Using caesium-137 measurements to establish a sediment budget for the catchment of a small reservoir in southern Italy

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Abstract Predicting the expected life of a reservoir and assessing the potential for increasing this life is a great challenge for the hydraulic engineer, as it involves predicting the sediment input to the reservoir. The rate of sedimentation in a reservoir will primarily reflect the amount of sediment eroded from the upstream catchment and the efficiency of sediment delivery to the reservoir. When fine particles dominate the soil texture of a catchment and the land use is conducive to erosion, a large proportion of the soil loss can commonly be ascribed to sheet erosion from the slopes. The fallout radionuclide caesium-137 (^{137}Cs) has been increasingly used to document rates of soil loss by sheet erosion in recent years, both as an alternative to conventional measurements and for calibrating physically-based soil erosion models. This paper reports an example of the application of the ^{137}Cs technique in a medium-scale (14.8 km^2) catchment upstream of a small reservoir in southern Italy, aimed at assembling information on soil erosion and redistribution on the catchment slopes, and flood plain sedimentation rates, in order to establish a catchment sediment budget. Data available from sediment (turbidity) monitoring undertaken at the catchment outlet prior to the construction of the reservoir have been used to estimate the catchment sediment yield. This estimate has been combined with the information provided by the ^{137}Cs measurements, to establish a sediment budget for the catchment. The sediment budget provides a valuable tool for understanding sediment inputs to a reservoir and their sensitivity to climate change, and for planning and implementing sediment control measures within the catchment, in order to reduce reservoir sedimentation rates.

Key words reservoirs; caesium-137; erosion rates; sedimentation rates sediment budget; Italy

INTRODUCTION

In southern Italy, the construction of small dams aimed at providing water for domestic supply, livestock or irrigation has attracted increasing attention in recent years. The topography of some Calabrian rivers, characterized by steep slopes in the lower reaches and large flat areas in the upper parts, makes these areas well suited to the construction of small reservoirs, which provide a cost-effective method of storing large volumes of water. However, one of the main problems facing the successful construction and maintenance of these reservoirs is sedimentation, and thus predicting their expected life. This is a great challenge for the hydraulic engineer, as it involves predicting the catchment sediment yield and sediment input to the reservoir. In southern Italy, a long-term campaign of measurements has been undertaken to provide information on the suspended sediment loads of the main rivers. Although existing information for the rivers of Calabria suggests that sediment yields are relatively low, there is evidence that rates of soil loss and therefore the intensity of soil degradation is substantially higher than suggested by the values of specific sediment yield (Porto *et al*., 2009). The rate of sedimentation in a reservoir will primarily reflect the amount of sediment eroded from the upstream catchment and the efficiency of sediment delivery to the reservoir. To date there are relatively few quantitative estimates of erosion and sediment delivery for the mountainous areas of Calabria. However, the limited amount of monitoring of erosion dynamics using plot or small catchment experimentation raises questions about the reliability of estimates derived from the extrapolation of such small-scale results. Alternative methods for estimating erosion rates from field measurements are therefore required. The fallout radionuclide caesium-137 (^{137}Cs) has been increasingly used to document rates of soil loss from sheet erosion in recent years, both as an alternative to conventional measurements and for calibrating physically-based soil erosion models. This paper reports an example of the application of the ^{137}Cs technique in a medium-scale (14.8 km^2) reservoir catchment in southern Italy, aimed at assembling information on soil erosion and redistribution on the catchment slopes and sediment storage within the channel and flood plain. Data available from sediment (turbidity) monitoring undertaken at the catchment outlet prior to reservoir construction have been used to estimate the catchment sediment yield. This estimate has been combined with the information provided by the ^{137}Cs measurements, to establish the sediment budget for the catchment. The sediment budget provides a valuable tool for understanding the sediment input to a reservoir and its sensitivity to climate change, and for planning and implementing sediment control measures within the catchment, in order to reduce future reservoir sedimentation rates.

