Using \(^{137}\)Cs Measurements to Calibrate and Validate the Sediment Delivery Distributed (SEDD) Model for Two Catchments in Southern Italy

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Abstract

Soil erosion has become a serious environmental problem in the agricultural and forest lands of southern Italy, where annual soil loss associated with extreme rainfall events can reach 100 t ha\(^{-1}\). There is a need to use numerical models to predict soil erosion and sediment delivery under different physiographic and land use conditions, in order to assess erosion risk and develop effective erosion and sediment control strategies. However, model validation and calibration is a key requirement for the successful use of such models. The use of fallout \(^{137}\)Cs measurements affords a useful means of assembling spatially distributed information on soil redistribution rates, which can be used to calibrate and validate sediment delivery models. In this paper, \(^{137}\)Cs measurements are used to calibrate and validate the SEDD model for two catchments of contrasting size, slope, and land use located in southern Italy. The Bonis catchment (1.39 km\(^2\)) is almost completely reafforested with black pine trees and has a mean slope of ca. 40\%. It is characterized by a high sediment delivery ratio. The Trionto catchment (31.61 km\(^2\)) is almost completely cultivated and is characterized by high values of soil erosion in its mountain areas that are balanced by deposition and sediment storage in its lowland areas, which results in a relatively low sediment delivery ratio. The sediment delivery ratios estimated using the \(^{137}\)Cs measurements made within the catchments have been used to calibrate the model specific parameter \(\beta\), which showed a strong dependence on the SDR values for individual subcatchments. The SEDD model was then successfully validated for different timescales using estimates of specific sediment yield obtained for both catchments.

Keywords: Soil erosion, distributed models, Caesium-137, sediment delivery ratio.
Introduction

Soil erosion is recognised as a serious environmental problem in the agricultural and forest lands of southern Italy, where annual rates of soil loss associated with extreme rainfall events can reach 100 t ha$^{-1}$. In order to assess soil erosion risk and develop effective erosion and sediment control strategies in this environment, there is a need to employ numerical models to predict soil erosion and sediment delivery under different physiographic and land use conditions. To provide reliable results, it is important that such models should be calibrated and validated for the local conditions. However, a general lack of data on the internal functioning and efficiency of the sediment delivery system, introduces problems in undertaking meaningful calibration and validation exercises. Recent advances in the use of fallout radionuclides, including caesium-137 ($^{137}$Cs), to assemble spatially distributed information on medium-term soil and sediment redistribution rates within a catchment now offers important new opportunities for model calibration and validation. This contribution presents some initial results of an attempt to use $^{137}$Cs measurements undertaken within two catchments in Calabria, southern Italy, to calibrate and validate the SEDD model, which was originally developed for use in southern Italy.

The sediment delivery distributed (SEDD) model

Ferro and Minacapilli (1995) have developed a spatially distributed approach for estimating the sediment yield of catchments ranging in size from several km$^2$ to several hundred km$^2$. In order to account for the spatial heterogeneity of soil erosion and sediment transport, the catchment is subdivided into morphological units or subcatchments, for each of which the sediment delivery ratio $SDR_i$ is assumed to be a function of travel time $t_{p,i}$, i.e.:

$$SDR_i = \exp(-\beta t_{p,i}) = \exp \left(-\beta \frac{l_{p,i}}{s_{p,i}} \right) = \exp \left[-\beta \left( \frac{N_p}{i=1} \frac{\lambda_{i,j}}{S_{i,j}} \right) \right]$$

where, $l_{p,i}$ and $s_{p,i}$ are respectively the length (m) and the slope (m m$^{-1}$) of the hydraulic path from the given morphological unit $i$ to the nearest stream reach; $\beta$ (m$^{-1}$) is a model specific parameter (Ferro and Porto, 2000); $N_p$ is the number of morphological units located along the hydraulic path, and $\lambda_{i,j}$ and $s_{i,j}$ are respectively the length (m) and the slope (m m$^{-1}$) of each morphological unit $i$ located along the hydraulic path $j$.

