VALIDATING THE USE OF ^{137}Cs MEASUREMENTS TO DERIVE THE SLOPE COMPONENT OF THE SEDIMENT BUDGET OF A SMALL RANGELAND CATCHMENT IN SOUTHERN ITALY

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ABSTRACT

The sediment budget is a key concept and tool for characterizing the mobilisation, transfer and storage of fine sediment within a catchment. Caesium-137 measurements can provide valuable information on gross and net erosion rates associated with sheet and rill erosion that can be used to establish the slope component of a catchment sediment budget. However, there is a need to validate the use of ^{137}Cs measurements for this purpose, since their reliability has sometimes been questioned. The study reported focuses on a small (3.04 ha) steepland (mean slope 37%) catchment in Southern Italy. It exploits the availability of information on the medium-term sediment output from the catchment provided by the construction of a reservoir at its outlet in 1978 and the existence of estimates of soil redistribution rates derived from ^{137}Cs measurements made on 68 replicate soil cores collected from the slopes of a substantial proportion of the catchment, to validate the use of ^{137}Cs measurements to construct the slope component of the catchment sediment budget. An additional 50 replicate soil cores were collected from the catchment slopes for ^{137}Cs analysis, to complement the data already available for constructing the slope component of the sediment budget. Nine cores collected from the area occupied by the reservoir were used to estimate the mean annual sediment input to the reservoir. In the absence of evidence that the poorly developed channel system in the catchment was either a significant sediment source or sink, it was possible to directly compare the estimate of net soil loss from the catchment slopes (7.33 Mg ha^{-1} yr^{-1}) with the estimate of sediment output from the catchment provided by the reservoir deposits (7.52 Mg ha^{-1} yr^{-1}).

Taking account of the uncertainties involved, the close agreement of the two values is seen as providing a convincing validation of the use of ^{137}Cs measurements to both estimate soil redistribution rates and as a basis for constructing the slope component of the sediment budget of a small catchment.

Keywords: fallout radionuclides; caesium-137; soil erosion; sediment budget; validation; Italy

1. INTRODUCTION

The catchment sediment budget is a valuable concept and tool for characterizing the mobilization, transfer and storage of fine sediment within a catchment (Walling & Collins, 2008; Gellis & Walling, 2011; Navas *et al.*, 2014). From a geomorphological or hydrological perspective, it provides a valuable means of representing the interaction between the processes of sediment mobilization, transfer and storage and the relative magnitude of the fluxes and stores involved. From an agricultural perspective, it provides a basis for viewing soil erosion and soil degradation within a broader landscape context (Cerdà *et al.*, 2009; Zhao *et al.*, 2013). From a management perspective, it provides key information required to develop an effective sediment management or control strategy for a catchment. Mitigation measures need to target important sediment sources and transfer pathways, in order to reduce sediment mobilization and transfer, and prediction of the effects of controlling particular sources requires a sound understanding of their connectivity to the sediment output from a catchment and the potential for remobilizing sediment from existing sediment sinks. However, whilst valuable as a concept and synthesizing tool, establishing a sediment budget can prove a difficult task due to the wide range of processes involved and their temporal and spatial variability. Most successful attempts to establish a sediment budget have involved the integration of several different techniques/methodologies that together provide the required information on sediment mobilization, redistribution, transport, and storage within a catchment (see Loughran *et al.*, 1992; Walling *et al.*, 2001, 2002; Keesstra *et al.*, 2009; Porto *et al.*, 2009b, 2011; Gellis & Walling, 2011; Navas *et al.*, 2013, 2014, Minella *et al.*, 2014). The use of fallout radionuclides, particularly caesium-137 (^{137}Cs), as a sediment tracer has been shown by many of those studies to provide an effective and valuable means to document the mobilization and redistribution of soil and sediment on the slopes of a catchment (Mekuria *et al.*, 2012; Li *et al.*, 2014).

Caesium-137 measurements are able to provide the spatially distributed data on medium-term (i.e. ca. 50 year) soil redistribution rates associated with sheet and rill erosion needed to characterize the slope component of a catchment sediment budget. However, the use of ^{137}Cs measurements to document soil redistribution rates has traditionally focussed on individual fields or very small watersheds where intensive sampling, commonly grid- or transect- based, can be undertaken (Ritchie & Ritchie, 2005). When larger areas are involved, as will generally be the case when establishing a sediment budget for a small or intermediate-sized catchment, alternative sampling strategies will be required. Cost and other operational constraints on the number of samples that can be collected and analysed necessitate new procedures, to upscale the approach traditionally applied to small areas (see Walling *et al*., 2014). One procedure, developed and reported by Porto *et al.* (2011), involves collecting soil cores for ^{137}Cs measurement from representative sampling points distributed across the slopes of a small or medium-sized catchment. The resulting dataset of soil redistribution rates is assumed to be representative of the catchment slopes and is used to characterize the relative frequency of points experiencing erosion and deposition and the frequency distributions representing the magnitude of the erosion and deposition rates involved. This information in turn provides the information required to derive the slope component of the sediment budget for the study catchment.

Although ^{137}Cs measurements have now been successfully used in many areas of the world as a means of estimating soil redistribution rates (see Ritchie and Ritchie, 2005; Mabit *et al*., 2013), some uncertainty exists regarding the reliability of the data obtained (see Parsons and Foster, 2011). Many of the concerns highlighted by Parsons & Foster (2011) have been addressed by Mabit *et al.*

(2013), but there remains a need to provide empirical validation of estimates of soil redistribution rates derived from ^{137}Cs measurements. Attempts to provide such validation necessarily face important practical problems, since the ^{137}Cs approach is a retrospective approach and provides estimates of redistribution rates for the period extending from the beginning of bomb fallout in the mid 1950s or from the time of peak fallout in 1963, to the time of sampling. It is clearly not possible to now set up experiments to provide independent estimates of soil redistribution rates for this period. Furthermore, since the potential for using ^{137}Cs measurements to estimate soil redistribution rates was not fully recognized until after the main period of bomb fallout, no contemporary validation experiments were established. There is therefore a need to seek out and exploit other more adventitious sources of data which can provide a basis for validation exercises.

The study reported in this contribution makes use of the independent information on net soil loss provided by the amount of sediment deposited in a reservoir constructed at the outlet of a small 3.04 ha catchment in Southern Italy, to compare the measured net soil loss with that estimated using ^{137}Cs measurements. A sampling campaign undertaken in 1999 had provided ^{137}Cs measurements and associated estimates of soil redistribution rates for a substantial proportion of the catchment and it was therefore not necessary to undertake a costly major ^{137}Cs sampling programme. It was only necessary to sample the lower part of the catchment, which had not been sampled previously. The overall ^{137}Cs sampling programme was designed to implement the approach to establishing the slope component of the sediment budget for the small study catchment developed by Porto *et al.* (2011). The validation exercise therefore also provided an opportunity to validate both the estimates of soil redistribution rates provided by the ^{137}Cs measurements and the use of a set of representative sampling points to establish the slope component of the sediment budget for a small catchment.

2. THE STUDY AREA

In 1978, the National Research Council of Italy (CNR) initiated a soil erosion monitoring programme in Calabria (Southern Italy), within the research framework of the ‘Soil Conservation

Project'. The primary aim of this long-term programme was to monitor the effects of afforestation on hydrological and erosion processes at the catchment scale (Porto *et al.*, 2009a). As part of this project, three small catchments (ca. 1.5 ha in size), within the larger Crepacuore basin and located near Crotone (35 m a.s.l., 39º09'02"N, 17º08'10"E), were instrumented to provide records of rainfall, runoff and sediment yield (**Fig. 1**).