THE STUDY AREA

The Alaco catchment (Fig. 1), located in the northeastern sector of the Serre Massif (Calabria, southern Italy) has a drainage area of 14.8 km^2 and ranges in altitude from 1242 m a.s.l. at the highest point to 924 m a.s.l. at the catchment outlet. Geologically, approx. 90% of the catchment is underlain by granitoids (Polia-Copanello Unit and Stilo Unit) (Calcaterra *et al*., 1996). Soils developed on these rock types are characterized by a range of textures, although sandy and silt-sandy soils are dominant. The catchment is uncultivated and large areas are covered by trees, which primarily include pines (*Pinus laricio* P.), but also some beech (*Fagus sylvatica* L.) and oak (*Quercus* spp.). Precipitation is almost uniformly distributed through the period extending from October to March, but frequent heavy rainstorms can occur in spring and summer. The mean annual rainfall, for the period 1961–1982, measured at Mammone (38°34′54″N, 16°26′39″E), is approx. 1900 mm (SIMI, 1920–2000).

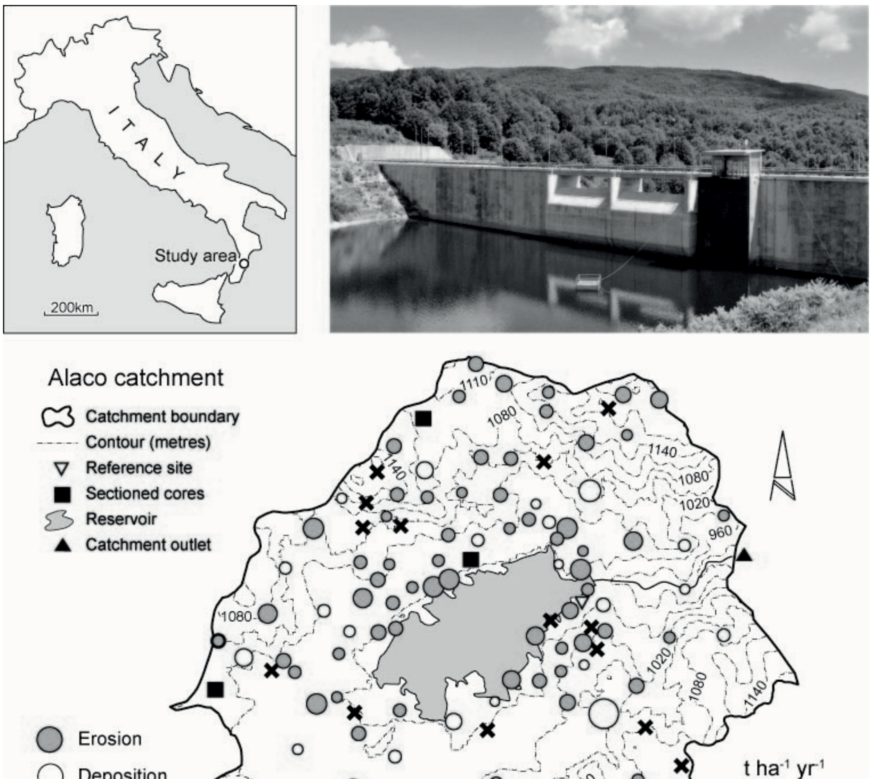

Fig. 1 The study catchment showing the soil sampling points. The grey circles represent the sampling points showing erosion, while the white circles indicate the points showing deposition. The size of the circles is proportional to the erosion or deposition rate, as shown. Stable sites are indicated by the crosses.

The reservoir upstream of the dam stores approx. 35 million m^3 of water that supplies the local population of the towns located downstream. To support the design of this and other dams in the region, the Italian Hydrographic Service (SIMI) undertook measurements of rainfall, runoff and suspended sediment concentration at the catchment outlet during the period 1961–1979. During this monitoring period, the annual suspended sediment yield, derived from the sediment concentration measurements, ranged from 0.085 t ha^{-1} year^{-1} in 1979 to 3.58 t ha^{-1} year^{-1} in 1973 (Fig. 2). These values, although considerably lower than the suspended sediment yields reported for the coastal areas of the same region (Porto *et al.*, 2001), can be seen as representative of the mountain areas of the Serre Massif.

