1 Assessing soil redistribution in a complex karst catchment using fallout ¹³⁷Cs and GIS

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15 **Abstract**

16 Caesium-137 derived from nuclear testing in the past century has been widely used as a
17 sediment tracer of soil redistribution, providing information on medium term (40–50
18 years) erosion rates. To date, most studies have focused on individual fields of limited
19 extent, but estimated rates and patterns of soil redistribution require upscaling to
20 catchment level. An attempt to assess soil redistribution processes with strong
21 geomorphic control on complex terrain, such as an internally drained karstic catchment,
22 is presented in this work. A comprehensive geomorphological survey of the Estanya
23 Lake catchment (Spanish Pyrenees) enabled the main geomorphic elements to be
24 identified with a grid resolution of 5 x 5 m, which was the basis for the terrain analyses.
25 A detailed DEM was constructed and improved after field identification of the drainage

system and point measures on gentle slopes with Total Topographic Station. A 100 x 100 m sampling grid was established to derive point data of ^{137}Cs inventories across the catchment. Geostatistical interpolation of point samples of ^{137}Cs inventories in soil was carried out to identify and assess the areas of sediment gain and loss by comparing with ^{137}Cs reference inventories. Profile activity models were used to calibrate ^{137}Cs data and to derive estimates of soil redistribution. GIS was used to provide spatially distributed erosion and deposition rates in the landscape for the whole catchment. The median values of soil erosion and deposition of 4.7 and 3.1 $\text{Mg ha}^{-1} \text{ year}^{-1}$, respectively, showed a large variability and reveal coupling between erosional and depositional forms in the catchment. The highest erosion and deposition rates were found in cultivated fields at the southern sector of the catchment. The spatial analysis of the results supports the importance of taking into account geomorphological features in karstic catchments as relevant controlling factors in soil redistribution processes.

Keywords: Soil redistribution; ^{137}Cs ; DEM; GIS; karstic catchment; erosional and depositional landforms.

1. Introduction

In the framework of accelerated soil loss processes related to land use changes in a climate change scenario, it is necessary to assess soil particle generation, sediment mobilisation and storage, as well as final export through the hydrological network. Hence, quantitative knowledge on soil erosion, mobilisation and deposition within a catchment is needed to understand sediment dynamics in a context of changing landscapes.

Accurate characterization of hydrological networks benefits from methodologies like digital elevation models (DEM) and Geographical Information Systems (GIS). DEMs may be used for calculating spatial variables that control geomorphic processes, are considered sound tools to define drainage networks (López-Vicente et al., 2009), and may allow inferring information on the geomorphological evolution of catchments (Barbieri and Marchetti, 2003). Although modelling karst areas using a DEM is more difficult than modelling normal landscapes (Tarboton et al., 1991), several studies have shown the usefulness of DEMs in characterizing karst features (e.g. Antonić et al., 2001). Data of digital elevation models, results of sampling analyses, aerial photographs and mapped geomorphological features can be assembled in a GIS (Tüfekçi and Şener, 2007). With the assistance of GIS techniques, a variety of quantitative variables related to the geomorphological characteristics of a catchment (e.g. elevation, slope, shape and terrain curvature) can be automatically derived (Apaydin et al., 2006).

Information on spatially distributed soil redistribution rates is required in a number of environmental studies, and for this purpose, fallout ^{137}Cs has proven to be an effective radiotracer in diverse environments (Walling et al., 2006; Ritchie and McCarty, 2008; Mabit et al., 2008; Kato et al., 2010). Up to the present time, most studies have focused on individual fields of limited extent, but a proper understanding of the patterns and rates of soil redistribution require comprehensive information on the complete cycle of sediments within a particular study area.

Up to date, there have been few attempts to upscale soil redistribution data to catchment scale (Mabit et al., 2002; Porto et al., 2003; Mabit and Bernard, 2007), despite this is a fundamental issue when investigating sediment mobilisation within a catchment and final export through the hydrological network (Porto et al., 2009, 2011). On this respect, spatially distributed soil erosion and deposition rates within catchments constitute

valuable data for identifying the main factors that control the processes and pathways involved in soil particle generation, sediment flux and storage, as well as export of sediment (Kato et al., 2010). In addition, radiotracers can be used to ascertain the dominant driver of sediment detachment and transfer, and to assess the potential contribution of overland flow or raindrop impact to sediment production at the catchment scale (Fukuyama et al., 2008).

There is a need to gain insight into the relationships between the ^{137}Cs inventory and the physical factors that control erosion (i.e. topographic curvature, slope length, upslope area and contributing area) in order to establish the relative importance of different erosional processes that shape the landscape, such as sheet flow or rilling (Zhang et al., 2009). The objective of this work is to assess soil redistribution processes in a complex terrain with strong geomorphic controls, namely an internally drained karst catchment. Fallout ^{137}Cs derived from nuclear testing in the past century, which has been widely used as a tracer of soil movement, and GIS techniques are integrated to provide spatially distributed information on erosion and deposition rates in a small-sized catchment of an endorheic lake in the Spanish Pyrenees. Another aim is to explore the use of fallout ^{137}Cs to elucidate whether the geomorphic elements identified in the catchment as erosional and depositional landforms have functioned alike in the medium term (40–50 years). Results of this study shed light on the cycle of soil particle generation at erosion sites, sediment transfer, and storage at deposition sites occurring in complex karst landscapes.