The sediment output $Y_i(t)$, from each morphological unit (or sub-catchment) $i$ into which the catchment is divided, is simply calculated by the following equation:

$$Y_i = SDR_i A_i SU_i$$

in which $A_i$ is the soil loss (t ha$^{-1}$) from the $i$th morphological unit (or sub-catchment), which has to be estimated by the selected erosion model; and $SU_i$ is...
the area (ha) of the morphological unit (or sub-catchment).

Soil loss $A_i$ is estimated by the following variant of the USLE (Wischmeier and Smith 1965):

$$A_i = R_{it} K_i L_i S_i C_i P_i$$  \hspace{1cm} (3)

where $R_{it}$ is the rainfall erosivity factor for a given temporal scale $t$ (event, annual, and mean annual) (t ha$^{-1}$ per unit of $K_i$); $K_i$ is the soil erodibility factor estimated by the procedure proposed by Wischmeier et al. (1971) (t h kg$^{-1}$ m$^{-2}$); $C_i$ is the cover and management factor; $P_i$ is the support practice factor; and $L_i S_i$ is the topographic factor. The latter can be calculated using the formulae proposed by McCool et al. (1987), (Renard et al., 1994):

$$LS_i = \left(\frac{l_i}{22.13}\right)^{m_i} (10.8 \sin \alpha_i + 0.03) \quad \text{if } \tan \alpha_i < 0.09 \quad (4a)$$

$$LS_i = \left(\frac{l_i}{22.13}\right)^{m_i} (16.8 \sin \alpha_i - 0.5) \quad \text{if } \tan \alpha_i \geq 0.09 \quad (4b)$$

where $l_i$ is the slope length of the $i$-th morphological unit. The slope length exponent $m_i$ is given by the following equation (McCool et al., 1989):

$$m_i = \frac{f_i}{1+f_i}$$  \hspace{1cm} (5)

where $f_i$ represents the ratio of rill to interrill erosion and can be expressed as follows:

$$f_i = \sin \alpha_i \left\{ \frac{0.0896 (3 \sin 0.8 \alpha_i + 0.56)}{3 \sin 0.8 \alpha_i + 0.56} \right\} \quad (6)$$

For the whole catchment the sediment yield value $Y_b (t)$ is equal to the sum of the sediment yields $Y_i$ of all morphological units (or sub-catchments) into which the basin is divided i.e.:

$$Y_b = \sum_{i=1}^{N_s} Y_i = R_i \sum_{i=1}^{N_s} K_i C_i L_i S_i \exp \left( -\beta \frac{f_{p,i}}{\sqrt{s_{p,i}}} \right) SU_i$$  \hspace{1cm} (7)

where $N_s$ is the number of morphological units (or sub-catchments) into which the catchment is divided.

The model requires values for the parameter $\beta$. These can be determined by a recursive approach using Eq. (7) coupled with independent sediment yield
measurements (Ferro and Porto, 2000). Alternatively, $\beta$ can be deduced from Eq. (1), once the basin sediment delivery ratio and the catchment topography are known.

**Description of the study area**

The study area (Fig. 1) selected for this investigation comprises two catchments located on the Sila Plateau of central Calabria, southern Italy.

![Fig. 1: The study catchments](image)

The Bonis catchment (Fig. 1) is located in the mountain area of Sila Greca, at a mean elevation of 1131 m a.s.l. The catchment has a drainage area of 1.39 km$^2$ most of which (ca. 93%) is covered by forest stands, dominated by Calabrian pine (*Pinus laricio* Poiret). Small areas covered by chestnut (*Castanea sativa* Mill.) and riparian forests of common alder (*Alnus glutinosa* L.) are also present within the catchment. Geologically, the catchment includes areas underlain by acid plutonic rocks (Callegari et al., 2003) that have developed sandy soils.
typical of Typic Xerumbrepts and Ulpic Haploxeralfs associations. Climatically, the catchment shows patterns of precipitation and temperature typical of the mountain areas of Calabria, with a short arid period in summer and rainfall almost uniformly distributed though the period extending from September to April (Iovino and Puglisi, 1989).