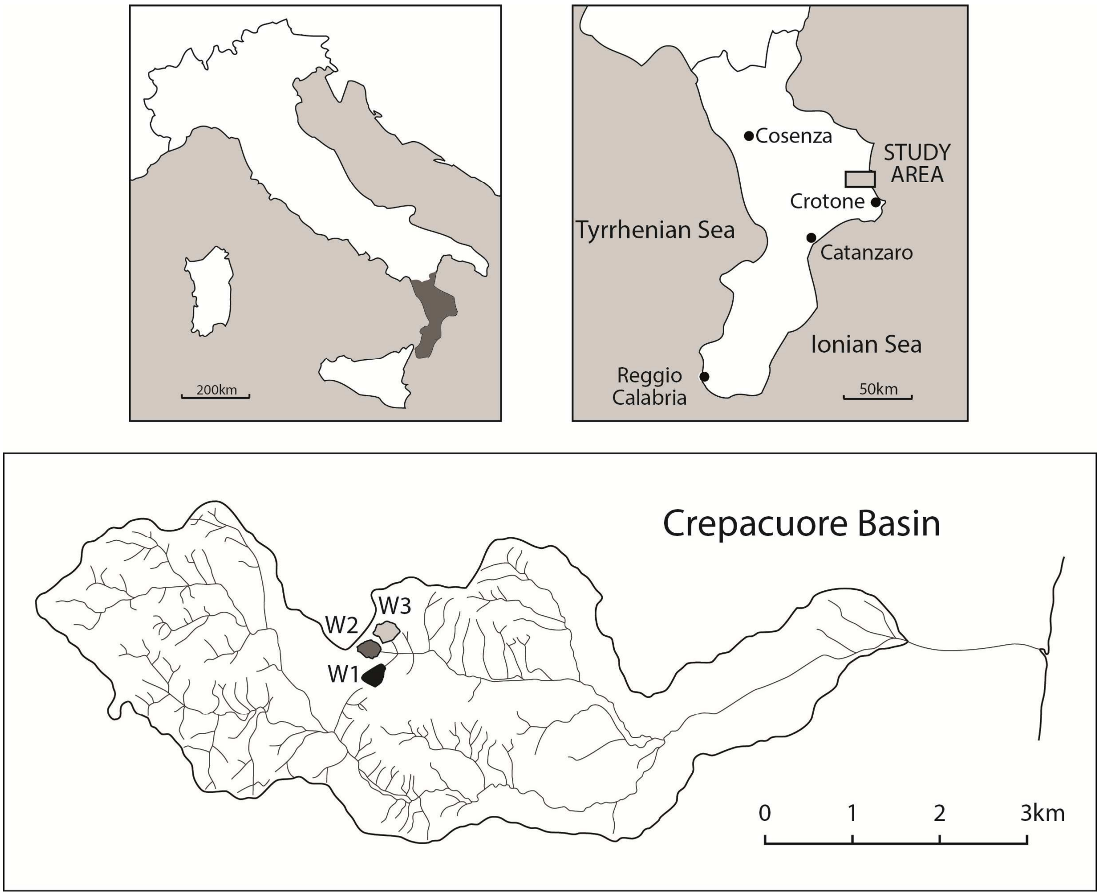

Fig. 1 – The study area

The catchments have never been cultivated and originally supported a rangeland vegetation cover dominated by *Lygeum spartum* Loefl. and *Atriplex halimus* L.. In 1968, two of these catchments (W2 and W3) were planted with *Eucalyptus occidentalis* Engl., while the third (W1) was left unmodified and under rangeland as a control (Cinnirella *et al.*, 1998). In 1978, a small earth dam was constructed below a marshy area located downstream of the W1 catchment outlet, with the aim of creating a water storage reservoir. When full, the reservoir upstream of this dam stores ca. 3000

m^3 of water that supplies the local farmer with water for irrigation and other purposes during the dry months of the year. The reservoir has no provision for overflow and retains all the runoff input from the upstream catchment area. The water used for irrigation and other purposes is abstracted via a pipe which passes through the dam. The reservoir has a surface area of ca. 0.18 ha during the rainy seasons and it occasionally becomes dry in summer. The reservoir and the sediment deposits that it contains have not been disturbed since the dam was constructed. The catchment of the reservoir includes both catchment W1 (1.47 ha) and the additional intervening area (1.57 ha) that supports the same vegetation cover. This is designated the ‘Corrado’ catchment which represents the focus of this study.

The Corrado catchment (see Figs. 2 and 3) has an area of 3.04 ha and ranges in altitude from 155 m a.s.l. at the highest point to 85 m a.s.l. at the catchment outlet where the dam is located. The dominant soils are classified as regosols and exhibit an Ap-C profile with a variable depth. Further details of the topography and soil texture within the Corrado catchment are provided in Table 1. The climate of the area is typically Mediterranean, with a mean annual rainfall for the period 1954-2012 of ca. 670 mm, at Crotone (10 km distant). Most of the rainfall falls between October and March. The annual potential evapotranspiration in this location is estimated to be 1100 – 1200 mm (based on the Penman-Monteith formula). Unlike catchments W2 and W3, no trees were planted in this catchment and it retains its rangeland vegetation cover, comprising both grass and shrubs (see Fig. 3). The dominant species are *Lygeum spartum, Asteriscus spinosus, Atriplex halimus, Carduus pycnocephalus, Pistacia lentiscus, Spartium junceum, Ferula communis and Arundo plinii.* The rangeland is grazed by sheep. Sheet and rill erosion are the dominant erosion processes within the Corrado catchment, and ^{137}Cs measurements should therefore provide meaningful estimates of gross and net erosion rates.

Table 1 Key characteristics of the study catchment

Drainage area (ha)	Mean altitude (m a.s.l.)	Mean slope (%)	Soil texture		
			Sand (%)	Silt (%)	Clay (%)
3.04	112	37	10.5	47.2	42.3

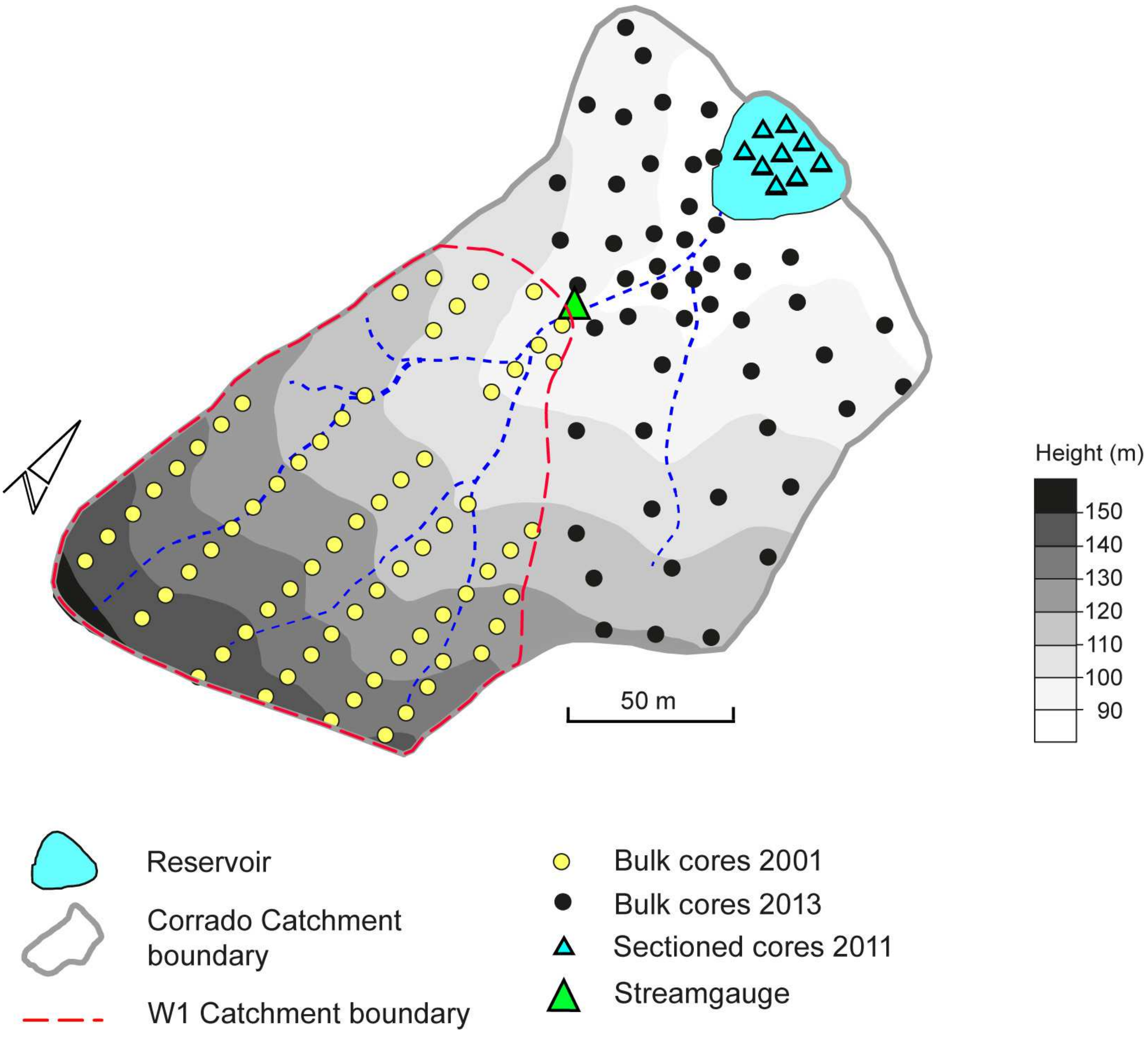

Fig. 2 – The Corrado catchment, showing the area occupied by catchment W1 and the additional contributing area above the dam, and the location of the sampling points within the catchment.