2. Study area

The catchment of the Estanque de Arriba Lake, forming part of the endorheic system of the Estaña lakes, is located in the central sector of the Outer Ranges of the Spanish

101 Pyrenees, close to the northern boundary of the Ebro Tertiary basin (Fig. 1). The studied
102 karst area is embraced within the Saganta relict polje (Sancho Marcén, 1988) and is
103 characterised by the presence of evaporite dissolution-induced dolines, some of which
104 host permanent lakes. The analysed catchment covers 79.5 has and is characterized by
105 an abrupt topography with an altitude range between 679 and 892 m a.s.l. and an
106 average slope gradient of around 24 %. Steep slopes (> 24 %) occupy as much as 44 %
107 of the catchment, whereas gentle slopes (< 12 %) take 26 % (Fig. 1).

108 The bedrock consists of gypsiferous marls, dolomites, limestones and ophites of
109 Mesozoic (Keüper and Muschelkalk Facies) and Neogene ages. The main soil types are
110 Calcisols, Leptosols and Haplic Regosols with small patches of Gleysols, Gypsisols and
111 Vertisols (Machín et al., 2008). The climate is of Mediterranean-continental type with a
112 mean annual precipitation of ca. 595 mm, mainly distributed in two rainy seasons;
113 spring and autumn. Summers are dry but with frequent high-intensity rainfall events
114 (López-Vicente *et al.*, 2008). The mean annual temperature is 12.2°C with common
115 thermal inversions during the winter. The main vegetation cover consists of evergreen
116 oak (*Quercus rotundifolia*) with some *Buxus sempervirens*, *Juniperus oxycedrus* and
117 submediterranean plants. The second plant community is dominated by dry-resistant
118 deciduous oaks (*Quercus faginea* and *Q. cerrioides*) with some *Buxus sempervirens*.

119 Since Medieval times the study area had farmland activity with agricultural and pasture
120 uses. Intense anthropogenic activity has greatly modified the landscape in the catchment
121 and affected the slope profiles, mainly by constructing stone-framed terraces for cereal
122 crops and orchards. Long-term history of land use in the area results in a complex land
123 use mosaic, where natural vegetation is locally interrupted by cultivated land, as is
124 typical of Mediterranean agricultural landscapes. Winter barley is the main crop in the
125 area (23 %) and occupies most of the gentle surfaces around the lakes, whereas steeper

slopes are covered by Mediterranean forests (dense 18 %, open 19 %), and scrublands (dense 11 %, sparse 11 %). Other minor land uses such as orchards and pastures (<5 %) are found throughout the study area.

The catchment holds a small pond and a main permanent freshwater lake (1.7 ha) fed by groundwater (IGME, 1982). The lakes are under regional protection since 1997 and are included in the European NATURA 2000 Network as a Site of Community Importance (SCI).

A detailed geomorphological survey allowed the identification of a variety of geomorphological features (López-Vicente et al., 2009), mainly dolines and associated deposits (Fig. 2). The main karst landforms include two collapse dolines in which the main lake is situated and an uvala. Other geomorphic elements include eight permanent gully systems, alluvial fans, flat-bottomed infilled valleys, doline deposits and Late Pleistocene-Holocene colluvial deposits (García-Ruiz et al., 2001). Karren is also common on exposures of calcareous strata and boulder-sized talus deposits cover some surfaces on the southern slopes. The main active processes are gully erosion as well as rill and interrill erosion that lead to sediment deposition in the bottom of the dolines. In addition, tillage erosion at the lower parts of the catchment greatly contributes to the siltation of the lakes, especially the small pond.

3. Materials and methods

3.1. Relief, topography, hydrological network and DEM

The complexity of the mountain relief in the karst catchment required detailed analyses of the topography, the geomorphological elements and the characteristics of the hydrological network, in order to construct a reliable digital elevation model. The DEM

of the study area was created by using successive methodological approaches and corrected with data obtained in several field campaigns (López-Vicente et al., 2009; 2011). As starting point, a grid DEM (5 x 5 m, cell size) constructed by DIELMO 3D Ltd. was the basis to derive the flow accumulation map using the combined flow accumulation algorithm (MDD8) included in the HydroTools 1.0 extension developed by Holger Schäuble (<http://www.terracs.com/en/home.html>). Because of errors in the flat areas like those surrounding the lakes, and also at the divides, it was necessary to correct the DEM by i) deriving contour lines at 3 m intervals from the grid DEM to avoid the errors associated with the main sinkholes; ii) field mapping and identification of the main morphological features, with the assistance of a coloured orthoimages (0.38 cm, cell size); iii) obtaining elevation data on a regular grid (100 x 100 m) by using a Global Positioning System (GPS); iv) (4) characterizing flat surfaces, gentle slopes and broad rounded ridges by using a Total Topographic Station (TTS) in a number of points; v) modifying the original contour lines to obtain a new grid DEM; vi) creating a new flow accumulation map from the new DEM and producing an error map comparing the original and the new DEM; vii) field mapping of the drainage system and subsequent changes to adequate the direction of water courses; viii) incorporating the hydrological effect of linear elements existing in the catchment like ditches and anthropogenic terraces.

The detailed analyses of the topographic features and the drainage system in the catchment allowed the identification of the main runoff pathways and a total of 4 internally drained sub-catchments within the Estanque de Arriba catchment (Table 1).

A land cover map was created with GIS and a coloured orthophoto. Eight land cover types were differentiated: urban, paths and roads, oak woodlands, Mediterranean forest, scrublands, crops, bank vegetation and pine woodlands. Finally, all the information

related to the topography, hydrology and land cover was combined to obtain the land use and catchment distribution map (Fig. 1).

