Using caesium-137 and unsupported lead-210 measurements to explore the relationship between sediment mobilisation, sediment delivery and sediment yield for a Calabrian catchment

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Abstract. Recent concern about the many environmental problems associated with the transport of fine sediment by rivers has generated a need to obtain spatially distributed evidence of the erosion rates operating within a catchment and to explore more explicitly the links between sediment mobilisation, transfer, storage and output. In the past few decades, the fallout radionuclides caesium-137 (137Cs) and unsupported lead-210 (210Pbex) have been successfully used as tracers to estimate soil erosion and deposition rates in many areas of the world. However, to date, most studies using this approach have focussed on relatively small areas, such as individual fields or small catchments. There is a need to explore the potential for upscaling the approach to larger areas or catchments. The present paper reports an attempt to use the fallout radionuclides 137Cs and 210Pbex to explore further the relationship between sediment mobilisation, sediment transfer and storage, and sediment yield for a medium-scale (31.61 km²) catchment located in Calabria, southern Italy. The results emphasise that the low value of specific sediment yield derived for the study catchment from measurements of the suspended sediment flux at the catchment outlet obscure the existence of appreciable erosion rates in many areas of the catchment. Much of this erosion is balanced by deposition and sediment storage, resulting in a relatively low sediment delivery ratio for the catchment.

Additional keywords: sediment load, soil erosion.

Introduction
Traditionally, concern about the problems associated with the transport of suspended sediment by rivers has focussed on reservoir sedimentation, siltation of river channels and water distribution networks, and the use and treatment of water containing appreciable amounts of fine sediment. Such problems are commonly most severe in areas with high suspended sediment yields. More recently, there has been a growing awareness of the wider environmental significance of the fine sediment loads of rivers, linked to sediment–water quality interactions, the importance of fine sediment in the transfer and fate of sediment-associated pollutants and contaminants, including pesticides and other organic pollutants (e.g. Kronvang et al. 2000; Warren et al. 2003), and the role of fine sediment in degrading aquatic habitats, through, for example, the siltation of fish-spawning gravels and the smothering of aquatic vegetation and benthic habitats (e.g. Wood and Armitage 1999; Soulsby et al. 2001; Heywood and Walling 2007). These changing perspectives have been paralleled by changing needs in the investigation of the sediment dynamics of catchments and river systems. Traditional perspectives primarily require information on sediment loads at the catchment outlet or at different points along the river and complementary information on suspended sediment concentrations, as provided by standard sediment monitoring programs. However, the wider environmental concerns noted above require information on the mobilisation, delivery and storage of fine sediment within the entire catchment and introduce the need for new approaches to investigate the sediment dynamics of a catchment.

One key consideration when investigating the sediment dynamics of a catchment is the relationship between the sediment yield at the catchment outlet and the rates of sediment mobilisation and transfer within the catchment. The sediment delivery ratio (see Walling 1983), which represents the ratio of the sediment yield at the catchment outlet to the gross erosion occurring within the catchment, provides a spatially lumped representation of this relationship. To date, however, most attempts to derive estimates of this ratio have been based on a comparison of the measured sediment yield from a catchment with an estimate of the erosion occurring within the catchment, derived from an erosion prediction procedure, such as the Universal Soil
Loss Equation (USLE) or some revised forms (RUSLE). There is a need to obtain more direct and spatially distributed evidence of the erosion rates occurring within a catchment and to characterise more explicitly the links between sediment mobilisation, transfer, storage and output. Such information is needed to better understand the extent to which the sediment yield measured at a catchment outlet provides a meaningful assessment of the rates of soil loss or degradation within the upstream catchment, the likely sensitivity of the sediment output from a catchment to changes in the erosion rates within the catchment, such as might be caused by climate or land-use change, and the potential for implementing soil conservation and other sediment control measures to reduce downstream sediment loads and related sediment problems.

The present paper reports an attempt to use the fallout radionuclides caesium-137 ($^{137}$Cs) and unsupported lead-210 ($^{210}$Pb$_{ex}$) to explore further the relationship between sediment mobilisation, sediment transfer and storage, and sediment yield in a medium-scale (31.61 km$^2$) catchment in Calabria, southern Italy. Although existing information on the suspended sediment loads of rivers in this region suggests that the sediment yields are relatively low, there is evidence that rates of soil loss and therefore the intensity of soil degradation are substantially higher than suggested by the values of specific sediment yield. Concerns for the longer-term sustainability of agriculture in this area mean that there is an important need to establish whether the relatively low specific sediment yields are a reflection of limited rates of soil erosion or much higher rates of soil erosion coupled with a low sediment delivery ratio.