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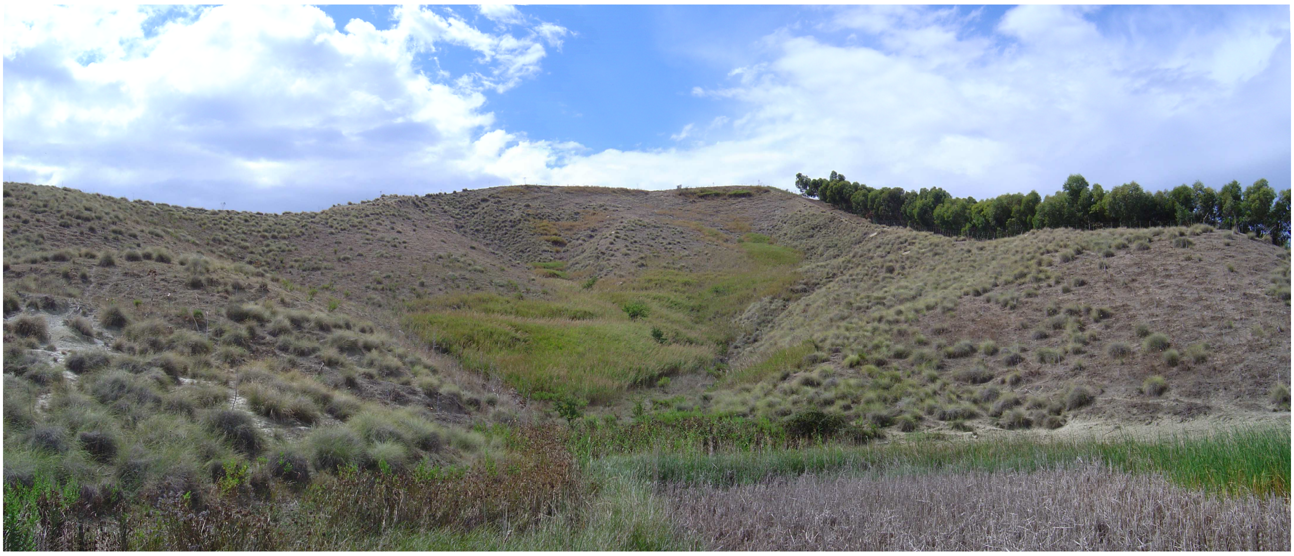

Fig. 3 - A view of the upper part of the Corrado catchment looking from the north.

3. METHODS

3.1 Soil and sediment sampling

The ^{137}Cs measurements used to estimate rates of erosion and sediment redistribution within the Corrado catchment were based on four sampling campaigns undertaken at different times. The first two sampling campaigns were undertaken within catchment W1 (see Porto *et al.*, 2004). The remaining two focussed on documenting the ^{137}Cs depth distribution in sediment cores collected from the reservoir, in order to estimate the sedimentation rate, and extending the sampling undertaken within catchment W1 across the remainder of the Corrado catchment. The first sampling campaign was undertaken in 1999 and this focussed on establishing the local reference inventory (Porto *et al.*, 2001). An area of undisturbed rangeland, adjacent to the W1 catchment, with minimal slope and similar altitude was selected as a reference site. One set of samples was collected from this site using a scraper plate (cf. Campbell *et al.*, 1988). The sampling frame isolated a surface area of 652 cm^2 for sampling and depth incremental samples were collected at increments ranging from

1 to 4 cm (progressively increasing with depth) to a depth of 50 cm. In addition, six 8.6 cm diameter soil cores were collected from the reference site to a depth of 50 cm and sectioned into 2 cm depth increments, in order to assess the local spatial variability of the ^{137}Cs inventory and characterize its depth distribution (Sutherland, 1994, 1996). The core tubes were driven into the soil using a motorized percussion driver and subsequently extracted using a hand-operated winch. A second field campaign was undertaken in 2001 and involved the collection of 68 replicate bulk cores within catchment W1 using a steel core tube (6.9 cm diameter). The core tube was driven into the soil using a motorized percussion driver to a depth of ca. 30 cm at most sampling points, but where there was evidence of deposition the coring depth was increased to ca.60 cm. The sampling points

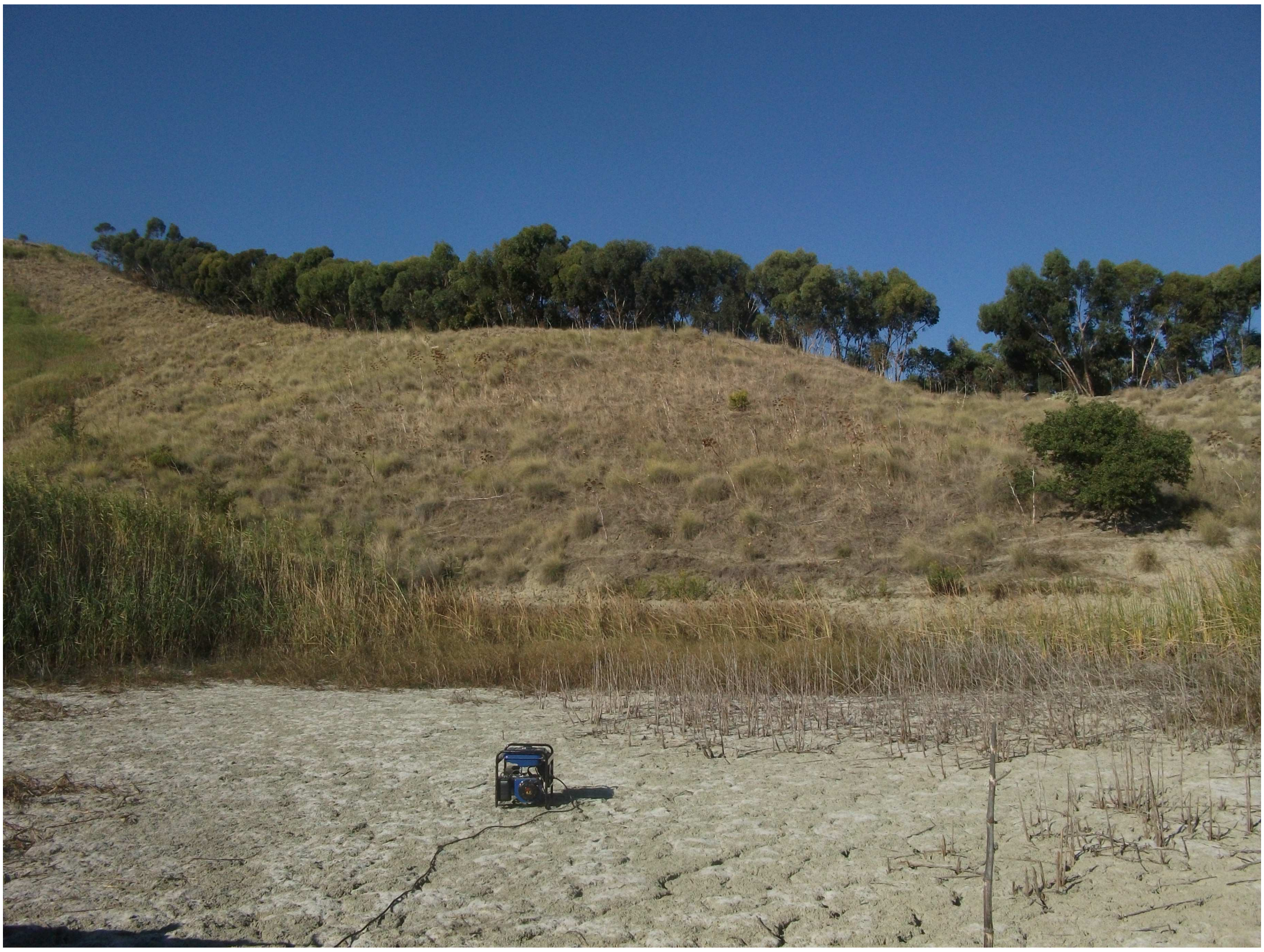

Fig. 4 – The sediment deposits in the reservoir constructed at the outlet of the Corrado catchment, prior to sampling

(see **Fig. 2**) were selected to provide a representative coverage of catchment W1. The replicate cores were combined to provide a single bulked core.

