

## **The use of fallout radionuclides in investigations of erosion and sediment delivery in the Polish Flysh Carpathians**

**W. FROEHLICH**

*Department of Geomorphology and Hydrology of Mountains and Uplands,  
Institute of Geography and Spatial Organization, Polish Academy of Sciences,  
Research Station, Frycowa 113, 33-335 Nawojowa, Poland*

**D. E. WALLING**

*Department of Geography, University of Exeter, Exeter EX4 4RJ, UK*

**Abstract** The Polish Flysh Carpathians are a mountain area where climate, relief and the erodible bedrock combine to produce an active erosional system dominated by fluvial processes. Poor land management has further intensified land erosion. An improved knowledge of the erosion and sediment delivery dynamics of the area is required to provide a basis for improved land management and for reducing rates of reservoir siltation. Classical methods for investigating rates of erosion and sediment delivery dynamics possess many limitations in terms of operational problems, the substantial resources required and their limited spatial and temporal coverage. The use of the fallout radionuclide caesium-137 as a sediment tracer appears to offer considerable potential for assembling information on erosion and sediment delivery dynamics in this environment and some preliminary results of radiocaesium-based investigations undertaken in the small (19.6 km<sup>2</sup>) Homerka drainage basin and the larger (4692 km<sup>2</sup>) basin of the Dunajec River above Roznowski reservoir are reported. These investigations have focussed on assessment of soil erosion on cultivated fields, identification of the main suspended sediment sources and elucidation of sediment delivery dynamics.

## **INTRODUCTION**

The Polish Flysh Carpathians are a mountain area of moderate altitude and relief where the tree cover extends to the summits. Much of the original forest cover has been removed by deforestation. The headwater zones and steep slopes are characterized by intensively exploited forests accessed by a dense network of unmetalled roads. In the lower parts much of the land is given over to arable cultivation. This land is divided into small plots bounded by terraces and is again characterized by a dense network of unmetalled roads, which frequently extend to the stream channels. The wetter areas at the base of the slopes and on the valley floors are occupied by meadows and pasture. The relatively high annual precipitation of 1000-1500 mm falls primarily during the summer months. During storm events, the dense network of unmetalled roads

and the numerous gullies promote rapid surface runoff which transports large amounts of sediment to the channels (cf. Froehlich, 1991). The critical threshold for the widespread occurrence of surface runoff is a storm rainfall of c. 20 mm (Slupik, 1973).

The area is characterized by highly active erosion, sediment transport and fluvial sedimentation processes, which in turn reflect the climate, the high relief energy, the erodible nature of the soils and rock and the effects of poor land management. Fluvial processes are dominant, and the channel network is being actively deepened in many areas. Locally, mass movements assume considerable importance (cf. Starkel, 1972). Measurements obtained from runoff plots located on cultivated slopes within the area point to high rates of soil erosion under certain crops. Values for potatoes are as high as  $22 \text{ t ha}^{-1} \text{ year}^{-1}$ , whilst typical values for winter crops, meadows and forest are  $2.4 \text{ t ha}^{-1} \text{ year}^{-1}$ ,  $0.1 \text{ t ha}^{-1} \text{ year}^{-1}$  and  $0.03 \text{ t ha}^{-1} \text{ year}^{-1}$  respectively. Sediment yields from the larger river basins are in the range  $90\text{--}1000 \text{ t km}^{-2} \text{ year}^{-1}$  (cf. Lajczak, 1988). It is, however, difficult to make direct comparisons between estimates of the intensity of erosion processes on the slopes and the sediment yields of Carpathian rivers, because of the wide range of techniques of unknown accuracy and precision which have been used and the different periods of record involved. Further integrated studies are required in order to obtain a clear appreciation and understanding of the erosion and sediment delivery dynamics of this region and of the role of land use and human activity in disturbing the natural conditions. Improved understanding of the spatial variability of soil erosion on slopes, of sediment sources and of sediment supply dynamics is essential for protecting soils against erosion and reducing rates of reservoir siltation.

Classical (standard) methods for investigating erosion and sediment delivery are for the most part expensive to apply, in terms of both equipment and manpower requirements and the timescales involved. As a result, most studies applying such methods have addressed very limited objectives, as well as covering only small areas and involving short periods of record. In consequence, it has proved difficult to produce meaningful assessments of the pattern of spatial variability of the processes involved. The high energy and active morphodynamic environments associated with mountain areas also introduce important technical constraints in the application of traditional classical techniques. It is therefore difficult to relate measurements of soil loss at different slope positions to sediment yield. In addition, it is difficult to use short-term, site-specific measurements in the interpretation of longer-term contemporary relief evolution. Little is currently known about the residence times of sediment particles moving through the fluvial system of drainage basins of different scales.