**Materials and methods**

**Study area**

**Study catchment**

The study area comprises a subcatchment of the River Trionto (Fig. 1), located on the Sila Plateau of central Calabria, southern Italy. The study catchment has a drainage area of 31.61 km$^2$ and ranges in altitude from 1467 m a.s.l. at the highest point to 983 m a.s.l. at the catchment outlet (39°26′58″N, 16°33′03″E). Geologically, the catchment includes areas underlain by several contrasting rock types, including sedimentary rocks (mainly flysch-type units), intrusive igneous rocks and intermediate and high-grade metamorphic rocks associated with crustal Alpine units (Sorriso-Valvo 1993; Molin et al. 2004). The major soil types are characterised by a range of textures, although sandy and silt–sandy soils are dominant (Dimase and Iovino 1996).

Large areas of the catchment (~68%) are cultivated and only a small part (~16%) is covered by trees, which include...
primarily pines, but also some beech and chestnut and some stands of alder, willow and aspen along the river corridors. The remaining portion (~16% of the catchment area) supports original rangeland with grass and scrub vegetation. Precipitation is almost uniformly distributed throughout the period extending from October to March; but in spring and summer frequent heavy rainstorms can occur and these account for ~20–25% of the annual total. The mean annual rainfall depends heavily on altitude and distance from the sea, and for the period 1922–2000 the mean annual rainfall ranged from 990 mm measured at Acri (39°29′38″N, 16°23′4″E) to 1302 mm at Longobucco (39°26′57″N, 16°36′40″E) (Servizio Idrografico e Mareografico Nazionale 2000). The area experiences a temperate climate, with mild to warm summers and cool winters.

**Catchment sediment output**

The Italian Hydrographic Service monitored the study catchment during the period 1964–1979, and measurements of rainfall, run-off and suspended sediment concentration are available for the catchment outlet. During the monitoring period, the annual suspended sediment yield, derived from sediment concentration measurements, ranged from 0.019 t ha⁻¹ in 1976 to 0.262 t ha⁻¹ in 1964, with a mean value of 0.103 t ha⁻¹ year⁻¹ (Fig. 2). These values, although considerably lower than the suspended sediment yields reported for coastal areas of the same altitude and distance from the sea, are consistent with other measurements within the study catchment (Porto et al. 2001), can be seen as representative of the mountain areas of the Sila Plateau. The presence of extensive flat areas within the catchment appears to reduce the sediment yield at the catchment outlet by promoting deposition during the conveyance of sediment through the catchment. In addition, part of the sediment load transported from the steepest mountain areas was trapped by 10 check dams built to stabilise the bed upstream of the catchment outlet during the same period as that covered by the sediment-measuring program. To account for the influence of these check dams on the sediment output from the study catchment, a program of field surveys was undertaken in 2006 that aimed to quantify the amount of sediment deposited upstream of each structure. The total amount of sediment deposited upstream of the check dams was estimated to be 5154 t. By taking into account the area of the catchment and the number of years over which the sediment accumulated (15 years), and assuming that, in the absence of the check dams, this sediment would have reached the catchment outlet, the sediment trapped by the check dams was estimated to be equivalent to a mean annual sediment yield of 0.11 t ha⁻¹ year⁻¹. Adding this value to the sediment yield estimated from the sediment concentration measuring program resulted in an estimate of the mean annual sediment yield of the catchment of 0.213 t ha⁻¹ year⁻¹.

**Soil sampling for ¹³⁷Cs and ²¹⁰Pbex analyses**

To use ¹³⁷Cs and ²¹⁰Pbex measurements to estimate the rates of erosion or sediment mobilisation and sediment redistribution within the study catchment, a program of soil coring was undertaken within the study catchment in March 2002. Two replicate soil cores were collected at 128 sites using a 6.9-cm diameter steel core tube inserted to 60 cm. The two cores were combined for radiometric analysis. Because of the difficulty of applying a grid-sampling scheme, owing to the presence of rocks and trees and some access problems, emphasis was placed on obtaining cores from a random selection of representative points distributed throughout the catchment. The sampling sites were selected to characterise the variability of vegetation cover, topography and altitude within the catchment, while still providing a uniformly spatial coverage (Fig. 1).