In 2011, after a long dry period which caused the reservoir to become dry, a third field campaign focussed on the sediment deposited in the reservoir (see **Fig. 4**). This involved the collection of nine sectioned cores from locations selected to provide a representative coverage of the area covered by the reservoir (see **Fig. 2**). In this case sampling was undertaken using a 11 cm diameter steel core tube driven into the reservoir sediments to a depth of ca. 100 cm, using the percussion driver. The resulting cores were sectioned at depth increments of 2 cm, to a depth of 100 cm. In 2013, a fourth field campaign was organised in order to cover the additional area of the Corrado catchment that was not included in the previous sampling programmes. In this case, 50 replicate bulk cores (**Fig. 2**) were collected using a steel core tube (10 cm diameter) driven into the soil by a motorized percussion driver. As in the 2001 sampling campaign, the coring depth was ca. 30 cm in most locations and up to ca. 60 cm at sites where there was evidence of deposition. The replicate cores were combined to provide a single bulked core. The sampling points were selected to provide a representative coverage of the area within the Corrado catchment not sampled previously. A number of scraper plate profiles were also obtained from several representative sites within the study catchment, using the same procedure as employed at the reference site, in order to characterize the depth distribution of ^{137}Cs.

3.2 Sample preparation and analysis for ^{137}Cs activity

Each soil or sediment sample was oven dried at 105° C for 48 h, disaggregated and dry sieved to separate the <2 mm fraction. A representative sub-sample of this fraction (ranging from 0.1 to 1.2 kg) was packed into a plastic pot or a perspex Marinelli beaker for determination of its ^{137}Cs activity by gamma spectroscopy.

The first and the second sets of samples collected in 1999 and in 2001, which included both the depth incremental samples collected using a scraper plate from the reference area, the six cores collected from the reference site and the 68 bulk cores from the catchment W1, were analysed using a high resolution HPGe detector in the laboratory of the Department of Geography at the University of Exeter, UK. Count times were ca. 30000s, providing a precision of ca. ±10% at the 95% level of confidence. The third and the fourth sets of samples, collected in 2011 and in 2013, which included the 9 sectioned cores from the reservoir and the 50 bulk cores and scraper plate profiles collected from the rest of the catchment, were analysed using high resolution HPGe detectors in the Department of Agraria at the University Mediterranea of Reggio Calabria. In both laboratories, the gamma detectors were calibrated using standards produced by adding a measured amount of certified liquid standard to a known amount of < 2 mm soil/sediment with a ^{137}Cs activity below the level of detection and representative of the samples to be analysed. Because of the expected lower activity of these samples, counting times were increased to ca. 80000s providing a precision of ca. ±10% at the 95% level of confidence. The total inventory or areal activity density (Bq m^{-2}) of each bulk core was calculated as the product of the measured ^{137}Cs activity (Bq kg^{-1}) and the dry mass of the <2 mm fraction of the bulk core (kg), divided by the surface area of the core or cores associated with the sample (m^{2}).

3.3 Estimating soil redistribution rates from ^{137}Cs measurements

The Corrado catchment is entirely uncultivated, and a conversion model based on a diffusion and migration model (see Walling & He, 1999; Walling *et al.*, 2002) was used to derive estimates of soil erosion and redistribution rates within the catchment from the ^{137}Cs measurements. This model takes account of the temporal distribution of the fallout input, the progressive post-depositional downward diffusion and migration of ^{137}Cs in the soil profile and the contrast in the interaction between fallout and soil loss associated with periods of active fallout and later periods when fallout had effectively ceased. Post fallout redistribution within the soil profile is modelled using a simplified one dimensional transport model characterized by an effective diffusion coefficient D (kg^{2} m^{-4} yr^{-1}) and a migration rate V (kg m^{-2} yr^{-1}) (Walling & He, 1993). The two lumped parameters D and V reflect all active redistribution processes, including physico-chemical processes involving the adsorption and desorption of ^{137}Cs by soil particles, downward migration of clay particles and soil mixing by faunal activity. Based on these assumptions, and also assuming a constant rate of lowering of the surface by erosion E (kg m^{-2}) and diffusional transport, the vertical distribution of ^{137}Cs within a soil, for any cumulative mass depth and time t', can be expressed (Porto *et al.*, 2013) as:

$$C_e\,(x,t,t') = e^{-\lambda(t-t')} \int_0^{\infty} \frac{I(t')}{H}\, e^{-\frac{y}{H}} \left\{ \left[e^{-\frac{[(x+E)+y]^2}{4D(t-t')}} + e^{-\frac{[(x+E)-y]^2}{4D(t-t')}} \right] \frac{1}{\sqrt{4\pi D(t-t')}} \right\} dy \qquad (1)$$

where:

$C_e(x,t,t')$ = the concentration of ^{137}Cs for any cumulative mass depth x and time t' (Bq kg^{-1}).

D = the effective diffusion coefficient (kg^2 m^{-4} yr^{-1});

H = the relaxation depth of the initial distribution of fallout expressed as a mass depth (kg m^{-2});

λ = the decay constant for ^{137}Cs (0.023 yr^{-1});

x = the mass depth from the soil surface downwards (kg m^{-2});

t = the time since the first deposition of ^{137}Cs (yr);

$I(t')$ = the annual fallout deposition flux (Bq m^{-2} yr^{-1}) at time t'.

Eq. (1) is integrated over a soil layer of variable thickness y (here expressed in kg m^{-2} as a mass length) assuming a diffusional transport in a water saturated porous medium (see Lindstrom & Boersma, 1971; Pegoyev & Fridman, 1978).

The ^{137}Cs concentration $C_e(x,t)$ (Bq kg^{-1}) in the soil profile at time t can be obtained by integrating $C_e(x,t,t')$ over time t':

$$C_e\,(x,t) = \int_0^{t} C_e\left(x,t,t'\right) dt \qquad (2)$$

Integration of $C_e(x,t)$ over mass depth x gives the total ^{137}Cs inventory A_u (Bq m^{-2}) for an eroding site at time t:

$$A_u(t) = \int_0^\infty C_e(x,t)\ dx \tag{3}$$

Assuming a constant value of H (5 kg m^{-2}), as suggested by Walling & He (1999), Eqs. (1) and (3) can be solved simultaneously for E (kg m^{-2}), with A_u (Bq m^{-2}) representing the measured inventory at an eroding point. The erosion rate R (kg m^{-2} yr^{-1}) may then be estimated by dividing the quantity E by the time t-t_0 (yr) since the commencement of ^{137}Cs fallout.

For a depositional site, the deposition rate D_R can be estimated from the ^{137}Cs concentration in deposited sediment $C_d(t')$ and the excess ^{137}Cs inventory (defined as the total measured ^{137}Cs inventory A_u less the local reference inventory A_{ref}) using the following relationship:

$$D_R = \frac{A_u - A_{ref}}{\int_{t_0}^{t} C_d\ (t')\, e^{-\lambda(t-t')} dt'} \tag{4}$$

Assuming that the ^{137}Cs concentration $C_d(t')$ of deposited sediment can be represented by the weighted mean of the ^{137}Cs concentration of the sediment mobilised from the upslope contributing area, $C_d(t')$ can be calculated as:

$$C_d(t') = \frac{1}{\int_S R\, dS} \int_S C_e(t')\, R\, dS \tag{5}$$

where S (m^2) is the upslope contributing area and $C_e(t')$ (Bq kg^{-1}) is the ^{137}Cs concentration of sediment mobilised from an eroding point, which can be calculated from Eq. (1), assuming $x = 0$.

The model can be further refined to take account of grain size selectivity associated with soil mobilisation and deposition processes, which will result in the enrichment of mobilized sediment in ^{137}Cs relative to the parent soil or depletion of deposited sediment in ^{137}Cs relative to the mobilised (transported) sediment (see Walling *et al.*, 2011).

