitivity for these ecosystems. Economic, societal and environmental changes are often an immediate threat to mountain systems and careful, evidence-based planning is needed (Alewell et al. 2008). One inherent parameter of ecological stability is the status of soils. In mountain ecosystems, soil health and stability underpins slope stability, water budgets, vegetation productivity, ecosystem biodiversity and nutrient production. Soil loss due to water erosion represents an increasing threat with climate change, which has been predicted to affect precipitation regimes, frequency of extreme meteorological events, snow melt and vegetation (IPCC 2007).

Sediment fingerprinting approaches offer potential to quantify the contribution of different sediment sources, evaluate catchment erosion dynamics and support the development of management plans to tackle problems as reservoir siltation. Although sediment has a variety of diverse roles and its regulation and management are complex, it is accepted that reservoir siltation is one of the worst off-site consequences of soil erosion and sediment delivery (Navas et al. 2004). In the last 30 years, sediment source fingerprinting investigations have expanded greatly in response to a growing need for information on sediment source and to technological advances which facilitate such work (Walling 2013). However, source fingerprinting techniques continue to be most widely applied in agricultural and forest catchments (e.g. Owens et al. 2000; Collins et al. 2010; Martínez-Carreras et al. 2010; Blake et al. 2012; Schuller et al. 2013) and examples in alpine catchments are limited.

This study represents a preliminary investigation to develop knowledge on soil erosion processes by applying a fingerprinting approach in the Benasque alpine catchment (Central Spanish Pyrenees). Working within a reservoir catchment, specific objectives are: (1) to identify the dominant source of sediment delivered to the reservoirs; and (2) to compare fingerprinting results depending on source characterizations.

MATERIAL AND METHODS

Study area:

The Benasque catchment is located within the Posets-Maladeta Natural Park (Central Spanish Pyrenees). The Natural Park, created in 1994, is an autonomous legislative body engaged in the conservation of natural species and values. The climate is defined as mountain type, wet and cold, with both Atlantic and Mediterranean influences. The village of Benasque at 1138 m a.s.l., receives an average annual precipitation of 1182 mm which further increases to more than 2500 mm at the highest divides. Above 1000 m a.s.l., the average annual temperature is lower than 10°C and at 2000 m the mean temperature is around 5°C (García-Ruiz et al. 2001). The hydrologic regime of the area is transitional nivo-pluvial (López-Moreno et al. 2002). The catchment includes two reservoirs Linsoles and Paso Nuevo (Fig. 1), both reservoirs, with storage capacity of c.a. 3 hm^3, regulate 118 and 283 km^2 of the Ésera River headwater, respectively, with a sediment trap efficiency of 45 and 60%, each (Palazón and Navas 2014). A well developed karst system (Fig.1) disconnected the upper part of the Ésera River to the upper Garonne River (Aran Valley, Spain) (Palazón and Navas 2013).

Rock outcrops cover more than 25 % of the catchment. The cultivated areas represent only 3% and are limited to the valley floors. The pine forest of *Pinus sylvestris* is at its greatest extent between 1200 and 1700 m a.s.l. Above 2000 m bare rocks with sparse plants increasingly dominate the landscape.

The soils of the catchment are stony and shallow, overlying fractured bedrock with textures from loam to sandy loam. Because the Benasque catchment was deglaciated at the beginning of the Holocene, the soils are young and strongly influenced by a periglacial environment. On steep slopes, where Leptosols and Kastanozems are developed, soils are shallow and regularly truncated. More developed soils, such as Cambisols and Phaeozems are found in the lower areas of the catchment and Fluvisols cover the valley floors (Fig. 1).