Each composite bulk core sample was oven-dried at 105°C for 48 h, disaggregated and dry-sieved to separate the <2-mm fraction. A representative subsample of this fraction (ranging from 1 to 1.2 kg) was packed into a 1-L perspex Marinelli beaker for determination of its ¹³⁷Cs and ²¹⁰Pbex activity by gamma spectrometry. The samples were sealed for 21 days before assay to achieve equilibrium between ²²⁶Ra and its daughter ²²²Rn. The ¹³⁷Cs and ²¹⁰Pbex activities in the samples were measured by gamma spectrometry using a high-resolution, low-background, low-energy, n-type HPGe detector (ORTEC, Oak Ridge, TN, USA) in the laboratory of the Department of Geography at the University of Exeter, UK. Count times were typically ~30 000 s, providing a precision of ~±10% at the 95% level of confidence for ¹³⁷Cs. The measurements were standardised to a fixed date at the end of 2002. The ²¹⁰Pbex activities in the samples were assayed at the same time as ¹³⁷Cs by measuring both the total ²¹⁰Pb and the ²²⁶Ra (via ²¹⁴Pb) activity. The ²¹⁰Pbex activity was calculated by subtracting the supported ²¹⁰Pb activity, estimated from the ²²⁶Ra activity, from the total ²¹⁰Pb activity. The precision of the final estimates of ²¹⁰Pbex activity was lower than that for ¹³⁷Cs (~±15% at the 95% level of confidence) because of the additional uncertainty introduced by the need to subtract the two measurements.

Additional sampling was carried out in the study catchment in late 2002 to obtain information on the local reference inventory and the depth distribution of ¹³⁷Cs and ²¹⁰Pbex in the soil profile. Because of the spatial extent of the study catchment and the local variability in rainfall, associated with altitude, sampling for the reference inventory was undertaken at three different sites that were at different altitudes. These sites were within undisurbed and uneroded areas characterised by permanent pasture and minimal slope. These additional samples were taken using a scraper plate (Campbell et al. 1988). This provided a surface...
area of 652 cm² and samples were collected at depth increments ranging from 1 to 4 cm, to a depth of 50 cm. For each reference site, two scraper plate samples were collected and the matching depth increments were bulked before analysis to take into account micro-scale variability in the reference inventory (cf. Owens and Walling 1996). Eight additional 6.9-cm diameter bulk cores were also collected from each reference site using the coring device and these samples were analysed separately to provide further estimates of the reference inventory.

In the case of the reference samples collected from the reference sites, each of the bulk cores and the individual composite depth increments provided by the two scraper plate profiles was assayed twice for its 137Cs and 210Pbex activity and the results were averaged to increase the precision of the measurements. For the composite samples collected from the two scraper plate profiles, an estimate of the total inventory was derived as the sum of the inventories of the individual depth increments. This was again judged to increase the precision of the resultant estimate over that of the individual measurements by virtue of the random nature of the uncertainty associated with gamma counting. The final estimate of the reference inventory for a sampling site was derived as the mean of the estimates provided by the individual bulk cores and the composite scraper plate profile. In the latter case, the large surface area (1304 cm²) was equivalent to 35 bulk cores. This approach was seen to reduce the uncertainty associated with microscale sampling variability and, when coupled with the replicate measurements undertaken on the individual samples, was judged to provide reliable and precise estimates of the reference inventory for the three sampling sites.

Several scraper plate profiles were also obtained from several representative sites within the study catchment to characterise the depth distributions of 137Cs and 210Pbex. These samples, collected in late 2002, were prepared in the same way as those collected in March 2002 and the activity of all samples has been standardised to the end of 2002.

Converting radionuclide measurements into soil redistribution rates

Estimation of the rates of erosion and deposition from 137Cs and 210Pbex measurements is generally based on the degree of reduction or increase in the measured inventory, relative to the local reference inventory (Walling 2004). For cultivated soils, the calibration relationship required to convert the magnitude of the reduction or increase in the radionuclide inventory to an estimate of the rate of soil redistribution commonly uses a mass balance model (e.g. Kachanoski and de Jong 1984; Walling and He 1999a, 1999b). A sampling point with a total radionuclide inventory \( A(t) \) (Bq m\(^{-2}\)) less than the local reference inventory \( A_{ref} \) (Bq m\(^{-2}\)) is assumed to represent an eroding site, whereas a point with a total radionuclide inventory greater than the local reference inventory is assumed to be a depositional site.