In recent years, geomorphologists have shown increasing interest in the use of the fallout radionuclide caesium-137 ( $^{137}\text{Cs}$ ) as a sediment tracer (e.g. Campbell *et al.*, 1982; Walling & Bradley, 1990). Caesium-137 was introduced into the stratosphere by the atmospheric testing of nuclear weapons during the

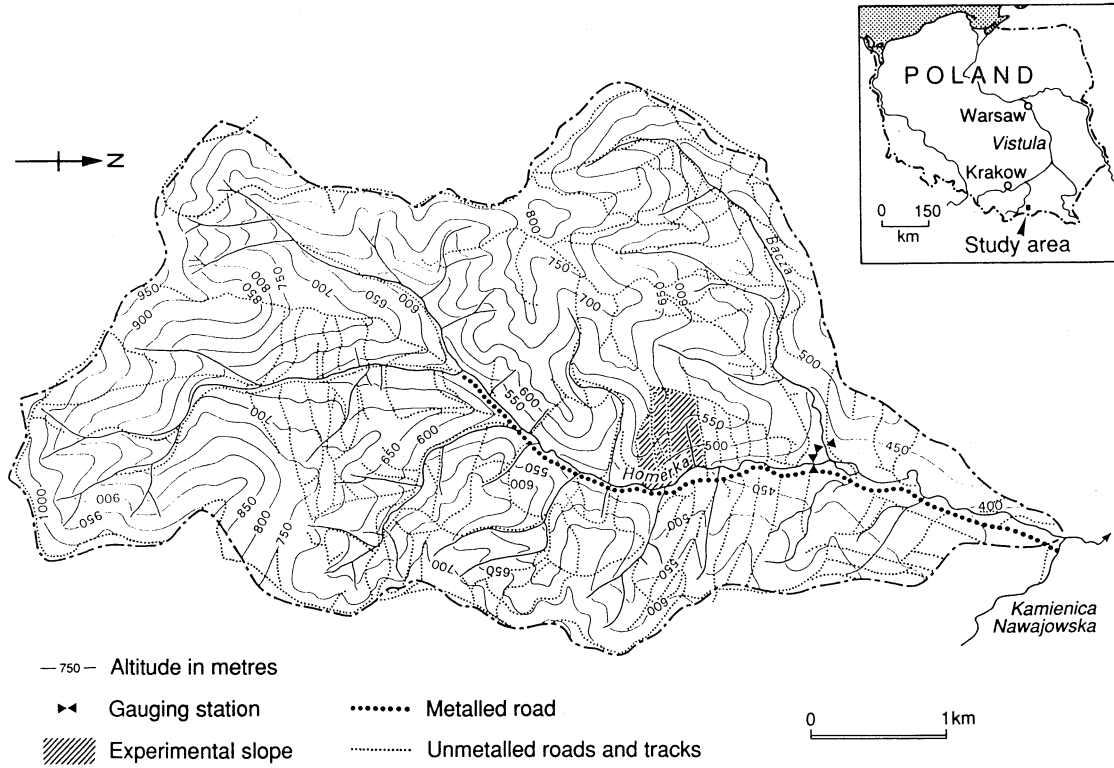
middle and late 1950s and the 1960s and the fallout, which was primarily associated with precipitation, occurred globally. In some areas, additional  $^{137}\text{Cs}$  fallout also occurred immediately after the Chernobyl disaster in 1986. In most environments, radiocaesium reaching the land surface is rapidly adsorbed by the upper horizons of the soil. Subsequent movement occurs in association with sediment particles and  $^{137}\text{Cs}$  therefore provides a very effective sediment tracer. Measurements of the redistribution of "bomb-derived" radiocaesium during the period since the fallout occurred offer a means of assessing the movement of sediment within the landscape over a timescale of 25-30 years. Where Chernobyl-derived fallout also occurred, shorter-term assessments may also be obtained.

The use of  $^{137}\text{Cs}$  as a tracer therefore affords a valuable means of investigating the mobilization of sediment and its transfer through the fluvial system over timescales of several decades and over a range of spatial scales, and therefore overcomes many of the limitations of classical monitoring techniques (cf. Walling, 1990). Caesium-137 measurements can be used as a basis for studying both the magnitude and spatial variability of rates of soil loss, identifying sediment sources, establishing sediment delivery ratios and assessing rates and patterns of sedimentation on alluvial fans and flood plains and in reservoirs (cf. Loughran *et al.*, 1982; Sutherland & de Jong, 1990; Walling & Bradley, 1988; Walling & Quine, 1991; Walling *et al.*, 1992). To date, however, the application of  $^{137}\text{Cs}$  measurements to investigations of erosion and sediment delivery has been largely restricted to areas of limited relief in lowland areas. Relatively little work has been undertaken in mountain areas, where altitudinal variations in precipitation, the importance of snow cover and the high energy environment necessitate some modifications to the approach.