The catchment is instrumented with three tipping bucket 20-minute-timestep recording raingauges, located at the outlet (975 m a.s.l.), and at the left side (1175 m a.s.l.), and right side (1258 m a.s.l.) of the main stream. Runoff is measured at the catchment outlet using a channel structure equipped with a mechanical stage recorder capable of measuring discharges up to ca. 17 m$^3$s$^{-1}$.

At the downstream end of the channel a large reinforced concrete storage basin (8 m x 15 m x 2 m) was constructed to trap the sediment passing through the monitoring structure system. This basin is periodically emptied and the sediment excavated from it is removed from the catchment.

The Trionto 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). The topography is highly variable in the upper and lower parts of the catchment, that are characterized by high slope gradients, but it is quite uniform at middle elevations, where large flat areas extend along the drainage lines. The land use and vegetation cover are dominated by extensive cultivated areas and only a small proportion of the catchment 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 soils, developed on contrasting rock-types that include sedimentary rocks, intrusive igneous rocks and intermediate and high-grade metamorphic rocks associated with crustal Alpine units (Sorriso-Valvo, 1993; Molin et al., 2004), are characterised by a range of textures, although sandy and silt-sandy soils are dominant (Dimase and Iovino, 1996). The area experiences a Mediterranean climate, with precipitation uniformly distributed through the period extending from October to March and frequent heavy rainstorms in summer, that account for ca. 20-25% of the annual total.

Catchment sediment yields

For the Bonis catchment, two field campaigns were undertaken in 2000 and 2003 aimed at quantifying the amount of sediment deposited in the storage basin and along the channel bottom at the catchment outlet during the period from November 1998 to August 2003. On both occasions, before emptying the siltation basin, the depth of the sediment deposited in the storage basin and the channel was measured using a grid scheme: a total of 267 and 95 sampling points were established respectively for the 2000 and the 2003 campaigns. During the field survey a total of 80 sediment samples were also collected using a steel core cylinder 100 cm long, in order to estimate the sediment bulk density. This provided a mean value of 0.19 t m$^{-3}$ during the first field campaign and a mean value of 0.41 t m$^{-3}$ during the 2003 field survey. The overall results,
Climatically, typical of the and rainfall September to the left side m. Runoff is ipped with a ca. 17 m³ s⁻¹. storage basin through the the sediment 0d ranges in the catchment variable in the y high slope ge flat areas n cover are portion of the it also some ong the river sedimentary metamorphic Molin et al., ed silt-sandy experiences a through the storms in

considering the five-year monitoring period, gave a mean value of sediment output of ca. 0.25 t ha⁻¹ yr⁻¹.

The Trionto catchment was monitored by the Italian Hydrographic Service (SIMI) during the period 1964-1979, for which measurements of rainfall, runoff and suspended sediment concentration are available for the catchment outlet. During the monitoring period, the annual suspended sediment yield averaged 0.103 t ha⁻¹ yr⁻¹.

![Fig. 2: The annual sediment yield from the Trionto catchment for the period 1964 to 1979](image)

During the same period, 10 check dams were built to stabilise the bed upstream of the catchment outlet. These structures filled during the period covered by the monitoring and were responsible for trapping a substantial portion of the sediment load transported from the steepest mountain areas before it reached the catchment outlet. For this reason, a programme of field survey aimed at quantifying the amount of sediment deposited upstream of each structure was undertaken in 2006. The estimate of the total amount of deposited sediment upstream of the 10 check dams was ca. 5154 t. Assuming that, in the absence of the check dams, this sediment would have reached the catchment outlet, this value was estimated to be equivalent to a mean annual sediment yield of 0.11 t ha⁻¹ yr⁻¹. In order to account for the interannual variability of this component of the sediment output, it was assumed that it was distributed between years in direct proportion to the annual values of the R-factor employed in the SEDD model.