Following Walling and He (1999a), the change in the activity of accumulated 210Pbex or 137Cs \( A(t) \) (Bq m\(^{-2}\)) per unit area with time \( t \) (year) at an eroding site can be represented as:

\[
A(t) = A(t_0) e^{-\int_{t_0}^{t} (PR/D + \lambda_1) dt'} + \int_{t_0}^{t} (1 - \gamma) I(t') e^{-\int_{t}^{t_0} (PR/D + \lambda_1) dt''} dt'
\]

where \( R \) is the erosion rate (kg m\(^{-2}\) year\(^{-1}\)), \( D \) is the cumulative mass depth representing the average plough depth (kg m\(^{-2}\)), \( \lambda \) is the decay constant for 137Cs or 210Pbex (year\(^{-1}\)), \( R(f) \) is the annual 137Cs or 210Pbex deposition flux (Bq m\(^{-2}\) year\(^{-1}\)), \( \Gamma \) is the proportion of the freshly deposited 137Cs or 210Pbex fallout removed by erosion before being mixed into the plough layer, \( P \) is the particle size correction factor, \( t_0 \) (year) is the year when cultivation started, and \( A(t_0) \) (Bq m\(^{-2}\)) is the 210Pbex or 137Cs inventory at \( t_0 \).

Where \( A(t) \) is greater than the local reference inventory \( A_{ref} \) at a sampling point, deposition may be assumed. In this case, the mean soil deposition rate \( R' \) can be calculated from the following equation:

\[
R' = \frac{\int_{t_0}^{t} R' C_d(t') e^{-\lambda(t'-t)} dt' \int_{S} R dS}{\int_{S} P P(t') I(t') (1 - e^{-R'/H}) (R + A(t')/D) dS}
\]

where \( H \) is the relaxation mass depth and \( C_d(t') \) is the radionuclide content of sediment mobilised from all the eroding areas that converge on the aggregating point. In general, \( C_d(t') \) can be assumed to be represented by the weighted mean of 137Cs or 210Pbex activity of the sediment mobilised from the upslope contributing area \( S \) (m\(^2\)). \( P \) is a further particle-size correction factor reflecting differences in grain size composition between mobilised and deposited sediment and \( \gamma \) is the proportion of the annual fallout susceptible to removal by erosion before incorporation into the soil profile by tillage.

Results

137Cs and 210Pbex inventories and depth distributions at the reference site

The 137Cs reference inventories (Table 1) ranged from 2805 Bq m\(^{-2}\) for the lowest site to 4682 Bq m\(^{-2}\) for the highest site. This variation primarily reflects the spatial variability of rainfall inputs over the catchment, in response to variations in altitude and distance from the sea. The importance of altitude in controlling rainfall is emphasised by the clear trend of increasing rainfall with increasing altitude, demonstrated by rainfall measuring stations in the vicinity of the study catchment. The reference inventories obtained for 210Pbex (Table 1), ranging from 11 692 to 14 456 Bq m\(^{-2}\), show a similar pattern of variability to that described for 137Cs, again emphasising the influence of altitude. The depth distributions of 137Cs and 210Pbex (Fig. 3a–f) are typical of an undisturbed site (Walling and Quine 1992), with ~90% of the total inventory occurring in the top 10 cm and a sharp exponential decline in activity below this depth.

Considering the likely variability of annual rainfall across the study catchment linked to altitude and the associated variability of the 137Cs and 210Pbex reference inventories within the catchment, the conversion models used to estimate soil redistribution rates were parameterised using the three individual reference inventories obtained for both 137Cs and 210Pbex. To achieve this, the catchment was divided into three elevation classes (A, B and C), each of which was characterised by the
Table 1. Reference inventory values