The mean annual suspended sediment yield for the monitoring period was 0.72 t ha^{-1} year^{-1}.

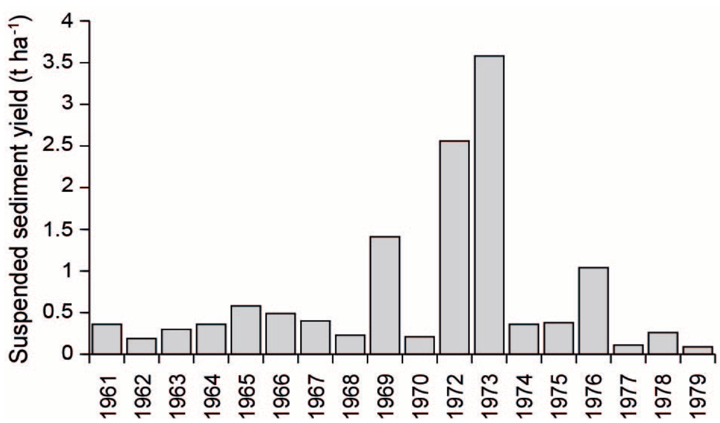

Fig. 2 Annual suspended sediment yields for the Alaco catchment.

THE MEASUREMENTS

Soil sampling for ^{137}Cs analysis

Soil sampling for ^{137}Cs analysis in the Alaco catchment involved three separate sampling campaigns. The first, undertaken in 2011, focused on establishing the magnitude and spatial distribution of soil redistribution rates within the catchment. During this campaign, replicate bulk soil cores were collected at 120 sites (Fig. 1) using a 11 cm diameter steel core tube inserted to a depth of ≥45 cm. The second campaign, undertaken in late 2011, aimed to establish both the magnitude and the depth distribution of the ^{137}Cs inventories at four undisturbed reference sites with minimum slope. These reference sites were located in small clearings between the trees (Fig. 1). For each site, eight separate cores were collected from an area of approx. 25 m^2 using an 11 cm diameter steel core tube inserted to a depth of 60 cm, in order to take account of micro-scale variability in the reference inventory (cf. Owens & Walling, 1996). Each core was sectioned using the same depth increments, which ranged from 1 to 4 cm, and the individual depth increments from the eight cores were bulked. The third sampling campaign, undertaken in 2012, aimed to provide additional information about the depth distribution of ^{137}Cs in the soils of the catchment. During this campaign, additional composite soil samples, each comprising specific depth increments from eight individual sectioned cores, were also obtained from four representative eroding and depositional areas within the catchment, in order to document the variability of the ^{137}Cs depth distribution over the study area.

All bulk core and depth incremental samples collected in the catchment were 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 (approx. 0.1 kg) was packed into plastic pots for determination of its ^{137}Cs activity by gamma spectroscopy in the radiometry laboratory of the Geography Department at the University of Exeter. Activities of ^{137}Cs in the soil samples were measured by gamma-ray spectrometry, using a high-resolution, low energy coaxial HPGe detector coupled to an amplifier and PC-based data collection system. Count times were typically approx. 80 000 s, providing results with an analytical precision of ~10% at the 95% level of confidence. The efficiency of the detection system was calibrated using standard samples prepared by adding known amounts of certified radionuclide standards to representative soil samples. The ^{137}Cs activities in the samples were obtained from the counts at 662 keV.

RESULTS

^{137}Cs inventories and depth distributions at the reference site

The ^{137}Cs reference inventory for the study areas based on the composited slices of the cores collected from the four reference sites are listed in Table 1. Because of the restrictions on the number of samples that could be transported to Exeter, UK, for analysis, the reported reference inventory is based on assay of the composited sections from all 32 cores (8 for each site). Considering the uncertainty associated with both measurement precision and local, micro-scale and sampling variability, a 10% precision error has been attached to the value for the reference inventory presented in Table 1 (Porto *et al*., 2013).

Table 1 ^{137}Cs inventories for the Alaco catchment.