The final record of sediment output from the study catchment, based on the measurements derived directly from the measurements of suspended sediment concentration and the estimates deduced from the field survey programme, is reported in Figure 2.
Soil sampling for $^{137}$Cs analysis

The soil sampling for $^{137}$Cs analysis undertaken in the Bonis catchment encompassed two separate sampling programmes. The first was designed to establish the magnitude and spatial distribution of erosion rates within the catchment and involved three campaigns. During the first campaign, undertaken in 2006, replicate soil cores were collected at 55 sites using a 11 cm diameter steel core tube inserted to depth of 45 cm. These soil cores, collected at the intersections of an approximate 150m x 150m grid, were supplemented by a further 55 bulk cores collected from sites selected to improve the coverage of topographic variability during an additional campaign in 2006 (Fig. 1). The third campaign, undertaken in 2007, aimed to establish the depth distribution of $^{137}$Cs at undisturbed reference sites with minimum slope. One such site was located within a small clearing between the trees (Reference site 1). In this case, eight separate cores were collected using a 11 cm diameter steel core tube inserted to depth of 60 cm. Each core was sectioned at depth increments ranging from 1 to 4 cm.

The second sampling programme, undertaken in late 2008, aimed to supplement information about the depth distribution of $^{137}$Cs in soil. During this campaign two additional reference sites were selected within an adjacent area of undisturbed rangeland with some scattered pines (Reference site 2 and 3). At each sampling point, eight separate cores were collected using a 11 cm diameter steel core tube inserted to depth of 60 cm. Each core sample was sectioned at depth increments ranging from 1 to 4 cm.

The depth increments provided by the three reference locations were then bulked before analysis in order to reduce the effects of microscale sampling variability on the estimated reference inventory.

Additional soil samples were also obtained from three representative eroding and depositional areas within the catchment, in order to document the $^{137}$Cs depth distribution over the study area.

In order to use $^{137}$Cs measurement to document sediment redistribution within the Trionto catchment, a programme of soil coring was undertaken in March 2002. This involved the collection of replicate soil cores at 128 sites within the catchment, using a 6.9 cm diameter steel core tube inserted to depth of 60 cm. The two cores were bulked together for radiometric analysis. The sampling sites were selected to characterize the variability of vegetation cover, topography and altitude within the catchment, whilst also providing a fairly uniform spatial coverage (see Fig. 1).

Additional sampling was carried out in the study catchment in late 2002, in order to obtain information on the local reference inventory and the depth distribution of $^{137}$Cs in the soil profile. Because of the spatial extent of the study catchment and the local variability of rainfall, largely associated with altitude, sampling to establish the local reference inventory was undertaken at three different sites, at different altitudes. These sites were within undisturbed and uneroded areas characterised by permanent pasture and minimal slope. In this case, sampling was undertaken using a scraper plate (Campbell et al., 1988). This provided a surface area of 652 cm$^2$ and samples were collected at depth increments ranging from 1 to 4 cm, to a total depth of 50 cm. For each reference...
site, two scraper plate samples were collected and the matching depth increments were bulked prior to analysis, in order to take account of 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 were analysed separately to provide further estimates of the reference inventory. A number of scraper plate profiles were also obtained from several representative sites within the study catchment, in order to characterize the depth distributions of $^{137}$Cs.

Each sample collected from the two study catchments 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 1 to 1.2 kg) was packed into a 1 L perspex Marinelli beaker for determination of its $^{137}$Cs activity by gamma spectroscopy using a high resolution low-background, low energy, n-type HPGe detector, in the laboratory of the Department of Geography at the University of Exeter, UK. Count times were typically ca. 30000s, providing a precision of ca. ±10% at the 95% level of confidence.

The spatial pattern of soil redistribution within the study catchments

Topographic maps for the Bonis and Trionto catchments, at a scale of 1:5000 and 1:25000, respectively, were used with the AUTOCAD software package in combination with a modelling tool of the WINSURFER package, in order to generate a digital elevation model for each catchment.