4. RESULTS

4.1 ^{137}Cs inventories

Figure 5 presents examples of the depth distribution of ^{137}Cs in the study area representative of the reference site (**Fig. 5a**), and sampling points characterized by erosion (**Fig. 5b**) and deposition (**Fig. 5c**). These depth distributions conform to those expected of uncultivated areas (e.g. Walling & Quine, 1995). All demonstrate the expected exponential decline of activity with depth, with the eroding site demonstrating progressive loss of soil from the surface of the profile and the depositional site providing evidence of progressive accretion. Because of the greater surface area associated with the samples collected from the reference site in 1999 using a scraper plate, the inventory indicated by these samples, rather than by the cores collected from the site, was used to establish the ^{137}Cs reference inventory for the study area. The inventory measured in 1999 was adjusted by taking account of radioactive decay to represent the value at the end of 2001 when the samples were collected from catchment W1. This value was calculated to be 2492 Bq m^{-2} (see Porto *et al.*, 2004). In order to estimate the soil redistribution rates for the set of samples (collected in 2013), this value was decay corrected to the year 2013 and was calculated to be 1849 Bq m^{-2}. Existing work by the authors in the local region indicated that Chernobyl fallout was of very limited importance in this part of Italy. It has been assumed that all the reference inventory was contributed by bomb fallout, when using the ^{137}Cs measurements to estimate soil redistribution rates.

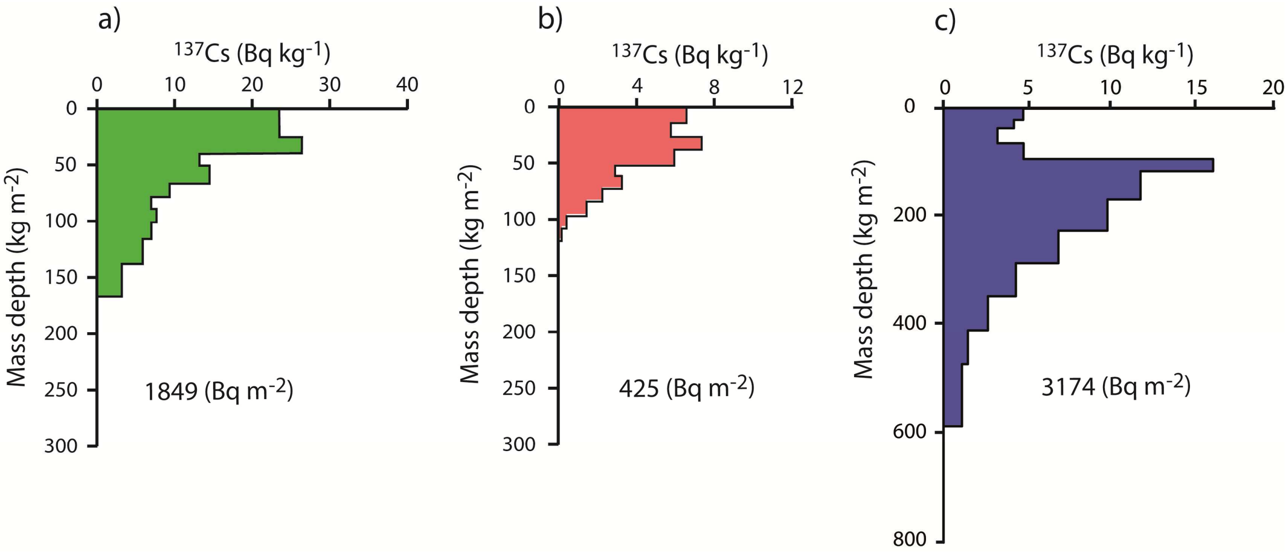

Fig. 5. The depth distribution of ^{137}Cs at the reference site (a), and sites experiencing erosion (b) and deposition (c)

The values of ^{137}Cs inventory associated with the 68 sampling points within the W1 catchment sampled in 2001 ranged from 4.1 to 4053 Bq m^{-2}, with a mean value of 1395 Bq m^{-2}. The values associated with the 50 additional points sampled within the Corrado catchment in 2013 ranged from 238 to 3164 Bq m^{-2}, with a mean value of 1284 Bq m^{-2}. The mean inventory associated with the samples collected in 2013 is significantly lower than would be expected if the difference between the two sets of values reflected only the effects of radioactive decay. The lower mean inventory for the 2013 samples also reflects the fact that those samples were collected from the lower part of the Corrado catchment, where the more sudbued topography results in lower erosion rates. The mean values of ^{137}Cs inventory associated with both the 2001 and the 2013 campaigns are lower than the appropriate reference inventory and indicate that soil erosion was dominant during the period following the commencement of bomb fallout in 1954. However, the presence of a small number of inventory values greater than the reference value in the combined dataset indicates that some deposition had occurred in different areas of the catchment.

4.2 Soil redistribution rates on the catchment slopes

Estimates of the soil redistribution rates associated with the individual sampling points for the two sampling campaigns were derived using Eqs. (1), (3) and (4), and the appropriate reference inventory values for 2001 and 2013. In the case of the 2001 sampling campaign, these estimates relate to the catchment W1 and the period 1954 to 2001, where 1954 is assumed to represent the onset of bomb fallout. For the 2013 sampling campaign, the estimates relate to the additional area not covered by the previous sampling campaign and to the period 1954 to 2013. Existing evidence provided by a comparison of the grain size distribution of surface soil within the catchment and suspended sediment collected at the outlet of catchment W1 (see **Fig. 6**) suggests that size-selective erosion and deposition are of limited importance within the study area. No particle size correction was therefore applied to the conversion model.

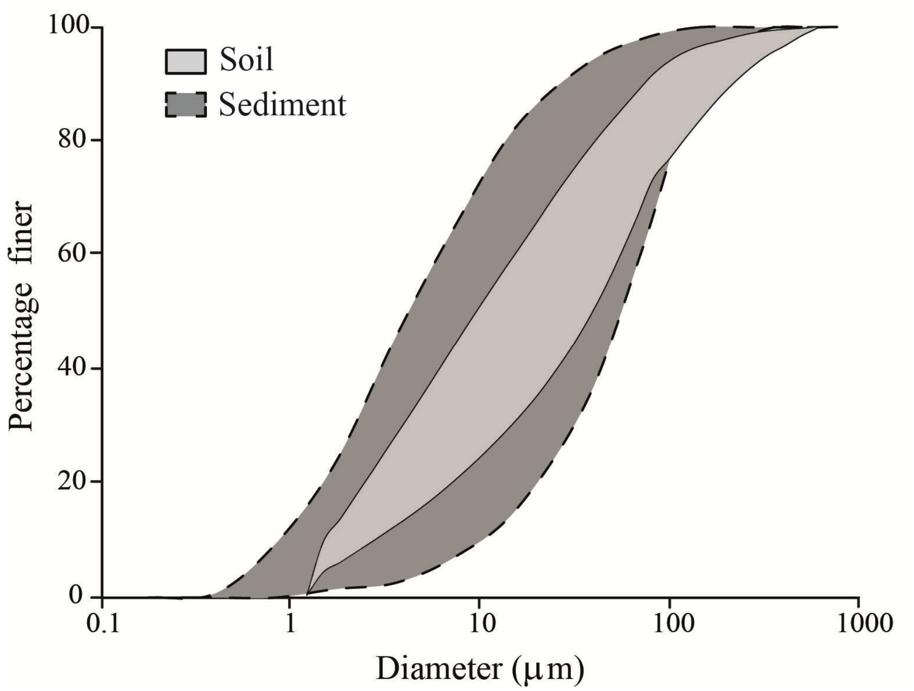

Fig. 6 A comparison of the range of the measured grain size distributions for sediment mobilised from the W1 catchment with the range of the grain size distributions of surface soil collected from the catchment

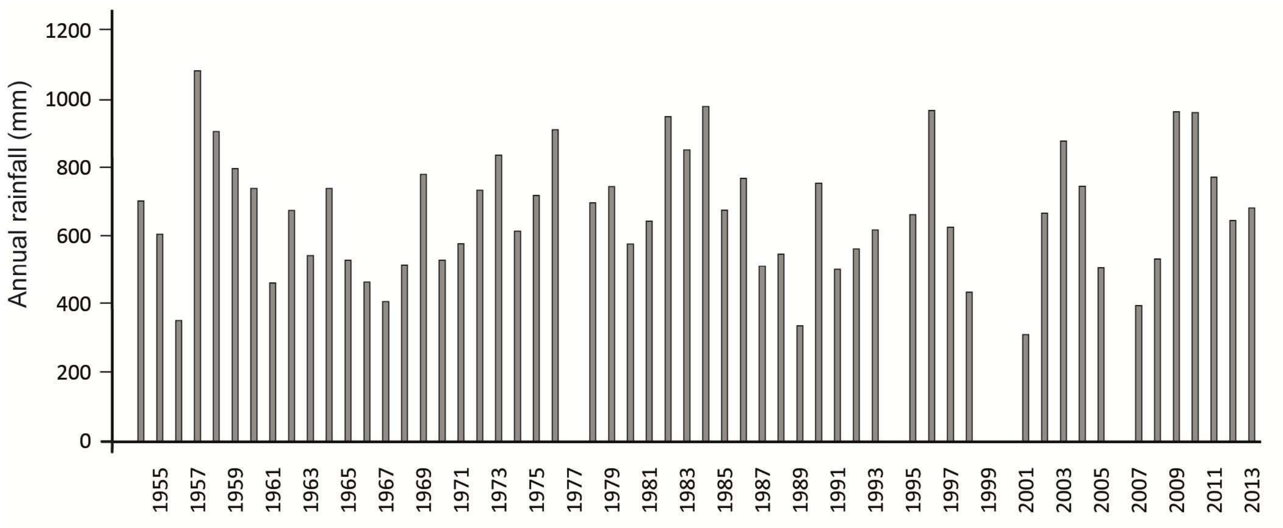

Fig. 7 - Annual precipitation totals for the study area during the period 1954 to 2013. (Totals are unavailable for some years)