Reference inventory		Inventories within the catchment		
Mean (Bq m^{-2})	Range (±10% uncertainty) (Bq m^{-2})	Mean (Bq m^{-2})	Range (Bq m^{-2})	Standard deviation (Bq m^{-2})
5795	5215–6375	4619	166–18226	2904

The representative depth distribution of ^{137}Cs for the four reference sites based on the composited slices from the 32 cores is presented in Fig. 3(a). This is typical of an undisturbed site (Walling & Quine, 1993; Porto *et al*., 2001, 2003), with ~95% of the total inventory existing in the top 10 cm and a sharp exponential decline in activity occurring below this depth.

^{137}Cs inventories within the study catchment

The values of ^{137}Cs inventory associated with the 120 sampling points in the study catchment ranged from 166 to 18226 Bq m^{-2}, with a mean value of 4619 Bq m^{-2} (see Table 1). Considering that an uncertainty of ±10% at the 95% level of confidence has been assumed for the estimates of the ^{137}Cs reference inventory, only when the measured inventory for an individual sampling site falls either above or below this range can it be assumed to be greater or less than the reference inventory and thus indicative of erosion or deposition. The results indicated that 15% of the ^{137}Cs inventory values obtained for the individual sampling points were not significantly different from the reference value, indicating that those sampling points were essentially stable with no significant erosion or deposition occurring (see Fig. 1). However, 63% of the inventories were significantly lower than the reference value, indicating erosion, and 22% were significantly greater, indicating deposition. That 85% of the sampling points show evidence of either erosion or deposition confirms that considerable soil redistribution has occurred within the study basin since the commencement of ^{137}Cs fallout in the mid 1950s. Figure 3(b) and (c) provides typical examples of the depth distributions of ^{137}Cs at the sampling points within the Alaco catchment. The profile presented in Fig. 3(b), with inventory of 1083 Bq m^{-2}, which is considerably lower than the reference inventory, is typical of an eroding site, whereas that shown in Fig. 3(c), with inventory value of 13 043 Bq m^{-2}, which is considerably higher than the reference values, is typical of a depositional site.

Using ^{137}Cs to estimate soil redistribution rates

Estimation of rates of erosion and deposition from ^{137}Cs measurements is generally based on the degree of reduction or increase of the measured inventory, relative to the local reference inventory.

In this study we used a conversion model for uncultivated land originally proposed by Walling & He (1999) and refined by Porto *et al*. (2003).

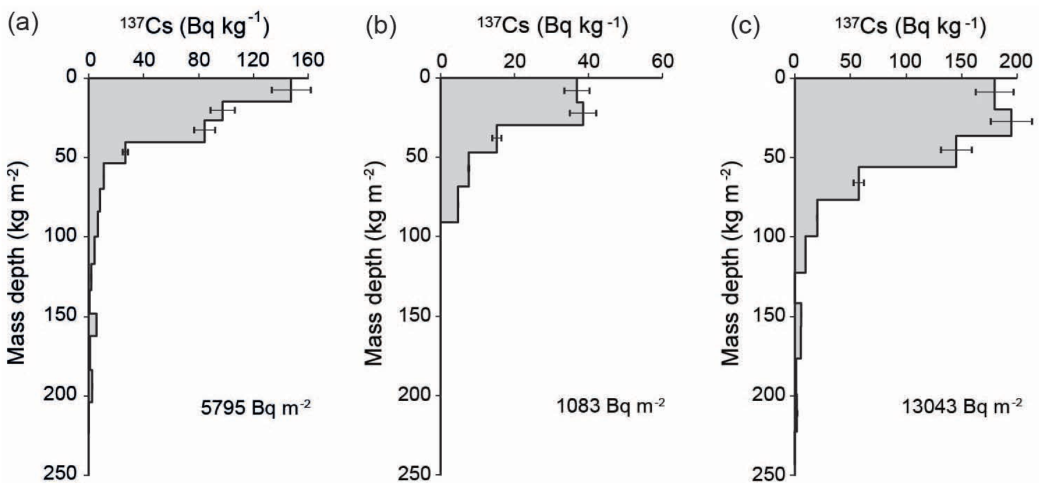

Fig. 3 The ^{137}Cs depth distributions for the reference site (a), an eroding site (b) and a depositional site (c) within the Alaco catchment. The error bars depict the 95% confidence limits of the measured radionuclide activities.