3.2 Soil types, sampling and analyses

In the catchment, according to the FAO classification, main soils are Leptosols, Regosols and Calcisols (Machín et al., 2008). Leptosols are very shallow soils developed on Muschelkalk carbonate rocks, Regosols are shallow and poorly developed soils on unconsolidated materials and Calcisols are better developed soils with an A horizon and a calcic horizon. The soils have a grain size distribution mainly composed of silt (65 - 67 %) followed by clay (21 -22 %) and sand (13 -14 %), which is slightly lower in Leptosols (11%). Because of the small size of the catchment and the scarce number of erosive rainy days per year, ca. 12 (López-Vicente et al., 2008), there are no permanent water courses and rills and small gullies are the only active erosional features on the hillslopes. The soil was sampled at the intersection points of an approximately 100 x 100 m grid, i.e. one sampling site every ha (Fig. 1). In areas of dense vegetation cover soil samples were collected in open areas between the trees to avoid rainfall concentration.

The scale of the sampling grid was considered appropriate to represent the soil diversity in the study area. We used an 8 cm diameter core driller to collect two replicates of bulk soil samples to the total depth of the soil profile at 76 sites. Depth of sampling was variable depending on the soil thickness: 15 – 20 cm for Leptosols, 30 – 40 cm for Regosols, and 50 – 60 cm for Calcisols in flat areas. Samples were stored at 4 °C until they were analyzed. The undisturbed depth profiles of ¹³⁷Cs in the catchment indicated that the upper 15 cm contained around 80 % of the ¹³⁷Cs (Gaspar et al., 2011). Soils at

deposition sites and cultivated sites had longer ^{137}Cs profiles (Gaspar et al., 2011) and therefore the sampling depth was extended to 60 cm to collect the entire ^{137}Cs profile.

3.3. Gamma analyses

Fallout ^{137}Cs (half-life 30.2 year) was introduced in the stratosphere as a result of thermonuclear weapons tests, with fallout beginning in 1952 and continuing to the mid 1970s, with a peak in 1963, the year of the Nuclear Test Ban Treaty. The radionuclide is rapidly adsorbed by the clay minerals and organic matter in the surface soil and its redistribution in the soil and across the land surface occur in association with soil and sediment particles, primarily in relation with land use practices, erosion and sediment transport processes (Walling and He, 1999), although some ^{137}Cs can be mobilized by chemical and biological processes.

In the laboratory, soil samples were air-dried, ground, homogenized, and quartered, before being passed through a 2-mm sieve. Details on the methods used in the analysis of ^{137}Cs were described by Navas et al. (2005). Radionuclide activity in the soil samples was measured using a high resolution, low background, low energy, hyperpure coaxial gamma-ray detector coupled to an amplifier and multichannel analyser. The detector had an efficiency of 30 %, and a 1.92 keV resolution (shielded to reduce background), and was calibrated using standard certified samples with the same geometry as the measured samples. Subsamples of 50 g were loaded into plastic containers. Gamma emissions of ^{137}Cs (in Bq kg⁻¹ air-dry soil) were measured in the bulk soil samples. Considering the appropriate corrections for laboratory background, ^{137}Cs activity was determined from the 661.6 keV photopeak. Counting times were 30000 s and the analytical precision of the measurements was approximately $\pm 6 - 8$ % (95 % level of

confidence). The content of ^{137}Cs in the soil sample is expressed as a concentration or mass activity (Bq kg^{-1} dry soil) and as activity per unit area or inventory (Bq m^{-2}).

3.4. Estimating soil redistribution rates and geostatistical interpolation

Estimates of soil redistribution rates derived from ^{137}Cs measurements are based on a comparison of the total inventory for an individual sampling point and the local reference inventory. Where inventories are lower than the local reference inventory, loss of radionuclide indicates soil loss by erosion. Similarly, inventories in excess of the reference level are indicative of addition of radionuclide and soil by deposition. The magnitude and direction of the measured deviations from the local reference level provide a quantitative assessment of soil redistribution (Walling and Quine, 1990; Walling and He, 1999).

The models reported by Soto and Navas (2004 a, b; 2008) for uncultivated and cultivated soils have been applied to estimate soil redistribution rates. For uncultivated soils the model is compartmental and divides the soil into horizontal layers 1 cm thick with homogeneous ^{137}Cs distribution in each compartment and a time step of one month. A ^{137}Cs linear transference (Smith and Elder, 1999) between each pair of adjoining compartments is supposed, whereby the isotope flux is proportional to the difference in concentration between the two compartments, the proportionality constant being a specific coefficient k . In addition to the downward movement, the model also takes into account the ^{137}Cs deposition on the surface, which is known precisely in certain parts of the world (e.g. Blagoeva and Zikovsky, 1995). The increases or decreases in concentration level due to ^{137}Cs fluxes are corrected by a volume factor of the layers. This volume (V_f) is taken as the working volume for ^{137}Cs adsorption, which is considered to be the same as that occupied by the soil fraction less than 2 mm. The

model considers the effective volume V_f to account for the stoniness, which in the Mediterranean soil environment is a main soil property.