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Sampling device</th>
<th>$^{137}$Cs Mean (Bq m$^{-2}$)</th>
<th>s.d. (Bq m$^{-2}$)</th>
<th>$^{210}$Pbex Mean (Bq m$^{-2}$)</th>
<th>s.d. (Bq m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Scraper plates</td>
<td>2880</td>
<td>–</td>
<td>11 720</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Cores</td>
<td>2726</td>
<td>212.1</td>
<td>11 663</td>
<td>1430</td>
</tr>
<tr>
<td>B</td>
<td>Scraper plates</td>
<td>3846</td>
<td>–</td>
<td>13 023</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Cores</td>
<td>3920</td>
<td>149.3</td>
<td>13 124</td>
<td>1128</td>
</tr>
<tr>
<td>C</td>
<td>Scraper plates</td>
<td>4725</td>
<td>–</td>
<td>14 572</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Cores</td>
<td>4639</td>
<td>247.1</td>
<td>14 340</td>
<td>1683</td>
</tr>
</tbody>
</table>

Fig. 3. The depth distributions of (a–c) $^{137}$Cs and (d–f) $^{210}$Pbex at the three reference sites.

value for the reference inventory associated with that altitudinal range (see Table 2). The subdivision was based on the area–elevation relationship for the study catchment presented in Fig. 4.

$^{137}$Cs and $^{210}$Pbex inventories within the study catchment

The values of the $^{137}$Cs inventory associated with the 128 sampling points in the study catchment range from 0.5 to 8770 Bq m$^{-2}$, with a mean value of 3267 Bq m$^{-2}$. To assess whether the individual values of the $^{137}$Cs inventory were less or greater than the reference inventory and, therefore, provide evidence of erosion or deposition, respectively, it was necessary to take into account, first, the different reference inventories allocated to the three elevation classes (Fig. 4) and, second, the uncertainty associated with the reference inventory values provided for the different elevation classes. Because only one value was available for the reference inventory associated with each elevation zone, this was unable to reflect the likely spatial
variability of the reference inventory within that class. Assuming that the estimates of the $^{137}$Cs and $^{210}$Pb$_{ex}$ reference inventories derived for the three reference sites represent precise estimates of that inventory with minimal uncertainty, and taking into account the likely variability of the reference inventory within the three elevation zones, the individual reference inventories for both $^{137}$Cs and $^{210}$Pb$_{ex}$ for the three zones were assumed to have an uncertainty of $\pm$10% at the 95% level of confidence. Only when the measured inventories for the individual sampling sites fall either above or below this range are they assumed to be greater or less than the reference inventory. The results indicated that 13% of the $^{137}$Cs inventory values obtained for the individual sampling points were not significantly different from the appropriate reference values, indicating that those sampling points were essentially stable. However, 56% of the inventories were significantly lower than the appropriate reference values, indicating erosion, and 31% were significantly greater, indicating deposition. With 87% of the sampling points showing evidence of erosion or deposition, it is clear that considerable soil redistribution has occurred within the study basin since the commencement of $^{137}$Cs fallout in the mid 1950s. The $^{137}$Cs inventory presented in Fig. 5a is close to the reference inventory and therefore limited soil redistribution.

Evidence of erosion and deposition rates associated with the sampling points in the study catchment

A computer-based conversion model was used to solve Eqs (1) and (2) and to estimate the erosion or deposition rates associated with the individual sampling points within the study catchment. An average plough depth ($D$) ranging from 200 to 350 (kg m$^{-2}$), which accounts for the different crop types within the catchment, a value of $H$ equal to 4, and a value of $\gamma$ equal to 1 based on the relationship between the timing of cultivation and the rainfall regime, were used.