This contribution presents a preliminary assessment of the potential for using  $^{137}\text{Cs}$  measurements, as an alternative and complement to classical monitoring techniques, to investigate erosion and sediment delivery processes in the Polish Flysch Carpathians and in mountain areas more generally. The work reported was undertaken in the Homerka experimental catchment where classical monitoring techniques have also been applied over the past 15 years (cf. Froehlich, 1982). The availability of data for this basin obtained using classical methods provides a basis for testing the consistency of the two approaches and for exploring the possibility of using the  $^{137}\text{Cs}$  approach to extrapolate site-specific results obtained by traditional means.

## THE STUDY AREA

The 19.6 km<sup>2</sup> drainage basin of the Homerka stream (Fig. 1) lies at an altitude of 375-1060 m above sea level and is typical of the largely deforested landscape of this region. Its upper part is characterized by straight or convex slopes and deeply incised V-shaped valleys developed on resistant



**Fig. 1** The Homerka basin and the location of the study area in Poland.

Magura sandstones. These areas lie in the lower subalpine zone and exhibit skeletal soils. The forests which occur in the headwaters account for 52% of the total area of the basin and are at present intensively exploited. They are associated with a dense network of unmetalled roads and timber transport trails. The agricultural areas are concentrated in the lower parts of the basin where the relief is more subdued. Here the slopes are mainly convexo-concave, and the cover of loamy regolith gives rise to deeper and less stony soils.

In order to permit detailed investigations of erosion and sediment delivery from a cultivated part of the basin, an area of 26.5 ha located at the boundary of the forest and the agricultural area had been designated as an "experimental slope" (Fig. 1). The slope is 500-700 m long and convexo-

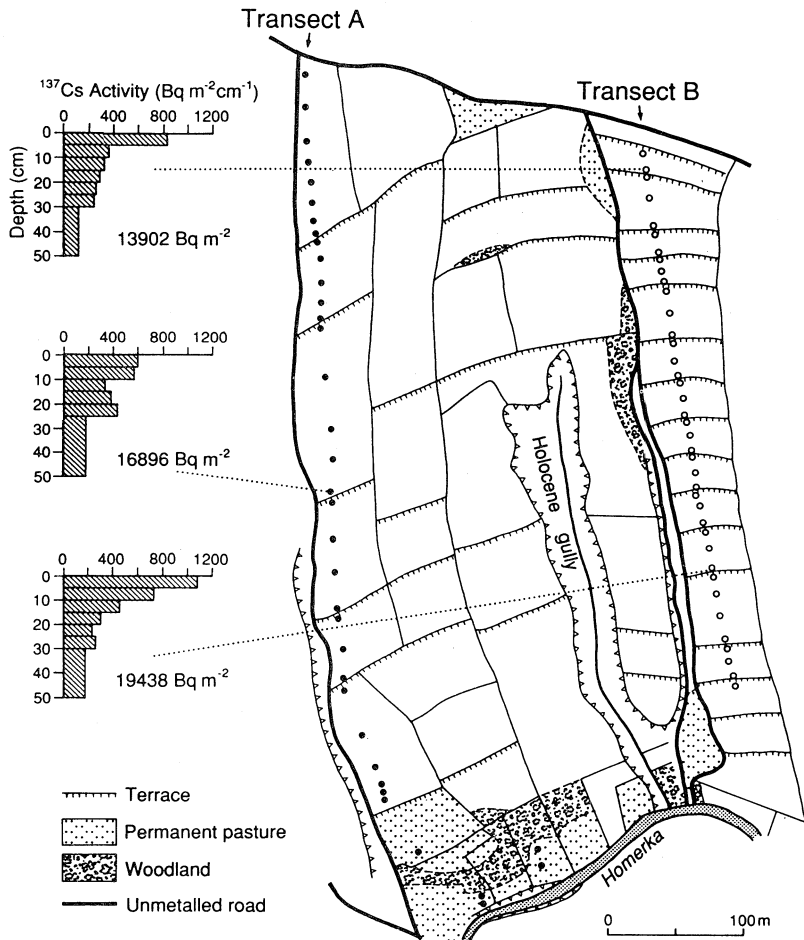


Fig. 2 The two core sampling transects employed for using radiocaesium measurements to investigate soil erosion and redistribution on the experimental slope. The  $^{137}\text{Cs}$  profiles associated with four cores collected from the upslope margins of terraces separating the field plots are illustrated.