Starting from a first monthly deposition on the soil surface

$$C(1, t) = C(1, t-1) + [d(t) / V_f(1)] \quad (1)$$

Where: $C(1, t)$ is the ^{137}Cs concentration at the first compartment at time t ; $d(t)$ is the ^{137}Cs activity deposited at the soil surface, and $V_f(1)$ is the effective thickness of the first compartment. The program calculates F which is the ^{137}Cs flux towards the adjoining compartment and the consequent drop in concentration in the first compartment:

$$C(1, t) = C(1, t-1) + [d(t) / V_f(1)] - [1 / V_f(1)] F [1 \rightarrow 2, t-1] \quad (2)$$

As in the first compartment, there exists in the remaining ones an entry flux, which increases the previous concentration and an exit flux, which reduces it. The program also calculates the radioisotope decay in the time interval being considered. The process is repeated for each time step, and each time includes deposition on the surface, the calculation of new concentrations in all compartments as a result of transfer between them, and the decrease in concentration as a result of radioactive decay.

Assuming that there is a constant rate of erosion the erosion rate is calculated according to equation (3).

$$C(z, t) = (1 / a(z)) [(a(z) - e) C(z, t) + e C(z+1, t)] \quad (3)$$

Where: $a(z)$ is the thickness of the different layers; e is the thickness lost each time step.

The ^{137}Cs loss term per surface unit in each compartment is calculated by multiplying the thickness e by the concentration of the compartment itself whilst the gain term is calculated by multiplying the thickness e by the concentration of the bottom

compartment. The process of concentration calculation is repeated for every unit of time.

A second variable is added to quantify the deposition rate; the thickness of soil deposition, S (cm), modifying the concentration of ^{137}Cs in all layers according to equation (4):

$$C(z, t) = S C(z-1, t) + (1 - S) C(z, t) \quad (4)$$

For cultivated soils as the soil is mixed by tillage, the model has just one compartment that extends from the soil surface to a cultivation depth “ H ” (20 – 25 cm in the study area) and assumes a temporary evolution of the ^{137}Cs concentration in the compartment. The ^{137}Cs activity deposited is homogeneously distributed in the compartment within its V_f . Thus, if $C(t)$ is the total inventory in a given t moment, $c(t-1)$ is the total inventory in the previous moment, and $D(t)$ is the atmospheric ^{137}Cs deposition in that interval. Then, equation (5) is formulated as:

$$C(t) = C(t - 1) + D(t) \quad (5)$$

To estimate the decreases of ^{137}Cs inventories caused by erosion the model uses equation (6), where E is the thickness of the soil layer that is eroded per unit of time:

$$C(t) = C(t - 1) (1 - (E / H V_f)) \quad (6)$$

Similarly, to estimate the increases of ^{137}Cs activity in the compartment for depositional sites, it uses equation (7), where F is the material deposited per unit of time. The model assumes that the deposited material comes from a short distance and has similar ^{137}Cs concentration than that of the analysed point.

$$C(t) = C(t - 1) (1 + (F / H V_f)) \quad (7)$$

To represent the spatial distribution of ^{137}Cs activities and inventories, we used kriging interpolation. This interpolation provides non-measured data in a raster grid by using the mean values of the nearest measured points (number of lags equals 12 and lag

distance equals 27.2), calculated on the basis of the distance between the sampling points and the semi-variance of their values. After examination of the average standard errors for the different kriging types assayed, an ordinary kriging with trend was selected to produce the output maps of soil erosion and deposition from the input points of ^{137}Cs inventories. Maps of isolines of the soil redistribution rate were derived to represent the spatial distribution of soil loss and gain within the catchment. All of the maps, interpolations, and mathematical operations were performed using ArcView GIS[®] 3.2 and ArcMap[™] 10.0.

To assess the statistical significance of the effects of physiographic conditions on the soil redistribution rates at the sampling points, an analysis of variance was performed. To that purpose the data were separated into accumulation and erosion landforms, into 6 geomorphological classes and into low, medium and high slope and α was set to 0.05. Correlation coefficients were used to assess the relationships between terrain curvature, altitude and slope with the radionuclide inventories and the soil redistribution rates.

4. Results and discussion

4.1. ^{137}Cs activities and inventories in the catchment.

The depth distribution of ^{137}Cs activities and inventories at 9 stable reference sites showed an exponential decrease with depth and the shape of the ^{137}Cs profile was consistent with those typically found at stable undisturbed sites where neither erosion nor deposition occurs. The reference inventory of $1570 \pm 80 \text{ Bq m}^{-2}$ established for the catchment (Soto and Navas, 2008; Gaspar et al., 2011) is within the range of values obtained in similar latitude - altitude locations in Spain (Navas et al., 2007).

For the 76 bulk soil cores sampled at the point sites, the ^{137}Cs activities and inventories (Table 2) showed significant variability, ranging from 0.4 to 43.8 Bq kg^{-1} and from 58

to 6396 Bq m⁻², respectively. A similar variability has been documented in other catchments (Stefano et al., 1999; Porto et al., 2006, Martinez et al., 2010), and especially in semiarid landscapes (Kato et al., 2010).

The median activity and inventory values were 9.3 Bq kg⁻¹ and 1501 Bq m⁻², respectively. Inventories lower than the reference for the catchment were recorded in 50 % of the points, 43 % exceeded the reference inventory, and 7 % had inventories that were within the confidence interval around the mean value of the reference sites. These latter points are considered to be within the stability range and have not experienced net soil movement. Therefore, a considerable amount of ¹³⁷Cs has been lost or gained due to water erosion or deposition, respectively, as well as tillage, whereas stability was less common.