Using a kriging interpolation method, the Bonis catchment was subdivided into 15 m x 15 m grid cells, whilst a grid size of 125 m x 125 m was used to subdivide the Trionto catchment. The $^{137}$Cs inventory values obtained from the sampling points were converted to estimates of the medium-term (ca. 45 yr) mean annual soil erosion and/or deposition rate using the diffusion and migration model and the mass balance model (Walling and He, 1997) for the Bonis and Trionto catchments, respectively. Considering the variability of annual rainfall across the Trionto catchment linked to altitude, an appropriate $^{137}$Cs reference value, depending on the altitude of the sampling point, was used. To achieve this, the catchment was divided into three areas of different altitude, for each of which the $^{137}$Cs reference value was specified as a range, incorporating a ±10% uncertainty. If the measured inventories for the individual sampling sites showed values above or below this range they were assumed to indicate deposition or erosion sites, respectively. If the measured values fell within the range, the corresponding sites were considered stable (see Porto et al., 2009).

The resulting interpolated spatial patterns of soil redistribution rates are depicted in Figure 3a,b. The results indicate that, as might be expected, the highest rates of soil redistribution are found in the higher zones of the catchment, whilst points providing evidence of deposition predominate in the lowest zone, with ca. 60% of the sampling points in this zone showing evidence of deposition.
Calibrating the sediment delivery distributed model

The soil redistribution patterns shown in Fig. 3a,b provided a basis for calibrating and validating the SEDD model for both the catchments. To do this each catchment was firstly discretized into smaller sub-catchments (10 and 11 for the Bonis and the Trionto catchment respectively). For each of these sub-catchments the sediment delivery ratio was calculated using the following formula:

\[
SDR_i = \frac{\sum X_e S - \sum X_d S}{\sum X_e S}
\]  

(8)

Fig. 3: The spatial pattern of soil redistribution rates estimated using $^{137}$Cs measurements for the Bonis catchment (a) and the Trionto catchment (b)
where $S$ is the cell size, $e$ indicates cells in eroding zones and $d$ the cells in depositing zones, and $X_e$ and $X_d$ are the interpolated $^{137}$Cs-based estimates of erosion and deposition rates for eroding and depositing cells respectively.

Following Eqs. (2) and (3), the SEDD model also required values for the USLE input parameters that were determined as follows.

The rainfall erosivity factor $R$ for each study catchment was calculated using rainfall data available for the meteorological station located in the vicinity of the study areas. A value of $R_j$ was firstly obtained for each erosive event, $j$, as the product of the storm rainfall kinetic energy $E$ and the maximum rainfall intensity measured over a 30-min time interval $I_{30}$. Then, the annual value of the rainfall erosivity factor $R_a$ was calculated by summing the values of $R_j$ for the events occurring during that year. The soil erodibility factor $K$ was estimated using the properties of the soil samples collected within the two catchments. The cropping and management factor $C_i$ was calculated from appropriate land use maps based on field data. The support practice factor $P_i$ was deduced from information concerning the type of tillage in cultivated areas and slope steepness in rangeland and forested areas. The topographic factor $L_s$ was calculated using Eqs. (4a,b), (5), and (6), with a subroutine provided by the LIBERTYBASIC software. With the exception of the rainfall erosivity factor, $R$, each parameter was calculated for each single cell. Due to the very low spatial variability of this parameter, only a single value of $R$ for each catchment was used in running the model.

In order to calibrate the SEDD model using the $^{137}$Cs measurements, Eq. (2) was firstly coupled with Eq. (8), with the aim of calculating the sediment yield $Y_{sc}$ for each sub-catchment. This calculation required the introduction into Eq. (3) of the appropriate values of the USLE parameters for each sub-catchment. In this case a mean cell-based value for each USLE-factor was used.

Once the modelled sediment yield $Y_{sc}$ was obtained, Eq. (7) was then applied in order to calculate the corresponding $\beta$ parameter for each sub-catchment. This step required firstly the calculation of the travel time

$$ t = \frac{1}{\sqrt{S_{p,i}}} $$

from each cell to the nearest reach of the stream network.

This calculation was made possible by an appropriate subroutine provided by the LIBERTYBASIC software and was based on the DEM. Again, a mean value of $t$ was used for each sub-catchment. The 10 and the 11 values of the $\beta$ parameter obtained with this procedure for Bonis and Trionto catchments, respectively, are plotted in Fig. 4a,b against the corresponding values of the sediment delivery ratio provided by the $^{137}$Cs measurements.