Following Porto *et al.* (2011), the estimates of mean annual soil redistribution rate obtained using the ^{137}Cs measurements undertaken on the samples collected from catchment W1 in 2001 and from the remaining unsampled area of the larger Corrado catchment in 2013 can be treated as representative random samples of point values of soil redistribution rate within the two parts of the study catchment. The mean annual net soil loss from the W1 sub-catchment was estimated to be 8.6 Mg ha^{-1} yr^{-1}, whereas that from the remaining area of the Corrado catchment was estimated to be 5.0 Mg ha^{-1} yr^{-1}. The lower mean annual net soil loss from the latter area is seen to be primarily a reflection of its more subdued topography. However, because the estimates of soil redistribution rate obtained for the two parts of the Corrado catchment reflect different time periods (i.e. 1954-2001 for catchment W1 and 1954-2013 for the rest of the catchment) they should not be seen as directly comparable. Recent work in an adjacent catchment involving a resampling investigation reported by Porto *et al.* (2014) has, however, indicated that there is no evidence of a significant shift in erosion rates between the periods 1954-1998 and 1999-2013. Furthermore, the longer-term record of annual precipitation totals covering the period 1954 to 2013 presented in **Fig. 7** provides no clear evidence of a significant change in the annual rainfall totals after 2001. The mean annual precipitation totals for 1954-2001 and 1954-2013 are very similar at 659 mm and 669 mm, respectively. The data obtained from catchment W1 for the period 1954-2001 and the rest of the catchment for the period 1954-2013 have therefore been treated as belonging to the same population. Further details of the range of soil redistribution rates documented by the data generated by the two sampling campaigns are presented in **Table 2** and in **Figs. 8** and **9**.

Table 2 Information on the magnitude of the onslope erosion and deposition rates associated with the Corrado study catchment.

Sub-Catchment	Total soil erosion ($Mg\ ha^{-1}\ year^{-1}$)	Total deposition ($Mg\ ha^{-1}\ year^{-1}$)	Net soil loss ($Mg\ ha^{-1}\ year^{-1}$)
	Equation (1) and (3)	Equation (4)	Equation (1) and (3)
W1 (1954-2001)	8.84	0.19	8.6
Additional area (1954-2013)	6.16	1.14	5.0

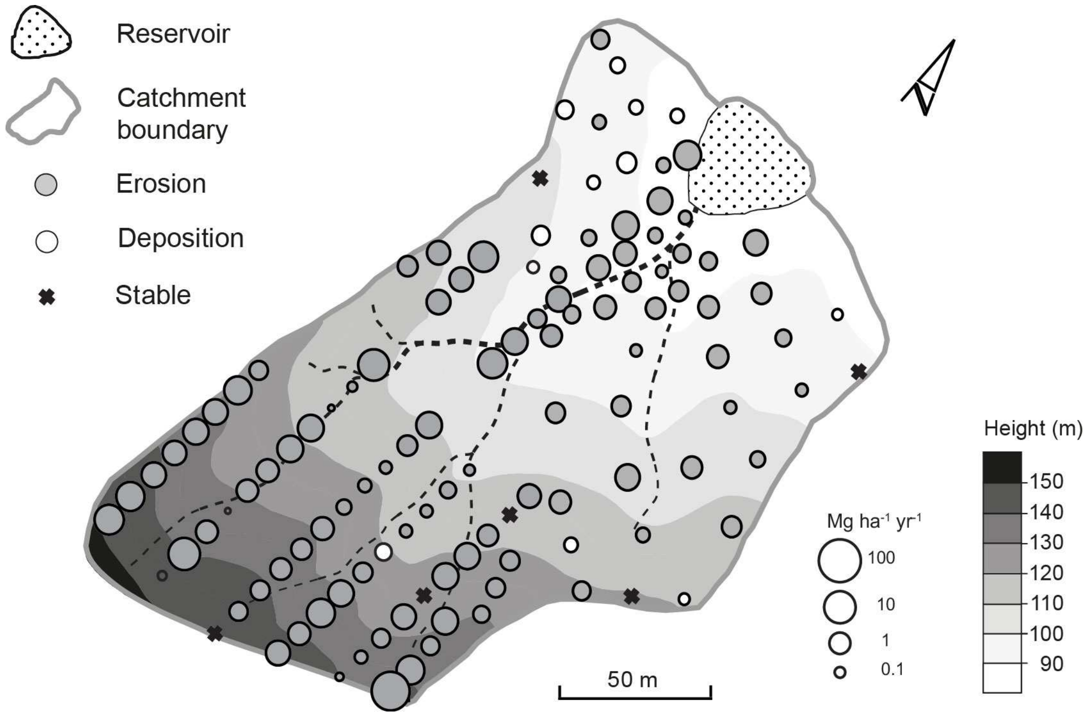

Fig. 8 - The spatial distribution of soil redistribution rates within the study catchment

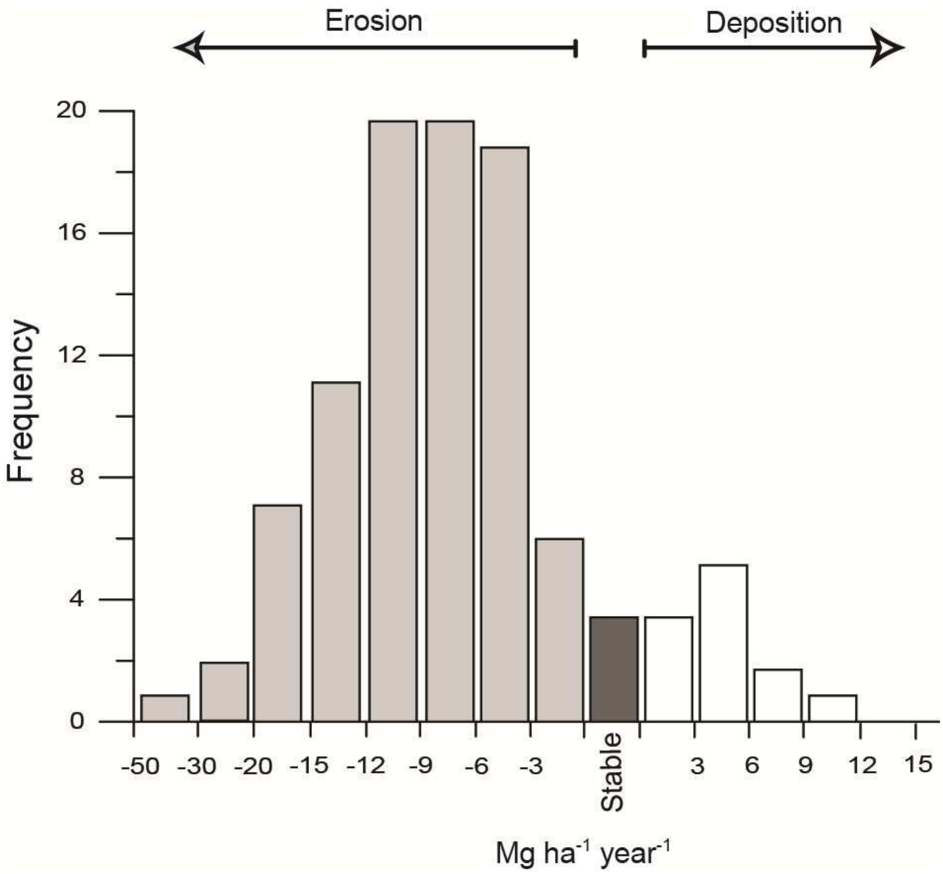

Fig. 9 - The frequency distribution of soil redistribution rates within the Corrado catchment based on the consolidated dataset of estimates provided by the ^{137}Cs measurements.