The spatial distribution of ¹³⁷Cs activities and inventories in the catchment was highly variable (Fig. 3). In general, the distribution of ¹³⁷Cs activities presented a marked contrast between the northern and the southern sectors of the catchment. The highest ¹³⁷Cs activities were coincidental with the limestone outcrops that constitute the more abrupt relief in the catchment. On the contrary, lower ¹³⁷Cs activity was recorded on the more gentle slopes situated around the lakes and on the western side of the catchment, coinciding with the areas underlain by marls and gypsum of the Keuper Facies. In addition, a strip with low ¹³⁷Cs activity also occurs on a scarp with stony and scarcely vegetated soils and the presence of rock pavements and karren on limestone.

In another catchment within the Pyrenees, Navas et al. (2011) found that ¹³⁷Cs activities were lower on steep and scarcely vegetated scrubland slopes than on gentle forest slopes. Schoorl et al. (2004) analysed the effects of lithology, morphology and land use on the levels of ¹³⁷Cs in stony shallow soils in SE Spain and found higher ¹³⁷Cs concentration and inventory associated with higher percentages of vegetation cover and higher soil

stoniness and bulk density in gneiss soils. Similar results were also reported by Lu and Higgitt (2000).

The spatial distribution of ^{137}Cs inventories was related to the activity values, as shown in figure 3. The lowest ^{137}Cs inventories were found on cultivated fields situated in the lowlands, midslope locations and occupying the bottom of dolines in two sub-catchments at the northern sector of the catchment. All these areas have lost between 50 and 75 % of the fallout ^{137}Cs in the catchment. The highest ^{137}Cs inventories were found on the steep forested slopes of the northern part of the catchment, where undisturbed shallow soils are most abundant. Fukuyama et al. (2008) also found higher ^{137}Cs inventories on the ridge top and upper slope than on the lower slopes in a small forested catchment in Japan.

The distribution of the atmospherically-derived ^{137}Cs depends on the spatial variability of fallout, which can be affected by climate, topography, surface roughness and land cover. Recent studies have documented a dependence of ^{137}Cs inventories on altitude and rainfall (Porto et al., 2009; Zhang et al., 2009) and although this was also recorded along a climatic gradient in the central Ebro basin, NE Spain (Navas et al., 2007), such differences are not found in this small catchment in which rainfall patterns are insignificant. Other sources of variation in fallout ^{137}Cs inventories are related to the impact of nuclear accidents (e.g. Higgitt et al., 1993; Golosov et al., 1999; Van der Perk et al., 2002). However, the impact of the Chernobyl accident in our study area was negligible.

The values of ^{137}Cs activities and inventories do not show a clear trend in relation to the altitude and steepness variables. In a karst landscape in China, Zhang et al. (2009) found that on forest land, ^{137}Cs inventories were positively correlated with the slope gradient

and with the altitude, whereas negative correlations were found with the altitude on cultivated land.

From the field survey of the study area, and as shown in the detailed geomorphological map (Fig. 2), several depositional landforms like doline floors, flat-bottom infilled valleys and colluvium-covered slopes, were identified. Erosional landforms in the catchment include slopes with different gradients and a relict planation surface of probable late Miocene age. According to the results of the ANOVA test, the type of landforms, i.e. accumulation and erosion landforms, was not significant factor affecting the variation of the ^{137}Cs inventories. However, when considering each of the six landforms separately, differences in the means of ^{137}Cs inventories are detected, although they are not statistically significant, perhaps due to the unbalanced size of the set of samples in each group. As can be seen in Table 2, the mean ^{137}Cs inventories are higher in the flat-bottom infilled valleys and doline floors than on the gentle and steep slopes. The latter have lower ^{137}Cs inventories, apart from those found in the colluvium-covered slopes, which reach the lowest values. Similarly, an unbalanced distribution of samples within the groups of each landform type in relation to their relative contribution in the catchment may preclude obtaining statistical significance in these differences. Therefore, as demonstrated in other studies conducted in areas of stony soils and abrupt relief (e.g. Schoorl et al., 2004; Zhang et al., 2009), both the morphology of the landforms and land use influence the spatial distribution of the radionuclide and soil.

4.2. *Spatial distribution of erosion and deposition rates*

The ^{137}Cs -derived method measures soil redistribution and therefore accounts for both soil erosion and deposition. A significant reduction in inventory values in 41 sampling points indicates that these points have experienced net soil loss over the past 45 years

since the onset of ^{137}Cs fallout in the mid 1950s. On the contrary, significant increases in inventory suggest that 35 points have experienced net soil gain and deposition over that period.

The basic statistics for erosion and deposition rates estimated in the catchment are presented in Table 3. The soil erosion rates show large variability and the median value was $4.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$. Three sampling points located at the upslope edge of fields on medium gradient Muschelkalk slopes had the maximum values. The soil deposition values were also highly variable and the median was $3.1 \text{ Mg ha}^{-1} \text{ year}^{-1}$. The three points with maximum deposition were located on the downslope edge of crop fields, on gentle slopes and on the flat-bottom infilled valley. These results are consistent with the geomorphic position of the points and the corresponding land uses.