The model converts the magnitude of the reduction or increase in the ^{137}Cs inventory to an estimate of the rate of soil loss or deposition, for uncultivated sites. Further details of this model can be found in Porto *et al*. (2003), but its main features are briefly summarised below.

The ^{137}Cs diffusion and migration model

The vertical distribution of ^{137}Cs within a soil will vary through time in response to the time-dependent fallout input and the post-depositional redistribution of ^{137}Cs within the profile. According to Walling & He (1999), by treating the soil as a semi-infinite homogeneous porous medium, the post-depositional redistribution can be characterized by a constant effective diffusion coefficient and a constant migration rate. Assuming that fallout inputs are initially uniformly distributed at the soil surface, the vertical distribution of ^{137}Cs concentration from the surface downwards can be represented by the following equation as:

$$C(x,t,t') = e^{-\lambda_{Cs}(t-t')} \int_0^{\infty} \frac{I(t')}{H} e^{-\frac{y}{H}} \left\{ e^{\frac{V_{Cs}(x-y)}{2D_{Cs}} - \frac{V_{Cs}^2(t-t')}{4D_{Cs}}} \left[e^{-\frac{(x+y)^2}{4D_{Cs}(t-t')}} + e^{-\frac{(x-y)^2}{4D_{Cs}(t-t')}} \right] \times \right.$$

$$\left. \times \frac{1}{\sqrt{4\pi D_{Cs}(t-t')}} - \frac{V_{Cs}}{2D_{Cs}} e^{\frac{V_{Cs}x}{D_{Cs}}} erfc\left[\frac{x+y+V_{Cs}(t-t')}{\sqrt{4D_{Cs}(t-t')}} \right] \right\} dy \qquad (1)$$

where: $C(x,t,t')$ = the concentration of ^{137}Cs for any mass depth x and time t'(Bq kg^{-1}); D_{Cs} = the effective diffusion coefficient (kg^2 m^{-4} year^{-1}); V_{Cs} = the downward migration rate (kg m^{-2} year^{-1}); H = the relaxation depth expressed as a mass depth (kg m^{-2}); λ_{Cs} = the decay constant for ^{137}Cs (0.023 year^{-1}); x = the mass depth from the soil surface downwards (kg m^{-2}); t = the time since the first deposition of ^{137}Cs (year); $I(t')$ = the input (Bq m^{-2} year^{-1}) at time t'; $erfc(u)$ = the error-function complement defined by Crank (1975).

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

$$C(x,t) = \int_0^t C(x,t,t')dt \tag{2}$$

For a soil affected by sheet erosion, with a constant annual erosion rate R (kg m^{-2} year^{-1}), the concentration of ^{137}Cs in the eroded sediment $C_e(t)$ (Bq kg^{-1}), assuming no enrichment, may be approximated by that of the surface soil $C_u(0,t)$ obtained from equation (2). According to Walling & He (1999), the erosion rate R may be estimated from the reduction in the ^{137}Cs inventory $A_u(t)$ (Bq m^{-2}), defined as the ^{137}Cs reference inventory A_{ref} less the measured total inventory $A(t)$, and the ^{137}Cs concentration in the surface soil $C_u(t')$ according to:

$$A_u(t) = \int_0^t R\,C_u(t')e^{-\lambda_{Cs}(t-t')}\,dt' \tag{3}$$

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 (Walling & He, 1999):

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

Estimating erosion and deposition rates using the ^{137}Cs measurements obtained for the sampling points within the study catchment

The diffusion and migration model described above was used to derive estimates of erosion and deposition rates for the 102 sampling points within the study catchment where the ^{137}Cs inventories showed that significant erosion or deposition had occurred (see Fig. 1). The model was parameterized using the reference profile depicted in Fig. 3(a). The ranges of the erosion and deposition rates estimated for the individual sampling points within the study catchment are presented in Fig. 4. The central class, designated stable, represents those sampling points where the measured inventories fell within the uncertainty range associated with the reference inventory.