Figure 8 indicates that appreciable rates of sediment mobilisation are widely distributed across the catchment, although the highest values are generally located within the higher parts of the catchment where the terrain is steepest. In contrast, the sampling points characterized by deposition are preferentially located in the lower parts of the catchment, where the potential for deposition is greatest. The pattern of sediment mobilisation and redistribution on the slopes of the study catchment demonstrated by the ^{137}Cs measurements and depicted in **Figs. 8** and **9** can be usefully summarised by the sediment budget for the catchment slopes presented in **Fig. 10**.

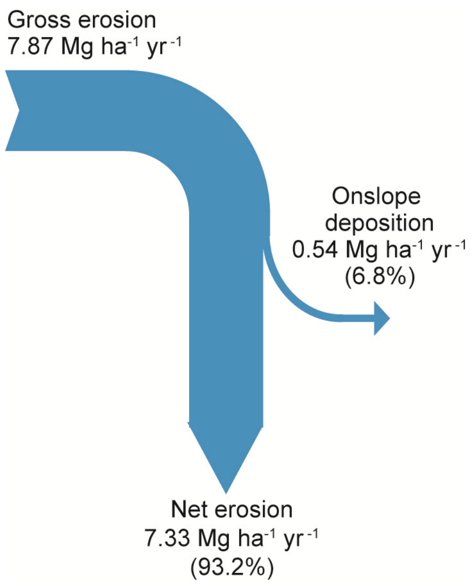

Fig. 10 A schematic sediment budget for the slopes of the Corrado catchment

In constructing the sediment budget depicted in **Fig. 10**, an estimate of the gross erosion (Mg yr^{-1}) from the catchment slopes was derived as the product of the mean erosion rate for the points indicated by the ^{137}Cs measurements to be characterized by erosion and the area of the catchment (ha) subject to erosion. The latter was estimated as the product of the proportion of the sampled points that documented erosion and the total area of the catchment above the reservoir. The same approach was applied to deposition within the catchment and the total deposition (t yr^{-1}) on the slopes of the catchment has been estimated as the product of the mean deposition rate for the sampled points evidencing deposition and the area of the catchment subject to deposition (ha). Subtraction of the total deposition within the catchment from the gross erosion provides an estimate of the net erosion, which is here interpreted to be equivalent to the sediment delivered to the reservoir. This assumes that the ephemeral channel network in the catchment is of very limited importance as either a sediment source or sink. This assumption is supported by the poorly developed nature of the channel network with very limited incision and by field observations which indicated very little sediment storage within the channel system. The values of gross erosion, deposition and net erosion as derived above have been divided by the total catchment area to generate the area specific values (Mg ha^{-1} yr^{-1}) presented in **Fig. 10**. The relatively high value of gross erosion (7.87 Mg ha^{-1} yr^{-1}) shown in **Fig. 10** reflects the fact that erosion occurs over 86% of the catchment surface. **Fig. 10** emphasizes that deposition is of very limited importance in the study catchment and accounts for only 6.8% of the gross erosion. The sediment delivery ratio for the catchment slopes, which represents the ratio of the net erosion to the gross erosion (i.e. 93.2%), must be seen as relatively high. This high value reflects an efficient conveyance system across the catchment slopes which can be linked to the small size of the catchment, the relatively steep slopes and the limited area with reduced gradients where deposition is likely to occur.

4.3 Sediment storage in the reservoir

The sediment budget based on the ^{137}Cs measaurements summarised in **Figure 10** indicates that the sediment output from the study catchment accounts for 7.33 Mg ha^{-1} yr^{-1} (ca. 93% of the gross erosion). In order to validate this estimate, an attempt has been made to quantify the sediment accumulated in the reservoir at the catchment outlet. In the absence of a detailed survey of the reservoir basin prior to impoundment and filling, the ^{137}Cs measurements undertaken on the nine sectioned cores collected from the reservoir during the 2011 sampling campaign were used for this purpose.

The depth distributions of ^{137}Cs associated with the nine sectioned cores (see **Fig. 2**) are illustrated in **Fig. 11**. Since the impoundment of the reservoir postdated the onset of bomb fallout in the mid 1950s and the period of peak fallout in 1963, it is not possible to identify the 1963 peak in ^{137}Cs activity and to use this as a marker horizon. Significant ^{137}Cs activity is found to the base of the sediment cores. However, in all cases, there is evidence of a minor peak of ^{137}Cs activity in the upper ca. 500 mm of the core which can be linked to Chernobyl fallout in 1986 (see Belyaev *et al.*, 2013; Du and Walling, 2012; Golosov and Walling, 2014). The peak represents the surface of the sediment deposit in 1986.

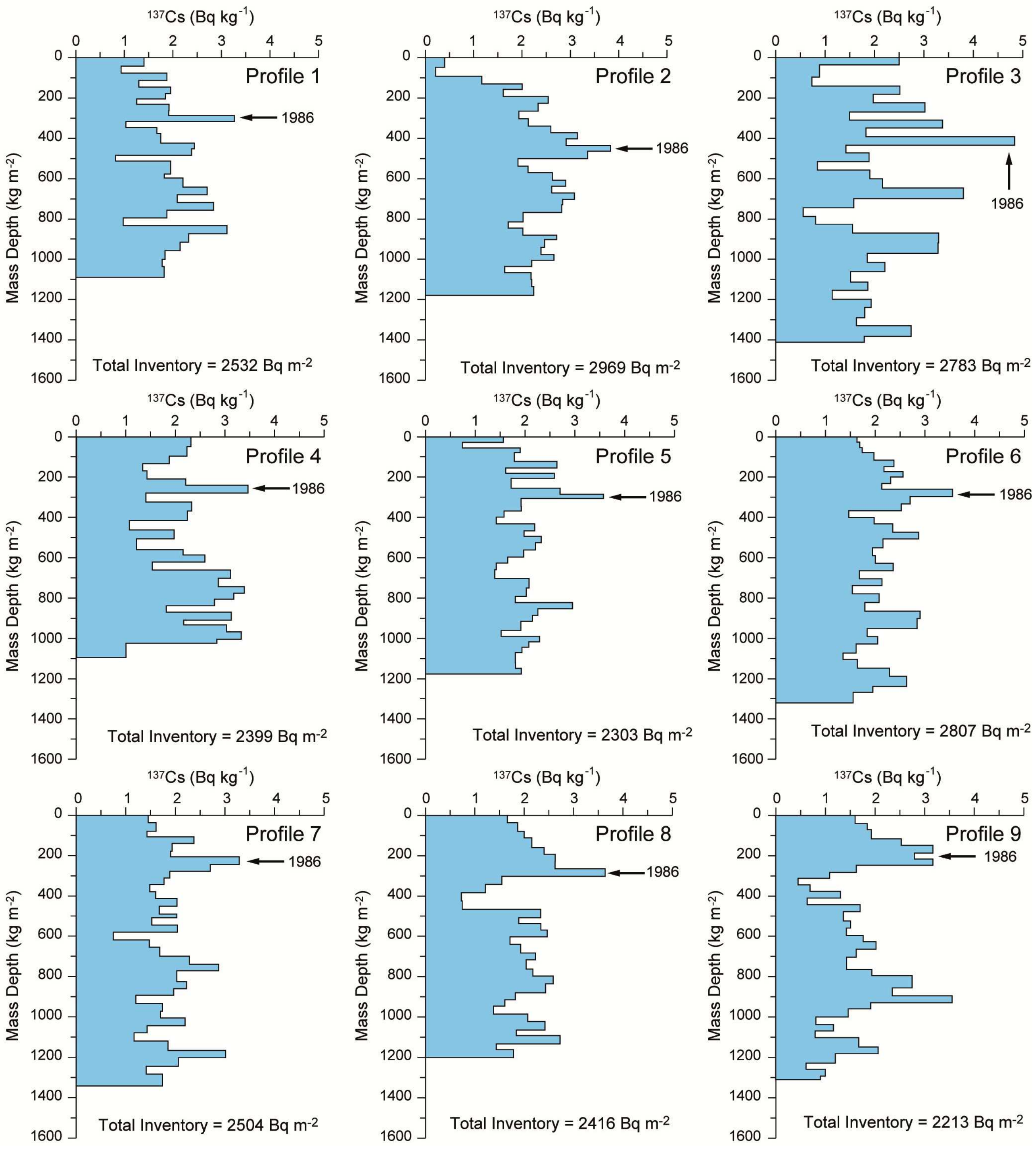

Fig. 11. The depth distribution of ^{137}Cs documented for the nine sampling points within the reservoir