concave in form. The silty clay soils increase in depth towards the foot of the slope. The slope is subdivided into numerous field plots (Fig. 2), which are tilled across the slope. The plots are separated by terraces and furrows and by the unmetalled roads which traverse the area from the watershed to the stream channel. During times of heavy rainfall these unmetalled roads, which are typical of cultivated slopes in the Carpathians, act as channels for surface runoff and in many places they are deeply incised into the slope, forming ravines up to 7 m deep. Bedrock is exposed along the floors of many of the unmetalled roads. These sunken roads are being continuously deepened by the concentrated runoff and by their increasingly intensive use, and access to the fields often becomes difficult. In such circumstances, the farmers are forced to construct new roads parallel to the old course. The zone of concentrated water flow and accelerated erosion is thereby gradually enlarged at the expense of the cultivated land. The length of unmetalled road traversing the experimental slope is 3.3 km, equivalent to a density of  $11.9 \text{ km km}^{-2}$ . The density for the overall basin is  $5.3 \text{ km km}^{-2}$ .

## METHODS OF INVESTIGATION

The application of radiocaesium measurements to studies of erosion and sediment delivery within the Homerka catchment began in 1984. The Chernobyl disaster in 1986 caused a substantial increase in  $^{137}\text{Cs}$  inventories in the area and introduced difficulties in making comparisons between samples analysed before and after the disaster. Measurements of the caesium-134 activity of soils and sediments can be used to apportion the total  $^{137}\text{Cs}$  activity between bomb- and Chernobyl-derived fallout, but some of the results presented in this contribution relate only to samples collected between 1984 and 1986, prior to the Chernobyl disaster, in order to simplify the interpretation. This contribution reports the results of investigations aimed at using radiocaesium measurements to assemble information on rates and patterns of soil erosion from the cultivated slopes, the dominant sources of suspended sediment transported by the Homerka Stream, and the delivery of sediment through the basin system.

The use of  $^{137}\text{Cs}$  measurements to evaluate rates and patterns of soil erosion is commonly based on measurements of either the total radiocaesium content or inventory ( $\text{mBq cm}^{-2}$ ) of the soil profile or the distribution of this inventory within the profile. A 75 mm diameter steel corer was used to collect soil cores to depths of 50 cm for the majority of these measurements, and in most cases the cores were sectioned at 5 cm intervals prior to analysis. Where more detailed information of the vertical distribution of  $^{137}\text{Cs}$  within a soil profile was required, samples were collected at 2 cm depth increments using a  $40 \times 20 \text{ cm}$  steel frame and scraper (cf. Campbell *et al.*, 1988; Walling & Bradley, 1990) in order to obtain samples of adequate mass for analysis. All samples were dried, disaggregated and sieved to pass a 2 mm mesh prior to

analysis by gamma spectrometry in the Department of Geography at the University of Exeter.

Information on suspended sediment sources was assembled using the "fingerprinting" approach described by Peart & Walling (1988). Samples of surface material from potential sources (forest, pasture, cultivated areas, unmetalled roads, gully walls and channel banks) were collected from an area of 1 m<sup>2</sup>, using a steel frame. It is not possible to compare directly the <sup>137</sup>Cs content of these source materials with that of the suspended sediment transported by the stream, because of contrasts in the grain size composition of source materials and suspended sediment and the known enrichment of the finer fractions in <sup>137</sup>Cs. The <0.063 mm fraction of the source materials was therefore separated for gamma spectrometry analysis and the resultant values of <sup>137</sup>Cs content were used for comparisons with those associated with the suspended sediment. Bulk samples of suspended sediment were collected from the main gauging station on the Homerka stream during flood events. The water samples ranged between 200 and 1000 l in volume, depending on the suspended sediment concentration, and were withdrawn from the stream into 120 and 180 l plastic containers using an electromagnetic pump. The suspended sediment was recovered from the water samples by sedimentation and centrifugation, and the <0.063 and >0.063 mm fractions were separated by wet sieving. The separated fractions were dried at 60°C and 100 g sub-samples were used for gamma spectrometry.