As shown in the map of figure 4, the spatial distribution of soil loss and deposition follows quite closely the distribution pattern of the ^{137}Cs inventories. The highest erosion rates found in the lowlands around the lakes and in the sub-catchment of the northern divide are on cultivated fields, where they reach as much as $108 \text{ Mg ha}^{-1} \text{ year}^{-1}$. These results seem to contradict the expected pattern because, as generally reported in other Mediterranean catchments (Porto et al., 2009), the highest rates of erosion are generally found in areas of greater relief and elevation, whereas deposition occurs in the lower areas. However, in our catchment, the most intense soil redistribution is related to land cultivation and tillage, which induces both erosion and deposition.

The depositional zones predominate in flat areas and in sectors with moderate to gentle slopes. The presence of extensive flat areas around the lakes favours sediment accumulation, acting as the main sediment sinks of the catchment. In these flat areas deposition rates reach a maximum of $84 \text{ Mg ha}^{-1} \text{ year}^{-1}$. These results demonstrate the important effect of agricultural activities on soil redistribution, as the most intense soil

redistribution occurs in the lowlands of the southern sector of the catchment, where farming is more widespread.

The relationships between soil redistribution rates and topographic attributes, although with moderate correlations, indicate that both soil erosion and deposition decrease as altitudes and slope gradients increase (Table 4). These results appear to be contradictory but can be explained by the fact that the forest area, which efficiently protects the soil from the erosion processes, extends over the steepest and highest area of the catchment. In such conditions, soils have better structure and soil properties and generally are more stable (Navas et al., 2008). Similar results have been found in nearby areas with temperate environments (Navas et al., 2005), as well as in a previous research in the adjoining catchment (Gaspar et al., 2011). The latter authors found stability conditions at the divides and in points located under forest cover on steep slopes. The protective role of the vegetation cover has also been reported in slopes of semiarid areas (Quine et al., 1994).

The spatial distribution of erosion and deposition reveals the complexity of the internally drained karst catchment. Some similarities are observed with the spatial distribution of ^{137}Cs -derived estimates from a gully catchment in the Loess Plateau (China), which showed that soil erosion rates increase from the ridge tops and interfluvies to the lower slopes (Yang et al., 2006). However, although the magnitude of erosion rates is comparable with that in the loess gully catchment, our highest rates for both erosion and deposition are mostly related to the agricultural use of the low and flat areas.

The relationships between the ^{137}Cs -derived estimates of soil redistribution rates and slope curvature were not statistically significant. This was also found by Fukuyama et al. (2008) in a small forested catchment characterized by steep slopes. These authors

conclude that the absence of correlation indicates that soil erosion induced by runoff dominates over the diffusion-like downslope transport processes in long-term soil redistribution, as topographic curvature is one of the key control factors for the latter processes and confirm the importance of advection processes in controlling erosion and sediment redistribution in the study catchment.

When analysing the actual processes occurring on the different landforms, significant concordance was found on erosional forms as they coincide with 34 points out of the 41 ones affected by net soil loss. However, this was not the case for depositional forms, because high deposition rates were estimated only at 6 out of the 35 points located on surfaces identified as aggradational landforms. Furthermore, in those 6 deposition points the estimated rates were much higher ($36.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$) than those computed on erosional landforms, which on average amounted to $8 \text{ Mg ha}^{-1} \text{ year}^{-1}$. The obtained spatially distributed estimates of soil erosion and deposition rates can be used for identifying and analysing the main controls affecting the processes of soil particle generation and erosion, as well as the storage and export of sediments in complex catchments.

As can be seen in Table 5, the largest number of net erosion sites is found on steep slopes, although the highest rates occur on low gradient slopes used for cereal farming. Several studies have illustrated the role of cultivation in triggering soil erosion in a variety of catchments under temperate (Navas et al., 2005, Mabit et al., 2002), subhumid (Di Stefano et al., 1999; Gaspar et al., 2011) and semiarid climates (Navas and Walling, 1992; Quine et al., 1994). The old planation surface located in the northern divide also shows net erosion, but rates are very low due to its nearly flat topography. On the contrary, the depositional forms as the steep colluvium-covered slopes are suffering erosion at the present. The few cases where estimated erosion occurred on

flat-bottom valleys and doline floors, typical depositional landforms, are due to tillage and the rates are considerably high. Deposition is recorded both on depositional landforms and on gentle to steep slopes. However, as shown in Table 5, deposition rates in the latter are significantly lower. Therefore, apart from some colluvium-covered slopes, which are undergoing erosion, there is close concordance between the actual processes of soil mobilization and the geomorphological landforms identified in the catchment. Erosion is generally linked to erosional landforms but the relationship is not so clear for deposition, because of the anthropogenic impact on the landscape and geomorphic processes mainly due to agricultural activity. On the other hand, although grading of the slopes means that soil movement is taking place, the most common process being water erosion, the natural cycle also includes deposition and intra-storage accumulation of the mobilized sediment.

This study illustrates that ^{137}Cs estimates of soil redistribution combined with GIS techniques integrating geomorphological information based on a detailed DEM, constitute a useful methodology for identifying landforms affected by net erosion and aggradation and for assessing spatially distributed erosion and deposition rates for medium time scales in complex catchments.