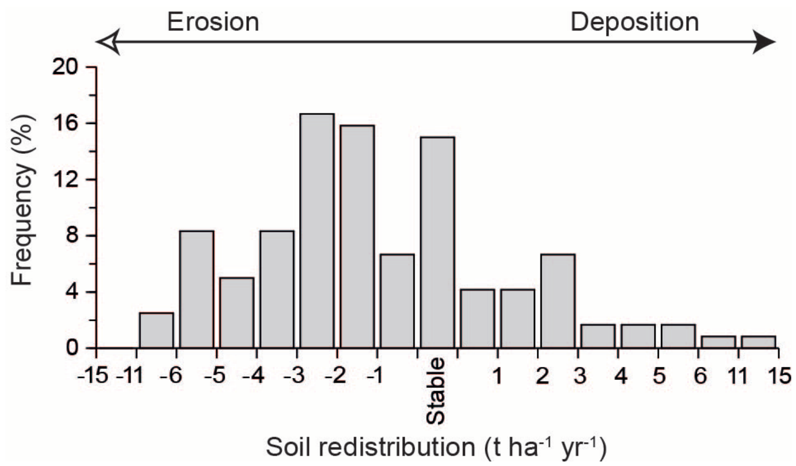

Fig. 4 The range of erosion and deposition rates (t ha^{-1} year^{-1}), estimated using the ^{137}Cs measurements obtained for the sampling points within the study catchment.

DISCUSSION

The results reported in Table 1, Fig. 1, and Fig. 4 clearly indicate that appreciable rates of sediment mobilisation exist throughout the catchment. Erosion is clearly dominant, but the presence of points documenting deposition emphasises that a proportion of the sediment mobilised within the catchment by erosion is deposited elsewhere within the catchment.

The pattern of sediment mobilisation and redistribution within the study catchment indicated by the ^{137}Cs measurements can be usefully summarised by the overall sediment budget for the catchment slopes presented in Fig. 5. This budget has been constructed as follows. An estimate of the gross erosion (t year^{-1}) associated with the catchment slopes has been derived as the product of the mean erosion rate for the sampling points characterized by erosion and the area of the catchment subject to erosion, as indicated by the proportion of the sampled points evidencing erosion. The same approach was applied to deposition within the catchment, to derive an estimate of the total deposition on the slopes of the catchment. Subtraction of the total deposition within the catchment from the gross erosion provides an estimate of the net erosion, which is here interpreted to represent the sediment delivered to the channel system. Sediment deposition and storage within the main channel system and on the small flood plains bordering the channel have been estimated as the difference between the net erosion and the measured mean annual sediment output from the catchment, and this is seen to represent the conveyance loss. The estimates of gross and net erosion, deposition and conveyance loss presented in Fig. 5 have been expressed as values for the total catchment area (t ha^{-1} year^{-1}). In the absence of information on channel erosion, this potential sediment source has not been included as providing an additional sediment input to the sediment budget for the catchment.

The estimate of gross erosion for the catchment (1.89 t ha^{-1} year^{-1}) shown in Fig. 5 is relatively low and reflects the large area of forest cover in the catchment, which is likely to be characterized by limited erosion. Figure 5 also emphasises that onslope deposition is important and accounts for 0.66 t ha^{-1} year^{-1}, corresponding to approx. 35% of the gross erosion. The sediment storage associated with the channel conveyance system accounts for 0.51 t ha^{-1} year^{-1} (approx. 27% of the gross erosion). This reflects the opportunity for sediment deposition within a channel system characterized by relatively low gradients and areas of flood plain. Considering the rate of gross erosion in the catchment, and the proportion of sediment entering storage both on the slopes of the catchment and in the channel system, a sediment delivery ratio equal to 38% was obtained.