Some preliminary information on rates of flood plain accretion, and therefore transmission losses of suspended sediment transported through the stream system, was obtained for an area of flood plain at the outlet of the Homerka catchment by collecting sediment cores from the flood plain and an area of undisturbed pasture above the maximum floodwater level. These cores were collected using a 75 mm diameter steel corer to depths of up to 20 cm. The sediment cores were sectioned into 2 cm increments for subsequent gamma spectrometry analysis. The Homerka drainage basin is a tributary of the Dunajec River which flows into the Roznowski reservoir constructed in 1940. The basin of the Dunajec above this reservoir extends to 4692 km<sup>2</sup> and is representative of a large Carpathian drainage basin. Sediment cores were collected from the delta area of the reservoir in order to provide information on both rates of sedimentation and the dominant source of the sediment entering the reservoir.

## INVESTIGATIONS OF SOIL EROSION

The soil erosion study focused on the area of the experimental slope. Two downslope transects crossing the field plots and their associated terraces were sampled (Fig. 2). Transect A comprises several relatively long field plots up to 100 m in length and with gradients between 12° and 18°, separated by terraces. Transect B is steeper and comprises much shorter

field plots, again separated by terraces. Bulk soil cores (75 mm diameter) were collected from the field plots to a depth of 35 cm. On the upslope edges of the terraces, cores were taken to a depth of 50 cm and sectioned in 5 cm increments to a depth of 25 or 30 cm. Information on baseline  $^{137}\text{Cs}$  fallout inventories necessary to interpret the subsequent pattern of radiocaesium redistribution was obtained from a series of three sectioned soil profiles representing areas of undisturbed grassland with minimal slope on the watershed of the experimental slope and from a single soil profile within a forest clearing in the headwater area of the basin. All samples were collected during 1988 and therefore contain both "bomb" and Chernobyl-derived radiocaesium fallout.

The total  $^{137}\text{Cs}$  inventories of the "input" sites ranged from  $5302 \pm 114$  to  $7226 \pm 134 \text{ Bq m}^{-2}$  at the top of the experimental slope and a value of  $7693 \pm 129 \text{ Bq m}^{-2}$  was obtained for the forest clearing. The caesium-134 contents of the profiles ranged from  $1597 \pm 76$  to  $1916 \pm 96 \text{ Bq m}^{-2}$ , providing a mean  $^{134}\text{Cs}$  input (corrected to May 1986, the period of Chernobyl deposition) of  $1782 \text{ Bq m}^{-2}$ . All four profiles exhibit an exponential decline in  $^{137}\text{Cs}$  activity with depth. Between 60 and 75% of the total  $^{137}\text{Cs}$  inventory is retained within the top 5 cm of the profile, and more than 90% in the upper 10 cm. The depth distribution of caesium-134 in these "input" profiles demonstrated an even stronger exponential decline with depth. No caesium-134 was detected below 8 cm.

In view of the variability of the estimates of  $^{137}\text{Cs}$  reference inventories for the experimental slope noted above, which largely reflects local variability in the receipt of Chernobyl fallout, it is suggested that  $^{137}\text{Cs}$  measurements are more useful for providing information about the general pattern of erosion and soil redistribution operating over the slope as a whole, rather than the detailed rates and patterns of erosion within individual fields. The total  $^{137}\text{Cs}$  inventories of the individual cores collected immediately above the terraces were in nearly all cases substantially greater than those associated with cores collected from within the plots, reflecting significant soil loss within the fields and deposition at the lower boundary of the fields on the terraces. The mean inventory of bomb-derived  $^{137}\text{Cs}$  associated with cores collected from *within* the field plots is  $4080 \text{ Bq m}^{-2}$ , whereas that for the terraces is  $8484 \text{ Bq m}^{-2}$ . The occurrence of deposition on the terraces is further substantiated by the increased depth to which radiocaesium is found at these locations (cf. Fig. 2). The average depth of cultivation in these fields is of the order of 20 cm and, assuming that the associated mixing would distribute radiocaesium to this depth, the four  $^{137}\text{Cs}$  profiles illustrated in Fig. 2 evidence deposition of *c.* 20 cm. If it is assumed that this deposition has occurred during a period of about 35 years since the first occurrence of significant bomb fallout, rates of deposition may be estimated at *c.*  $5 \text{ mm year}^{-1}$ . The radiocaesium measurements indicate that appreciable rates of soil erosion are occurring within the fields, but also that a substantial proportion of the eroded soil is redeposited on the terraces and is not transported beyond the field system.