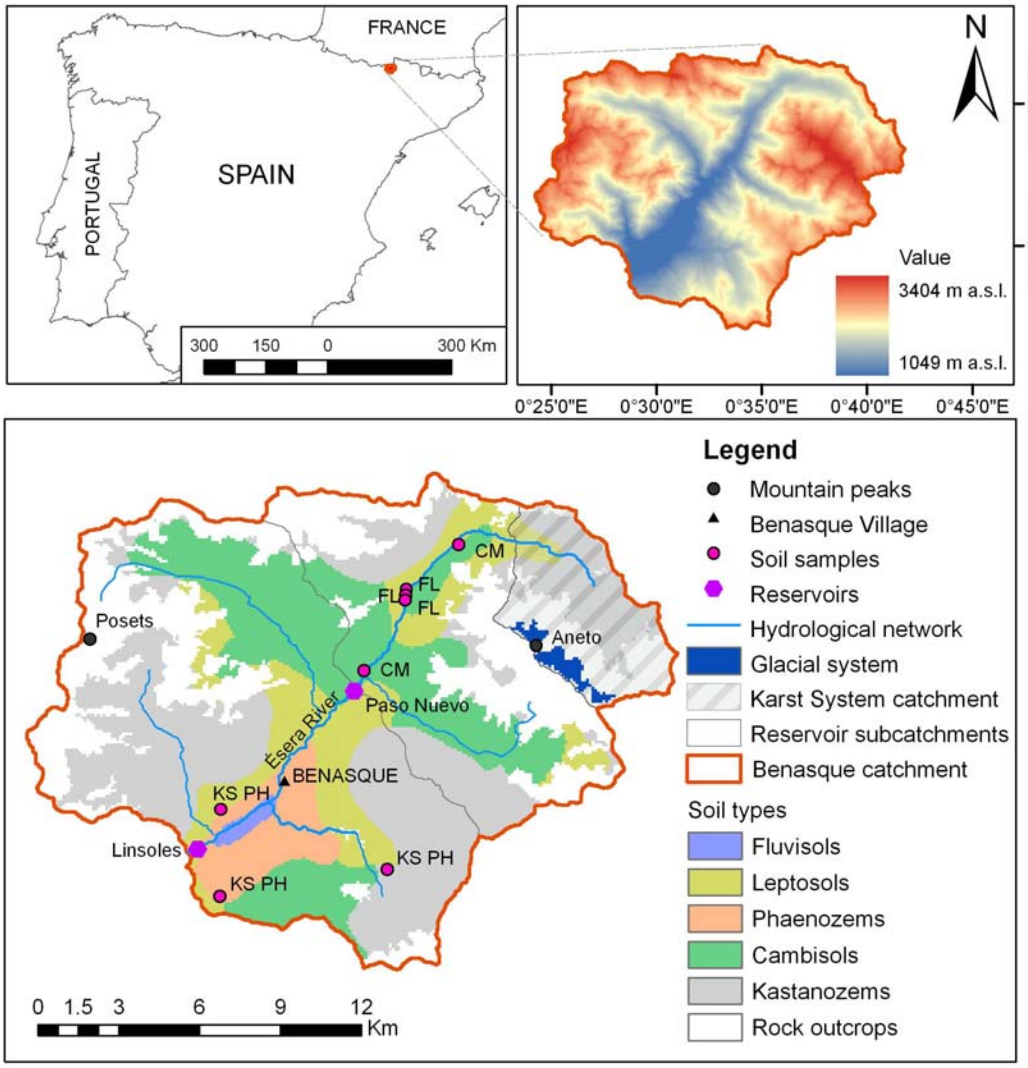

Figure 1. Location of the Benasque catchment in Spain, digital elevation model (DEM) of the catchment, distribution of the soil types and sampling points.

Sample collection and analysis:

Sediments from the Paso Nuevo and Linsoles reservoirs were collected to compare reservoir silt to soil sources in accessible areas of the reservoir delta. In each reservoir, a composite sediment sample was prepared in the field with a minimum of 6 samples of exposed reservoir deposits. To characterize the signatures of potential sediment source materials, representative sites were selected in areas where there was high potential sediment yield connectivity from hillslope to channel with easy access. A total of 32 individual soil samples were collected from 0 to 5 cm depth and combined in the field to form composite samples. From those, 2 were composite samples from Cambisols, 3 from Fluvisols and 3 samples from Kastanozems and Phaeozems.

Leptosols were not sampled because in addition of being very poorly developed, they occupy areas, which were difficult to access (Fig. 1). For this preliminary research, it was decided to concentrate efforts on the better-developed soils of the catchment.

All samples were initially oven-dry at 35 °C, gently disaggregated and sieved to <63 μm to isolate a standardised grain size fraction. A total of 35 properties were analyzed for each sample, including: massic activities of environmental radionuclides; textural classes; elemental composition and magnetic susceptibility.

Sediment fingerprinting procedure:

The standard sediment source fingerprinting procedure is based on (i) statistical analysis of difference to identify a subset of tracer properties or optimum composite fingerprint that discriminate the sediment sources followed by (ii) the use of multivariate mixing models to estimate the proportional contributions from each source (e.g. Smith and Blake 2014).

The ability of the 35 analysed fingerprinting properties to discriminate between the potential sediment sources was investigated by conducting a stepwise Discriminant Function Analysis (DFA) based on the minimization of Wilks' lambda.