The concave surfaces of the catchment (Fig. 1) include 21 deposition points with a median value of $4.3 \text{ Mg ha}^{-1} \text{ year}^{-1}$ and 19 erosion points with a median value of $2.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$, of which 11 points occur in areas with natural vegetation cover and show slightly lower erosion rates ($1.2 \text{ Mg ha}^{-1} \text{ year}^{-1}$). Erosion sites were more abundant on the convex surfaces (22) than deposition sites (14). In addition, median values of erosion rates of $4.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$ were slightly higher than the values on concave surfaces. Furthermore, deposition rates were also lower ($2.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$) than the median estimates on concave surfaces. On agricultural landscapes underlain by till

deposits in the USA, Ritchie and McCarty (2008) also found lower erosion rates on concave slopes than on convex slopes. Similar soil redistribution patterns were also reported by Pennock and Frick (2001) in Canada. Although this general trend of soil redistribution patterns on concave and convex surfaces was also observed in our study, it was not as straightforward as expected, because of the physiographic complexity of this catchment with significant variation in terrain attributes and the impact of cultivation as the main factor affecting soil redistribution processes

At catchment scale, it is generally accepted that soil redistribution estimates by fallout ^{137}Cs are highly correlated with topographical attributes and, therefore, it may be possible to distinguish between depositional and erosional classes, even when the differences between topographical and morphological classes are quite small (Martz and de Jong, 1987). Conceptual models by Campbell et al. (1982) and Loughran et al. (1989) established ^{137}Cs lateral distribution variations at slope scales that explained the soil redistribution processes along hillslopes. Such soil redistribution patterns have also been found in semiarid slopes in Las Bardenas (Navas and Walling, 1992; Quine et al., 1994) and in abrupt reliefs of SE Spain (Schoorl et al., 2004). In the latter case, Schoorl et al. (2004) found limited accumulation on slightly concave slope positions and medium to low soil loss at convex and straight slope segments, although land use was also found to be a key factor affecting the distribution pattern of ^{137}Cs and soil.

The results shown in Table 6 support the concept that land use is a key control factor of soil redistribution in the catchment. Cereal crops and pastures are the land covers affected by highest erosion, whereas dense scrubland and forest efficiently protect the surface from soil erosion processes.

The estimated soil loss and soil deposition values correlate positively and significantly (95 % confidence level) to increasing values of contributing area (A_i) for each sampling

point (Fig. 5a, b). Therefore, the larger the contributing area, the higher the rates of both soil loss and deposition can be expected. Although both positive and negative correlations have been found between the values of sediment yield and the size of the contributing area in different studies (de Vente et al., 2007), it is well accepted that positive correlation is the predominant relationship between soil redistribution values (both loss and deposition) and the upslope contributing area for small catchments (de Vente and Poesen, 2005; López-Vicente and Navas, 2010). This trend and correlation values similar to those presented in Fig. 5a were obtained by Fukuyama et al. (2008) in undisturbed forested slopes in Japan using ^{137}Cs and $^{210}\text{Pb}_{\text{ex}}$ measurements to estimate erosion rates. Nonetheless, this correlation weakens in our study when the slope steepness factor is combined with the contributing area ($A_i * S_i$) (Fig. 5c) to explain the variability in soil loss for individual sampling points. This fact, which is apparently contradictory and is not in agreement with the results of Fukuyama et al. (2008), is explained by the more important role played by the A_i factor than the S_i factor in our catchment. Our study area is highly modified by anthropogenic activity and almost all the gentle slopes are used for cultivation, which stimulates intense human-induced soil redistribution clearly modifying the natural dynamics of soil erosion. However, the ratio between the A_i and S_i factors improves the correlation with the soil deposition values (Fig. 5d). Therefore, the results of this study shows that the combined use of the contributing area and slope steepness factor could be a more interesting tool for identifying erosion and deposition-prone areas than the use of any of these factors individually.

5. Conclusions

The spatial distribution of ^{137}Cs inventories in the studied internally drained karst catchment provided the basis for estimating soil redistribution, erosion and deposition at the catchment scale. This contribution illustrates the potential of ^{137}Cs measurements to quantify medium-term soil erosion and redistribution rates and provides quantitative data for understanding sediment dynamics in complex karst catchments.

Erosion and deposition processes that contribute to the current landscape form are comparable both in magnitude and surface extension, as is expected in an internally drained catchment with no outlet for sediments. Cultivation plays a more important role than natural factors on soil erosion, sediment transport and deposition within the catchment. The case study also illustrates the importance of the intra-storage of the mobilized sediment within the catchment.

The results of this study show the potential of combining detailed geomorphological mapping and ^{137}Cs measurements with GIS methods to derive information about contemporary soil redistribution processes occurring on the different geomorphic elements identified in the catchment. Upscaling to larger catchments highlights the need to develop cost-effective methodological strategies to provide sound information on soil redistribution processes from a limited number of sampling points.

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725

726 **Figures**

727 Fig. 1. The study area. Location of the catchment of the Estanque de Arriba Lake within
728 the Ebro River basin (NE Spain). Image in 3D of the catchment produced with
729 ArcScene using orthophotographs. DEM and location of the sampling points. Maps of
730 land use, slope steepness and terrain curvature.

731 Fig. 2. Geomorphological map of the analysed catchment..

732 Fig. 3. Spatial distribution of ^{137}Cs activities and inventories and isolines of percentage
733 of ^{137}Cs gain and loss in the catchment.

734 Fig. 4. Spatial distribution of estimated soil erosion and deposition rates in the
735 catchment.

736 Fig. 5. Relationships between: (a,b) the contributing area and the soil erosion and
737 deposition rates, (c) the product of the contributing area and the slope steepness factors
738 and the soil erosion rates and (d) the ratio of the contributing area and the slope
739 steepness factors and the deposition rates in the Estanque de Arriba catchment.

Table 1. Characteristics of the subcatchments in the catchment (4) that holds the Estanque de Arriba and main geomorphic elements.