## INVESTIGATIONS OF SUSPENDED SEDIMENT SOURCES

Information on the sources of the suspended sediment transported by a river is of fundamental importance in both geomorphological investigations of erosion rates and landform development and in any attempt to develop measures for reducing sediment loads (Froehlich, 1982; Walling, 1983). Such information is difficult to obtain using traditional monitoring techniques, but the fingerprinting technique has been shown by several workers to offer a viable alternative. In this approach, the physico-chemical properties of the suspended sediment transported by a river are compared with those of the equivalent grain-size fraction of material from potential sediment sources (cf. Oldfield *et al.*, 1979; Peart & Walling, 1986, 1988). Evidence for the Homerka basin assembled using traditional long-term monitoring techniques by Froehlich (1982) suggested that unmetalled roads and active gullies provide the major source of suspended sediment. This conclusion was, however, based primarily on measurements undertaken in the area of the experimental slope and it was necessary to test its applicability to the entire basin, particularly since the intensity of erosion occurring on unmetalled roads was known to vary with the age of the road. Furthermore, there was a need to assess the extent to which conclusions based on the Homerka basin were representative of the Flysch Carpathians more generally, and an attempt has been made to identify the dominant sources of the sediment transported by the Dunajec River. In this context  $^{137}\text{Cs}$  has been used as a fingerprint tracer.

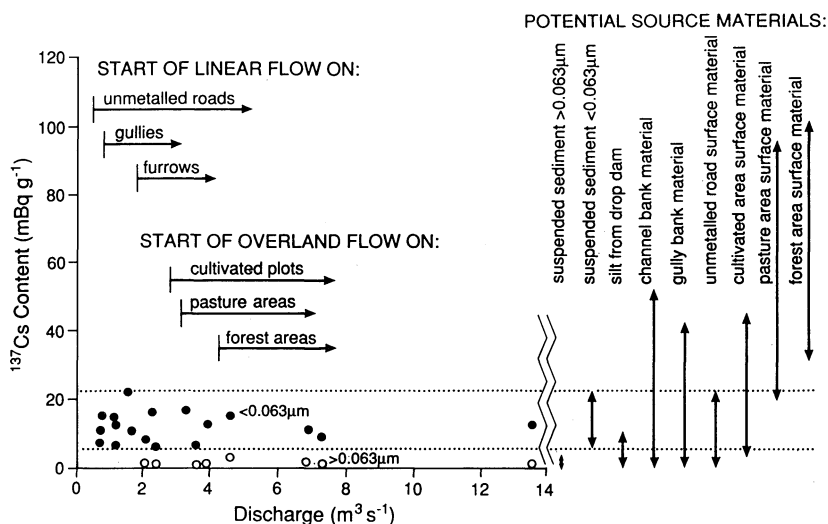
Measurements of the  $^{137}\text{Cs}$  content of the  $<0.063$  mm fraction of suspended sediment collected from the Homerka stream at the main gauging station in the pre-Chernobyl period, indicated a range between 6.3 and 22.6  $\text{mBq g}^{-1}$ , with a mean of 11.9  $\text{mBq g}^{-1}$  and a standard deviation of 4.4. Comparison of these values with typical values for potential source materials (Table 1, Fig. 3) suggests that they closely match those associated with material collected from the surface of unmetalled roads. Sediment eroded from the surface of forest and pasture areas is very unlikely to represent an important sediment source, since its  $^{137}\text{Cs}$  content is substantially higher. Material eroded from cultivated areas and from channel and gully banks could represent a source of suspended sediment, but is thought unlikely to constitute a major source because the range of  $^{137}\text{Cs}$  levels associated with these materials extends well above that representative of suspended sediment. The evidence provided by the radiocaesium fingerprints therefore suggests that the major source of the suspended sediment transported by the Homerka stream is the unmetalled roads which occur throughout both the forested and the agricultural zones of the basin. The use of additional fingerprinting properties could provide more conclusive evidence concerning the relative importance of cultivated areas and channel and gully banks as sediment sources, but is likely to confirm the importance of unmetalled roads. This importance is further underscored by the evidence obtained from a small part of the basin using traditional monitoring techniques referred to above and by analysis of available information on the

**Table 1** Caesium-137 concentrations associated with suspended sediment, silt deposited in the stilling basin above a drop structure, and potential suspended sediment sources within the Homerka basin.

Samples	Mean concentration (mBq g <sup>-1</sup> )	Standard deviation (mBq g <sup>-1</sup> )
Suspended sediment <0.063 mm	11.9	4.4
Suspended sediment >0.063 mm	0.8	0.8
Silt from drop structure	3.7	5.3
Channel bank material	13.5	15.3
Gully bank material	16.5	17.9
Surface material from unmetalled roads	3.8	6.3
Surface material from cultivated fields	21.7	12.0
Surface material from pasture	49.0	27.6
Surface material from forest	57.5	38.0

runoff processes operating in the basin which is discussed below.