Similar to other approaches (e.g. Evrard et al. 2011), the multivariate mixing model seeks to solve the system of linear equations by means of mass balance equations represented by:

$$\sum_{j=1}^{m} a_{i,j} \cdot x_j = b_i$$

While satisfying the following constraints:

$$\sum_{j=1}^{m} x_j = 1$$

$$0 \leq x_j \leq 1$$

where, b_i is the value of tracer property i ($i = 1$ to n) in the reservoir sample, $a_{i,j}$ is the concentration of tracer property i in source type j ($j = 1$ to m), x_j is the unknown relative weighting contribution of source type j to the reservoir sample, m is the number of potential source types, and n is the number of tracer properties selected as the optimum composite fingerprint.

To solve the system of linear equations the new approach adopted here was written in C programming language and designed to deliver a user-defined number of best possible solutions over a defined number of Monte Carlo iterations. The unique solution from the generated iterations (p=random positive numbers) for each sediment sample was characterized by the mean weighting source contribution, the standard deviation of the user-defined solutions and their lower goodness of fit (GOF) index (based on Collins et al. 2010) defined by:

$$GOF = 1 - \frac{1}{p} \times \sum_{i=1}^{n} \left(\frac{\left| b_i - \sum_{j=1}^{m} x_j \bar{a}_{i,j} \right|}{b_i} \right)^2$$

This method is argued to guarantee a similar set of representative solutions in all unmixing cases based on likelihood of occurrence. The model was configured to select the 100 results with highest GOF obtained from 10^6 generated random positively solutions. In this study the model was solved for three sources characterizations by:

mean, corrected mean and median concentrations of tracer property values of source samples, to assess and compare unmixing results.

RESULTS AND DISCUSSION

The DFA led to selection of K, Sr, ^{238}U, Sb and LF as the optimum source fingerprinting with the 100% of correctly classified sources. Mean proportional contributions from Kastanozems/Phaeozems, Cambisols and Fluvisols sources varied between reservoir samples and tracer source characterizations (Table 1). For both reservoirs, Fluvisols were identified as the main source contributing almost double than the other sources suggesting that stream connectivity is a main control of sediment input to the reservoirs as Alatorre et al. (2010) indicated for the same area. Differences between reservoirs in source apportionments appear to be due to local fluvial dynamics and proximity of soil underlying the different contributing areas. Paso Nuevo reservoir has a higher fluvial dynamic with more steep slopes and greater percentage of Cambisols than Linsoles reservoir (Fig 1).

Table 1. Mean percentages of source contributions (standard deviations) and GOF from the fingerprinting results for the mean, median and corrected mean characterization of the sources for the Paso Nuevo and Linsoles reservoirs sediment samples.

	Sources	GOF	Kastanozems and Phaeozems	Fluvisols	Cambisols
Paso Nuevo	Mean	98	0(0)	65(1)	35(1)
	Cor. mean	100	7(6)	61(23)	32(22)
	Median	97	0(0)	60(1)	40(1)
Linsoles	Mean	95	30(0)	70(0)	0(0)
	Cor. mean	100	12(8)	74(17)	14(14)
	Median	94	26(0)	64(0)	9(0)

The outputs of the mixing model for the different characterizations of the tracer sources also varied between assessments but Fluvisol contributions appeared to be similar between reservoir assessments. The assessment with sources defined by the corrected mean yielded the greatest GOF values but the highest standard deviations. Dissimilarities between reservoir contributions were greatest for the corrected mean source characterization assessment.

Comparing results for the mean source characterization assessment with the results obtained by Palazón et al. (2014) for the same samples but using different GOF which was based on Motha et al. (2003), GOF values were highest for this study. Furthermore, comparing with the previous work, relatively lower contribution from Fluvisols but higher from the other soil sources was observed in this study .

In general, land cover sources were the most evaluated sediment sources in the literature (e.g. Martinez-Carreras et al. 2010; Smith and Blake 2014), though, discrimination of the soil sources with the fingerprinting procedure was possible for the alpine Benasque catchment because of its distinctive soil characteristics.

CONCLUSION

This method is argued to ensure a similar set of representative solutions in all unmixing cases based on likelihood of occurrence and user defined top number solutions. The method is user friendly and facilitates calculations of the second part of the fingerprinting procedure.

The fingerprinting approach suggested that Fluvisols were the main contributing source to the sediment accumulated in the reservoirs.

These initial findings demonstrate that fingerprinting approach can offer insights in the sediment contribution from soil sources to reservoirs in alpine environments.

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