The current depth of this peak provides a basis for estimating the sedimentation rate between 1986 and the time of sampling at the point where the core was collected (see Walling and He, 1993). In using ^{137}Cs measurements undertaken on the cores collected from the study area to estimate soil redistributioon rates it was assumed that the ^{137}Cs inventories of the cores were dominated by bomb fallout and that the contribution of Chernobyl fallout was negligible. The validity of this assumption is confirmed by the sediment cores collected from the reservoir and more particularly by two lines of evidence. The first is the lack of clear evidence of a significant increase in the ^{137}Cs activity of the sediment deposit above the 1986 peak. An increase would be expected if the Chernobyl fallout input was substantial, since it would have caused an increase in the ^{137}Cs activity of the surface soils in the catchment in 1986, which would be reflected in an increase in the ^{137}Cs activity soil mobilized from the catchment surface and deposited in the reservoir after 1986. The second is the limited magnitude of the ^{137}Cs peaks in the sediment cores ascribed to Chernobyl fallout. These are estimated to contribute no more than ca. 75 Bq to the total inventories of the cores, which represents about 4% of the reference inventory. The peak ^{137}Cs concentrations asssociated with Chernobyl fallout occur at mass depths ranging from 216.4 kg m^{-2} for profile 9 to 463.5 kg m^{-2} for profile 2 (see **Table 3** for details).

The sedimentation rate can be estimated from the depth of sediment above the ^{137}Cs peak, which denotes the reservoir surface in 1986 i.e:.

$$R' = \frac{M}{T} \qquad (6)$$

where

R' = deposition rate (kg m^{-2} yr^{-1});

M = cumulative mass depth of the 1986 peak (kg m^{-2});

T = period elapsed between 1986 and the time of sampling (yr).

The nine estimates of deposition rate obtained for the cores collected from the reservoir are listed in **Table 3**.

Table 3 Deposition rates calculated within the reservoir of the Corrado catchment

Sectioned core	^{137}Cs inventory (Bq m^{-2})	Cumulative mass depth of the 1986 peak (kg m^{-2})	Deposition rate (kg m^{-2} year^{-1})
SITE 1	2531.6	317.0	12.7
SITE 2	2968.8	463.5	18.5
SITE 3	2782.7	434.0	17.4
SITE 4	2398.8	279.7	11.2
SITE 5	2303.2	306.3	12.3
SITE 6	2807.2	297.3	11.9
SITE 7	2504.3	244.1	9.8
SITE 8	2416.3	301.5	12.1
SITE 9	2212.9	216.4	8.7

The mean deposition rate for the nine cores was calculated to be 12.7 kg m^{-2} yr^{-1}. This value was combined with an estimate of the surface area of the sediment deposit (0.18 ha) derived from field surveys to provide an estimate of the mean annual input of sediment to the reservoir of 22.86 Mg yr^{-1}. This is equivalent to a soil loss from the catchment slopes of 7.52 Mg ha^{-1} yr^{-1}, which is in close agreement with the estimate of net soil loss from the surface of the study area derived from the ^{137}Cs measurements of 7.33 Mg ha^{-1} yr^{-1}. Since the sides of the reservoir basin occupied by the sediment deposit were steep and the base of the basin was relatively flat, the estimate of surface area represented the surface area of the sediment deposit, assuming vertical sides. The reservoir had no spillway and had not overflowed since its construction and its trap efficiency was therefore assumed to be 100%.

5. DISCUSSION

As indicated above, the estimate of mean annual sediment input to the reservoir of 7.52 Mg ha^{-1} yr^{-1}, based on the information provided by the cores, is in close agreement with the estimate of the mean annual net soil loss from the slopes of the catchment derived from the ^{137}Cs measurements of 7.33 Mg ha^{-1} yr^{-1}. This agreement could be seen as clearly confirming the validity of the sediment budget for the catchment slopes derived from the ^{137}Cs measurements and depicted in **Fig. 10**.

However it is important to review the various sources of uncertainty associated with this comparison. These are discussed below.

1) The comparison involves estimates of net soil loss from the surface of the Corrado catchment derived from ^{137}Cs measurements which relate to two different periods (1954-2001 and 1954-2013). Furthermore, the estimates of deposition rate for the reservoir relate to a shorter period (1986-2011). The comparison therefore necessarily assumes that the erosional response of the Corrado catchment has been essentially stationary over the period 1954 to 2013 and that the time base of the individual estimates is sufficiently long to ensure that the resulting estimates of mean annual rates of soil loss from the catchment surface and the sediment input to the reservoir are reliable and can therefore be directly compared. Recent work in an adjacent catchment reported by Porto *et al.* (2014) used a ^{137}Cs re-sampling approach to demonstrate that the estimates of mean annual soil loss for the periods 1954-1998 and 1999-2013 showed no evidence of a significant change in erosional response. In addition, consideration of the mean annual precipitation totals for the periods 1954-2001, 1954-2013 and 1986 to 2011 provides values of 659 mm, 669 mm, and 639 mm, respectively. These again show little variability and are consistent with the assumption of a stationary response of the study catchment over the period 1954 to 2013. Estimates of mean annual soil loss and sediment yield based on periods of different length, will also be influenced by the inherent variability of the annual totals, as reflected by the standard error of the mean. This issue was addressed by considering the available data on annual sediment yield for the W1 sub-catchment. An estimate of the coefficient of variation of the record of annual sediment yield from this catchment of ~100% can also be assumed to be representative of the local environment and emphasises the potential influence of inter-annual variation in the magnitude of erosion and sediment yield on estimates of mean annual sediment flux. However, since the estimates of mean annual net soil loss from the slopes of the Corrado catchment and mean annual sediment input to the reservoir are based on periods

of 47 and 59 years and 25 years, respectively, they are judged to provide meaningful values of mean annual sediment flux which can be directly compared.

2) The comparison also involves the assumption that channel erosion does not contribute to the estimate of sediment flux at the catchment outlet, derived from the sediment deposit in the reservoir. This is compared directly with the estimate of net soil loss from the surface of the Corrado catchment provided by the sediment budget based on ^{137}Cs measurements. As indicated previously, the ephemeral channel network in the study catchment is poorly developed and field observations suggest that such channels are of very limited importance as a sediment source. Furthermore, field observations failed to provide any evidence of significant sediment storage in the ephemeral channel network, which could represent a conveyance loss associated with sediment delivery to the catchment outlet and therefore preclude direct comparison of the estimate of net soil loss from the surface of the catchment with the estimate of sediment output based on the reservoir deposits.

3) It is difficult to provide precise estimates of the uncertainty associated with the estimate of net soil loss provided by the ^{137}Cs measurements and with the estimate of sediment export based on the amount of sediment deposited in the reservoir. However, the sources of uncertainty associated with the latter are judged to be limited and a precision of ca.± 20% at the 95% level of confidence in suggested. In the case of the estimate of net soil loss from the catchment surface, the consistency of the estimates of soil redistribution rates provided by the two independent sampling campaigns in different parts of the Corrado catchment undertaken at different times add confidence to the values obtained. Furthermore Porto *et al.* (2014) have suggested from work in an adjacent catchment that the estimate of mean annual net soil loss derived from ^{137}Cs measurements using similar procedures to those used in the current study are characterized by a precision of ca. ±30% at the 95% level of confidence. Uncertainty associated with the estimates of net soil loss from the surface of the catchment

and sediment output from the catchment is therefore not seen as introducing significant problems in terms of the results presented.

Overall, the uncertainty considerations discussed above are not seen as adversely influencing the conclusion that the close agreement between the estimate of mean annual net soil loss from the slopes of the Corrado catchment derived from the ^{137}Cs measurements and the estimate of mean annual sediment yield at the catchment outlet provided by the sediment deposits in the reservoir provides a convincing validation of the estimates of soil loss derived from the ^{137}Cs measurements and the associated sediment budget for the slopes of the study catchment.

6. CONCLUSIONS

The results presented from this investigation are seen as providing a convincing validation of the use of ^{137}Cs measurements to estimate soil redistribution rates and to generate the data needed to construct a sediment budget for the slopes of a small catchment. As such they confirm the potential for using ^{137}Cs measurements as a key component of sediment budget investigations. These findings are consistent with the findings of previous studies in southern Italy aimed at validating the use of ^{137}Cs measurements to provide estimates of soil redistribution rates resulting from sheet and rill erosion (see Porto *et al.*, 2003; 2004).

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