The annual $^{210}$Pb$_{ex}$ fallout deposition flux for each elevation zone was estimated from the $^{210}$Pb$_{ex}$ inventories measured at the reference sites, assuming a steady state with the fallout input balanced by radioactive decay. A record of the annual $^{137}$Cs fallout for the individual elevation zones was reconstructed based on the measured reference inventories and the known temporal distribution of $^{137}$Cs fallout in the northern hemisphere (Cambray et al. 1989).
There are, however, important differences between the estimates of erosion and deposition rates provided by the \(^{137}\text{Cs}\) and \(^{210}\text{Pb}_{\text{ex}}\) measurements, which are presented in Fig. 6. The results presented in Fig. 6 emphasise that there is clear evidence of soil redistribution processes on a relatively short-term magnitude greater than the estimated specific sediment yield. Many of the estimates of erosion rates are one or two orders of magnitude greater than the estimated specific sediment yield. This contrast reflects the different temporal sensitivity of the two radionuclides, with the \(^{137}\text{Cs}\) measurements providing an estimate of average soil redistribution rates for the period extending from the commencement of \(^{137}\text{Cs}\) fallout in the mid 1950s to the present. Fallout was minimal during much of this period (i.e. since the mid 1970s) and the \(^{137}\text{Cs}\) inventories primarily reflect the longer-term influence of soil redistribution processes on a relatively short-term input of fallout in the late 1950s and 1960s, which has remained in the soil. In contrast, the annual fallout of \(^{210}\text{Pb}_{\text{ex}}\) is essentially constant and, in view of its shorter half-life (22.3 years), current inventories are likely to be more sensitive to erosion and soil redistribution occurring during the past 10–15 years. The higher values of the soil redistribution rate provided by the \(^{210}\text{Pb}_{\text{ex}}\) measurements could, therefore, reflect either increased erosional activity in recent years, owing to, for example, changing land use or land management practices or changing rainfall patterns, or, alternatively, an increased incidence of high magnitude events during this shorter time window than during the longer time window reflected by the \(^{137}\text{Cs}\) measurements. The trend in Fig. 7 show a decrease in annual rainfall between the two periods. However, this is paralleled by an increase in erosivity between the two periods, which points to an increase in the incidence of higher magnitude events during the most recent period.

![Image](image1.png)

**Fig. 6.** The range of erosion and deposition (t ha\(^{-1}\) year\(^{-1}\)) rates associated with the 128 sampling points within the study catchment, estimated from the (a) \(^{137}\text{Cs}\) and (b) \(^{210}\text{Pb}_{\text{ex}}\) measurements.

The ranges of the erosion and deposition rates estimated for the individual sampling points within the study catchment, based on \(^{137}\text{Cs}\) and \(^{210}\text{Pb}_{\text{ex}}\) measurements, are presented in Fig. 6a, b. The central class designated stable represents those sampling points where the measured inventories fell within the uncertainty range allocated to the appropriate reference inventory.

**Discussion**

The results presented in Fig. 6 emphasise that there is clear evidence of active erosion and deposition within the catchment. Many of the estimates of erosion rates are one or two orders of magnitude greater than the estimated specific sediment yield. There are, however, important differences between the estimates of soil redistribution rates provided by the \(^{137}\text{Cs}\) and \(^{210}\text{Pb}_{\text{ex}}\) measurements. Similar differences have been reported in other studies (e.g. Walling et al. 2003; Fukuyama et al. 2008). As indicated above, the overall distribution of results between erosion and deposition is similar for the two radionuclides, but the estimates of both erosion and deposition rates provided by the \(^{210}\text{Pb}_{\text{ex}}\) measurements tend to be significantly higher than those provided by the \(^{137}\text{Cs}\) measurements. Although it is difficult to provide a definitive explanation for this, it seems likely that this contrast reflects the different temporal sensitivity of the two radionuclides to ongoing soil redistribution.

![Image](image2.png)

**Fig. 7.** The trend in (a) rainfall amount and (b) Arnoldus erosivity index for four rainfall measuring stations in the vicinity of the study catchment during the periods 1964–1979 and 1980–2000.
The essentially constant annual fallout of $^{210}$Pb$_{ex}$ also means that current inventories will reflect the fate of fallout delivered during a period extending back beyond that influencing the $^{137}$Cs inventories. Although the influence of the intensity of past soil redistribution on current inventories will progressively decline back through time, the contrasts between the magnitude of the estimates of soil redistribution rates provided by the $^{137}$Cs and $^{210}$Pb$_{ex}$ measurements could also reflect the longer ‘memory’ of the $^{210}$Pb$_{ex}$ measurements.

A total of only 128 sampling points within a 31.6-km$^2$ study catchment is clearly inadequate to provide a detailed representation of the spatial pattern of erosion and soil redistribution within the study catchment or to provide an effective basis for detailed geostatistical analysis of the results (e.g. Mabit and Bernard 2007). However, the maps presented in Fig. 8 provide some evidence of the spatial distribution of the soil redistribution rates estimated from the $^{137}$Cs and $^{210}$Pb$_{ex}$ measurements within the study catchment. In addition, Table 3 indicates that, as might be
Table 3. Distribution of the erosion and deposition rates between the three altitudinal zones