Existing evidence relating to the generation of storm runoff within the Homerka basin indicates that the frequency of occurrence of surface runoff on unmetalled roads and in gullies and the furrows between fields is considerably greater than on the cultivated areas. This is further emphasized on Fig. 3 where the typical discharge levels at the main gauging station on the Homerka stream associated with initiation of linear flow on the unmetalled roads and in the gullies and furrows and of overland flow on the cultivated plots and within the areas of pasture and forest are shown. The relationship between the <sup>137</sup>Cs



**Fig. 3** The use of <sup>137</sup>Cs measurements to fingerprint suspended sediment sources. The relationship between the <sup>137</sup>Cs content of suspended sediment and discharge, the discharge thresholds associated with the occurrence of storm runoff from various sources within the basin, and the range of <sup>137</sup>Cs concentrations associated with suspended sediment and potential source materials are illustrated.

content of suspended sediment and the discharge of the Homerka stream shown in Fig. 3 shows no evidence of shifts associated with the incidence of overland flow contributions from the cultivated plots and pasture and forest areas of the basin and with the initiation of runoff from furrows between the fields. This in turn again strongly suggests that surface runoff from the unmetalled roads and perhaps also gullies represents the major source of sediment transported by the stream.

This conclusion is further supported by other field observations in the drainage basin which suggest that direct delivery of sediment to the channel from cultivated fields is likely to be restricted, since the pasture areas which exist at the foot of the slopes and bordering the stream channel would act as efficient sinks for sediment transported by overland flow (cf. Froehlich, 1982). Furthermore, the evidence provided by the  $^{137}\text{Cs}$  inventories of cores collected from the experimental slope and discussed above indicate that substantial redeposition of eroded sediment occurred on the downslope terraces bounding the individual plots. Any sediment delivered from the cultivated fields to the channels is likely to move via the furrows, which are in turn connected to the unmetalled roads. Concentrations of suspended sediment observed in the furrows are, however, much smaller than those measured on the unmetalled roads and in the stream channels, again emphasizing the limited connection between the cultivated fields and the river channels. Some sediment from the cultivated fields is, however, transported into the unmetalled roads and gullies by deflation processes during the winter and this will be delivered to the streams during the spring floods (cf. Froehlich, 1982; 1991). Therefore, although the unmetalled roads have been identified as the major source of suspended sediment and much of this sediment will be eroded during the incision of the roads, some of the material will represent sediment particles originating from the cultivated fields and transported to the unmetalled roads by deflation. In the absence of such roads, this material would not reach the stream and their existence may therefore be viewed as being of crucial importance to the sediment budget of the basin. The relative unimportance of surface soils in forest and pasture areas as sediment sources, suggested by the  $^{137}\text{Cs}$  fingerprints, is also further underscored by the low frequency of occurrence of overland flow observed in these areas (cf. Gerlach, 1976; Gil, 1976; Froehlich, 1982).

The  $>0.063$  mm fraction of suspended sediment is characterized by very low  $^{137}\text{Cs}$  activity, ranging from 0.0 to  $2.5 \text{ mBq g}^{-1}$ , with a mean value of  $0.8 \text{ mBq g}^{-1}$  and a standard deviation of 0.82. These low levels reflect both the preferential association of radionuclides with the finer fractions (cf. Tamura, 1964; Frissel & Penners, 1983) and the dominance of unmetalled roads and gullies and channel banks as sediment sources. Some samples of the finer sediment were recovered from sediment basins located above the drop structures constructed along the Homerka stream (Table 1, Fig. 3). These were characterized by a relatively low  $^{137}\text{Cs}$  content ranging from 0.1 to  $10.7 \text{ mBq g}^{-1}$ , which conforms with the range associated with both the

$>0.063$  mm and the  $<0.063$  mm fractions of suspended sediment. This provides confirmation of the representativeness of the  $^{137}\text{Cs}$  fingerprints of the suspended sediment samples.

Sediment samples collected from the surface of alluvial deposits within Roznowski reservoir in the period immediately prior to the Chernobyl disaster were characterized by  $^{137}\text{Cs}$  concentrations in the range  $9.1\text{--}9.8\text{ mBq g}^{-1}$ . These conform closely with the concentrations associated with suspended sediment from the Homerka stream and suggest that unmetalled roads and gullies represent the main sediment source throughout the Dunajec basin. The vertical distribution of  $^{137}\text{Cs}$  concentrations within the sediment core collected from Roznowski reservoir in 1990 is also illustrated in Fig. 4. Some indication of rates of sedimentation at this sampling location can be obtained by linking the shape of the  $^{137}\text{Cs}$  profile to the known temporal pattern of  $^{137}\text{Cs}$  fallout. Measurable  $^{137}\text{Cs}$  concentrations first appear in the profile at a depth of 80–90 cm and these probably coincide with the onset of significant  $^{137}\text{Cs}$  fallout in 1954, although some downward migration or diffusion of the radiocaesium within the sediment column can be expected. The distinct peak at 40–42 cm can be closely related to the peak rates of fallout in the years 1963–1964, whilst the peak that occurs at a depth of 6–8 cm undoubtedly reflects the fallout associated with the Chernobyl disaster in mid 1986. Sedimentation rates at this point are therefore of the order of  $2\text{ cm year}^{-1}$ , although there is some evidence that they have declined over the period involved. Such a decline is consistent with the