Figure 4 shows a very clear dependence of the model specific $\beta$ parameter on the SDR values, suggesting that, when applying the SEDD model, the $\beta$ parameter cannot be assumed to be constant within the same catchment.
Validating the sediment delivery distributed model

The results presented in Fig. 4a,b, together with the measurements of sediment output available at the catchment outlet, afford a basis for applying the SEDD model at the catchment scale. In fact, a visual inspection of Figure 4 suggests that the relationship between $\beta$ and SDR can be expressed by the following empirical equation:

$$\beta = -a \cdot \ln \text{SDR} + b$$

(9)

where the parameter $a$ assumes the values of 0.0000685 and 0.0005449 and the parameter $b$ the values 0.00000125 and 0.0000572 for the Bonis and Trionto catchments, respectively.
Results provided by Eq. (8) based on the $^{137}$Cs measurements from the two entire catchments, suggest a value of SDR of ca. 0.86 and 0.35 for the outlets of the Bonis and Trionto catchments, respectively. Following Eq. (9), these values provide a value of the $\beta$ parameter of ca. 0.000012 for the Bonis catchment, and ca. 0.00068 for the Trionto catchment. These two values of the $\beta$ parameter can be assumed representative of the catchment outlets. Assuming that the $\beta$ parameter and the USLE factors $K$, $C$, $LS$, and $P$, are time invariant for those locations, Eqs. (7), (8), and (9), together with the sediment output measurements provided at the catchment outlets, can be used to validate the SEDD model at different temporal scale.

For the Bonis catchment, for which two values of sediment yield had been documented for the periods 1998-2000 and 2000-2003, Eq. (7) also required the production of two values of the rainfall erosivity factor $R_p$ covering those periods and provided by the same meteorological station.

For the Trionto catchment, for which measurements of sediment yield were deduced at the annual scale, Eq. (7) required the introduction of the 15 annual values of the rainfall erosivity factor $R_e$.

A comparison of the measured annual values of sediment yield with those calculated by the SEDD model, using the approach suggested above, is provided by Figure 5. The reasonable agreement between the two sets of sediment yield values confirms the applicability of the Sediment Delivery Distributed model if the parameter $\beta$ is calibrated using $^{137}$Cs measurements.

The results presented in Figure 5 must be seen as a first attempt to use data derived from fallout radionuclide measurements to calibrate the SEDD model.

Several simplifications were necessary in the example presented here. For example, the 110 and 128 sampling sites for the Bonis and Trionto catchments, respectively may not be sufficient to represent with satisfactory accuracy the variability of sediment redistribution over the entire catchments. In this case, further work is clearly required to quantify more precisely the uncertainties associated with the estimates of soil redistribution rates provided by $^{137}$Cs measurements. Also, other assumptions and process representations incorporated
into this model still require further testing and elucidation. For example, the effects of channel erosion, that have been neglected by the authors for small basins, could be of considerable importance in large catchments, where surface erosion is not the dominant process.

**Conclusions**

A distributed approach is an important requirement for representing soil erosion and deposition processes within a catchment. In such contexts, although the coupling of sediment delivery models with Geographical Information Systems has proved to be very effective, their calibration and validation have generally been restricted to comparison of predicted and measured outputs at the catchment outlet. The use of $^{137}$Cs measurements to derive estimates of soil redistribution rates *within* a catchment provides an effective means for testing the performance of such models. The results presented here, which involved the use of the SEDD model within two contrasting catchments, demonstrated that the sediment delivery ratio derived from the $^{137}$Cs data provides an effective means of calibrating the model specific parameter \( \beta \) in SEDD. These findings, that are based on a clear dependence of this parameter on the SDR values calculated for 10 and 11 sub-catchments into which the study catchments were divided, must, nevertheless, be seen as preliminary. Further work is required to quantify more precisely the uncertainties associated with the estimates of soil redistribution rates provided by $^{137}$Cs measurements and to verify the assumptions incorporated into the SEDD model.

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**References**


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