Sub-catchment number	Surface	Lithology			Soil type			Geomorphology
	ha	Keüper	Muschelkalk	Recent deposits	Leptosol	Calcisol	Regosol	Main features
		Percentage from the total surface						
1	7.5	8	85	7	55	40	5	Doline (n=1)
2	1.0	0	86	14	97	3	0	Doline (n=1)
3	0.5	1	99	0	1	99	0	Doline (n=1)
4 “Lake”	70.6	17	61	22	44	17	39	Doline (n=4)
								Uvala (n=1)
								Gullies (n=8)
								Regularized slopes
								Rock pavements
All	79.5	16	64	20	45	19	36	

Table 3. Basic statistics of soil erosion and deposition rates (Mg ha⁻¹ year⁻¹) in the soils of the catchment.

Soil redistribution Mg ha ⁻¹ year ⁻¹	n	Mean	SD	SE	Range	CV %
Erosion rate	41	21.4	30.3	4.7	108.0	141.7
Deposition rate	35	13.2	23.2	3.9	83.3	176.2

SD standard deviation
SE standard error

Table 4. Pearson correlation coefficients between soil erosion and deposition rates and altitude and slope gradient.

	Erosion rate Mg ha ⁻¹ year ⁻¹	Deposition rate Mg ha ⁻¹ year ⁻¹
Altitude m	-0.347	-0.541
Slope gradient °	-0.444	-0.380
Bold face numbers are significant at the 95 % confidence level		

Table 5. Mean of soil erosion and deposition rates for six different geomorphological forms.

	Erosion rate			Deposition rate		
		Mg ha ⁻¹ year ⁻¹			Mg ha ⁻¹ year ⁻¹	
	n	Mean	SD	n	Mean	SD
Colluvial deposit	3	10.1	8.5		-	-
Doline deposit	2	39.2	18.4	3	33.0	44.2
Flat valley deposit	2	56.3	73.6	3	40.0	37.7
Late Miocene erosion surface	1	0.4	-	2	5.8	5.2
Regularized low slope	6	53.8	40.0	10	13.9	27.3
Regularized steep slope	27	12.3	20.0	17	5.4	4.8
SD standard deviation						

Table 6. Soil redistribution rates for the different slope ranges and land uses in the catchment.

	n		n	Mean	SD	Median	Min.	Max.
						Mg ha ⁻¹ year ⁻¹		
Slope ranges %								
0-12	13	Erosion	5	57.4	46.5	52.2	0.4	108.3
		Deposition	8	32.6	35.4	24.6	1.0	83.6
12-24	21	Erosion	10	24.5	32.4	7.4	0.8	101.0
		Deposition	11	9.4	22.7	2.4	0.3	77.8
> 24	42	Erosion	26	13.2	20.2	4.0	0.3	78.3
		Deposition	16	6.1	5.4	3.3	0.5	17.7
Land uses								
Abandoned fields	6	Erosion	4	17.3	31.9	1.8	0.4	65.1
		Deposition	2	6.5	7.8	6.5	1.0	12.0
Bare soil	4	Erosion	4	9.6	14.3	3.4	0.7	30.9
		Deposition		-	-	-	-	-
Cereal crop	19	Erosion	11	40.3	40.5	26.2	0.8	108.3
		Deposition	8	42.8	35.4	39.9	1.7	83.6
Grazing	4	Erosion	3	54.5	40.4	33.8	28.7	101.0
		Deposition	1	2.4	-	2.4	2.4	2.4
Forest dense	13	Erosion	6	6.8	10.0	2.8	0.4	26.6
		Deposition	7	3.5	3.9	2.7	0.3	11.8
Forest open	12	Erosion	6	12.2	15.0	6.2	0.8	38.9
		Deposition	6	4.8	4.2	2.9	1.0	10.9
Scrubland dense	7	Erosion	2	2.8	1.8	2.8	1.5	4.1
		Deposition	5	2.9	1.5	2.4	1.3	5.2
Scrubland sparse	11	Erosion	5	8.5	11.8	3.8	0.3	29.4
		Deposition	6	5.9	6.0	3.7	1.8	17.7
SD standard deviation

Geology

- Muschelkalk Facies
- Keuper (gypsum) Facies
- Keuper Facies

Structural features

- Scarp
- Minor scarp
- Contour line (each 20 m)

Planation surface

- Late Miocene

Karst processes

- Karren
- Uvala
- Collapse doline
- Doline
- N limit of the Saganta relict polje
- Doline deposit

Hydrological processes

- Spring
- Gully
- Flat-bottom infilled valley

Endorheic areas

- Secondary divide
- Endorheic boundary
- Lake

Hillslope features

- Talus
- Rock pavement (> 80%)
- Colluvial deposit
- Steep slope

Anthropogenic elements

- Irrigation ditch

Soil Erosion and Deposition

- Lake
- Catchment boundary
- Endorheic sub-catchment boundary
- Sampling point

Kriging prediction map (soil deposition)

$\text{Mg ha}^{-1} \text{ yr}^{-1}$

- 40 - 75
- 10 - 40
- 3 - 10
- 1.5 - 3
- 0.5 - 1.5
- 0 - 0.5

Kriging prediction map (soil erosion)

$\text{Mg ha}^{-1} \text{ yr}^{-1}$

- 40 - 97
- 10 - 40
- 3 - 10
- 1.5 - 3
- 0.5 - 1.5
- 0 - 0.5

Soil Erosion

Soil Deposition