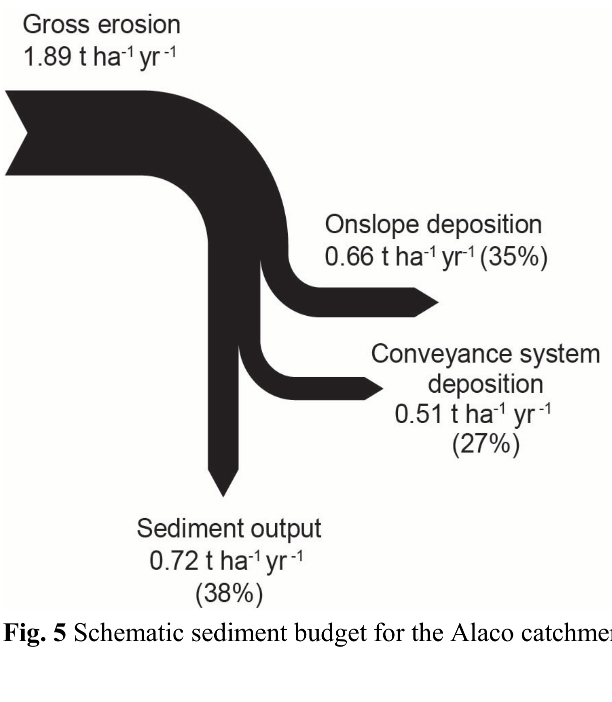

Fig. 5 Schematic sediment budget for the Alaco catchment.

However, it is important to recognise that the estimate of channel system deposition or conveyance loss presented in Fig. 5 has been derived by subtracting the measured sediment output from the catchment from the net soil loss from the catchment slopes. For this reason, the sediment budget reported in this paper must be seen as preliminary. Further work is needed to quantify the importance of the flood plain areas in the study catchment as a sediment sink. An additional sampling campaign was undertaken within the study catchment in September 2012 in order to document the rates of sedimentation on the flood plains bordering the main channel system. To date, however, the ^{137}Cs measurements on a number of sectioned and bulk cores collected from representative flood plain areas are still in progress.

Another important issue relates to the extent to which the information provided by the sediment budget can be seen as representative, in terms of the future operation of the reservoir. In this context it is important to recognize that the periods covered by the measured sediment yield and the estimates of soil redistribution rates are different. The estimates of the long-term mean gross and net erosion rates derived from the ^{137}Cs measurements relate to a period of approx. 55 years, extending from the commencement of fallout (1954) to the time of sampling. The direct measurements of sediment output, available from the catchment outlet, cover a period of only 19 years (from 1961 to 1979). Recent assessments of climate change in Calabria, based on detailed long-term rainfall records, have documented a trend of increasing rainfall erosivity during the last 10–15 years (see Porto & Walling, 2012). This situation suggests that in recent years soil erosion rates may have been greater than average values for the past approx. 55 years documented using the ^{137}Cs measurements or those associated with the measured sediment output (1961–1979). Currently, no estimates of contemporary soil erosion rates are available for the study catchment, but further work involving the use of $^{210}Pb_{ex}$ measurements is in progress. The radionuclide $^{210}Pb_{ex}$, with a half-life of 22.3 years, has been shown to be more sensitive to erosion occurring during the past 15–20 years and the results it provides can represent a valuable complement to those provided by ^{137}Cs measurements, in terms of obtaining evidence of possible changes in erosion rates in recent years.

CONCLUSIONS

The results presented above demonstrate that ^{137}Cs measurements can provide a valuable basis for establishing the sediment budget of a medium-sized catchment. Sampling of the catchment slopes provides estimates of gross and net erosion that can be related to the measured sediment export from the catchment, to establish a tentative sediment budget, as depicted in Fig. 5. The sediment budget constructed for the Alaco catchment demonstrates that the specific sediment yield for the catchment derived using turbidity measurements at the catchment outlet does not provide a good indication of the intensity of erosion rates on the slopes of the catchment. Net and gross erosion rates on the slopes of the catchment are estimated to be of the order of two to three times greater than the sediment yield at the basin outlet. Storage, associated with both slope and channel transfer pathways, represents a key component of the sediment budget and exerts an important control on the downstream sediment yield. The tentative sediment budget constructed for the study catchment provides a useful tool for understanding sediment inputs to the reservoir and their sensitivity to climate change and for planning and implementing sediment control measures within the catchment, in order to reduce the reservoir sedimentation rates.

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