<table>
<thead>
<tr>
<th>Subarea</th>
<th>Mean soil redistribution rate* (t ha(^{-1}) year(^{-1}))</th>
<th>No. sampling points</th>
<th>Stable</th>
<th>Erosion</th>
<th>Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>137Cs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>4.10</td>
<td>5</td>
<td>12</td>
<td>26</td>
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</tr>
<tr>
<td>B</td>
<td>-4.07</td>
<td>7</td>
<td>30</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-11.96</td>
<td>4</td>
<td>30</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>210Pbex</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>25.18</td>
<td>5</td>
<td>17</td>
<td>21</td>
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</tr>
<tr>
<td>B</td>
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<tr>
<td>C</td>
<td>-19.69</td>
<td>5</td>
<td>24</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

expected, the highest rates of soil redistribution are found in the two higher zones of the catchment. Furthermore, points providing evidence of deposition predominate in the lowest zone, with ~60% of the sampling points in this zone showing evidence of deposition for both 137Cs and 210Pbex. This general pattern is further confirmed by comparing Fig. 8 with Fig. 1. This comparison emphasises that most of the points showing deposition are found in the lower areas of the catchment and that higher erosion rates are associated with areas of higher elevation and greater relief. Although, as noted above, the proportions of the sampling points showing erosion or deposition were similar for the two radionuclides, comparison of the two maps presented in Fig. 8 emphasises that for some points the magnitude of the estimates was quite different, shifting from erosion to deposition and vice versa.

The data presented in Figs 6 and 8 also emphasise that appreciable rates of soil mobilisation are found in many parts of the study catchment and that the relatively low measured sediment yield does not provide a representative reflection of those rates. However, to compare the results provided by the two approaches more directly, the measured sediment yield should be compared with the estimate of net soil loss provided by the 137Cs and 210Pbex measurements. Figs 6 and 8 indicate that a substantial proportion of the sediment mobilised within the catchment is likely to be deposited during transfer towards the catchment outlet and stored within depositional areas, and the estimates of net soil loss provided in Table 4 further confirm that only a small proportion of the mobilised sediment is likely to find its way to the catchment outlet. Based on the 128 sampling points, the net soil loss from the study catchment estimated from the 137Cs and 210Pbex measurements was 3.54 and 3.36 t ha\(^{-1}\) year\(^{-1}\), respectively, reflecting sediment delivery ratios of 35 and 14% respectively.

The values of net soil loss presented in Table 4 are, nevertheless, still greater than the measured sediment yield from the catchment. Close agreement of the two estimates would, however, not necessarily be expected. The periods covered by the measured sediment yield and the 137Cs and 210Pbex measurements are clearly different, and it has been shown above that the period 1980–2000 was characterised by increased annual erosivity compared with the period during which the catchment sediment yield was measured (i.e. 1964–1979). However, perhaps more importantly, the small number of sampling points associated with the radionuclide measurements is likely to underrepresent the depositional areas within the catchment, many of which will be located along the main linear transport pathways and not randomly distributed across the basin. Furthermore, both estimates of sediment output involve appreciable uncertainties. Against this background, the results provided by the two independent approaches are seen to be similar and therefore reasonably consistent.

Conclusions

The present study demonstrates the potential for using 137Cs and 210Pbex measurements to obtain information on soil erosion and redistribution rates within a medium-sized catchment. Despite the relatively small number of sampling points for which erosion and deposition rates were estimated, the resultant data provide consistent evidence of the incidence of relatively high erosion rates in many parts of the catchment and also of substantial deposition, particularly within the lower areas of the catchment. The deposition is reflected by the relatively low rate of net soil loss, which is consistent with the low measured sediment yield for the catchment. The use of 137Cs and 210Pbex measurements should not be seen as an alternative to more traditional sediment measurement programs, but rather as providing a potentially important complement to such measurements by producing
key information on the operation of sediment mobilisation and redistribution processes within a catchment. To date the use of fallout radionuclides has been almost exclusively limited to studies of individual fields and very small catchments (i.e. <1.0 km²). The present study has demonstrated the potential for upsampling the approach to medium-sized catchments an order of magnitude or more greater in size. Further work is clearly required to quantify more precisely the uncertainties associated with the estimates of soil redistribution rates provided by 137Cs and 210Pb measurements and to optimise sampling strategies to extract the maximum information from a limited numbers of samples. However, the present study demonstrates the viability of the approach.

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References


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