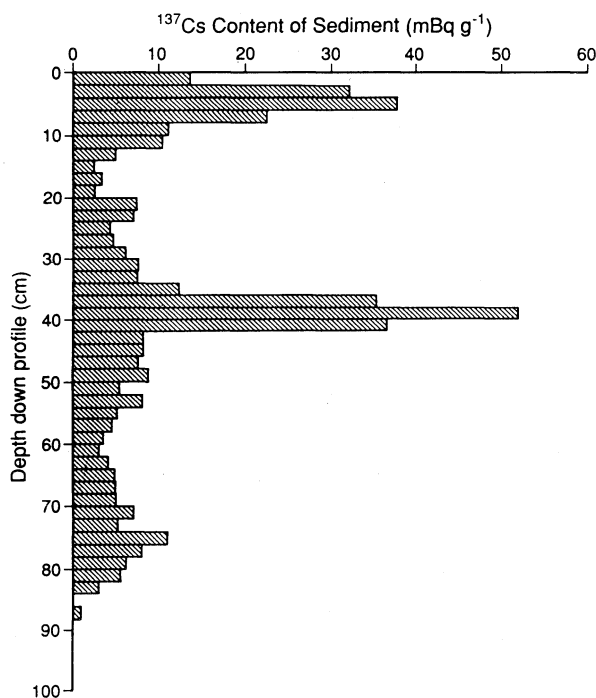


Fig. 4 The vertical distribution of  $^{137}\text{Cs}$  in a sediment core collected from the delta at the head of Roznowski reservoir.

location of the sampling point on a delta at the head of the reservoir, where the area is inundated during the main flood season but the depths of inundation have decreased through time as sedimentation proceeded. Caesium-137 concentrations associated with the levels in the core that immediately predate the Chernobyl incident are of the order of 5-10 mBq g<sup>-1</sup>. These <sup>137</sup>Cs concentrations will directly reflect the radiocaesium content of sediment eroded from the upstream basin and deposited at the site, since fallout inputs of <sup>137</sup>Cs in the 1970s were extremely low, and they are again consistent with unmetalled roads and gullies and channel banks providing the main sediment sources within the Dunajec basin.

## **SUSPENDED SEDIMENT DELIVERY WITHIN CARPATHIAN DRAINAGE BASINS**

The results presented above indicate that unmetalled roads and, to a more limited extent, gullies and channel banks represent the main suspended sediment sources within the study area. Significant rates of soil loss have been documented within cultivated fields, but little of this eroded material leaves the cultivated areas. Most is deposited on the terraces bordering the field plots and sediment delivery ratios associated with such erosion are likely to be very low. In contrast, sediment delivery from erosion occurring on unmetalled roads and in gullies and river channels is likely to be near 100%, since the erosion sites are directly linked to the channel network and the linear concentrated flow affords an efficient transport agent. It is, however, important to assess the significance of transmission losses associated with the transport of sediment through the main channel network. Overbank deposition on flood plains is likely to represent the major transmission loss and a preliminary attempt has been made to use caesium-134 measurements to document recent rates of deposition on the flood plain bordering the lower reaches of the Homerka stream and the main tributaries of the Dunajec. Figure 5 illustrates typical caesium-134 profiles associated with a flood plain near the junction of the Homerka stream with the Kamienica Nawajowska River. Figure 5(a) depicts the vertical distribution of caesium-134 associated with a core collected from an area of undisturbed pasture above the maximum flood level, whilst Fig. 5(b) depicts the caesium-134 profile measured in a core collected from the flood plain itself. The presence of caesium-134 reflects only inputs of Chernobyl-derived fallout and in the case of the first core most of the caesium-134 activity occurs, as expected, near the surface. Some downward diffusion or migration has obviously occurred (probably along macropores), but the profile shape closely reflects fallout inputs to the surface. The profile shape encountered in core 2 is, however, very different and almost the reverse of that associated with core 1. The total inventory is also substantially greater. These features of core 2 reflect sediment deposition at the sampling point. At the time of Chernobyl fallout in mid 1986, the level which is now 14 cm below the surface would

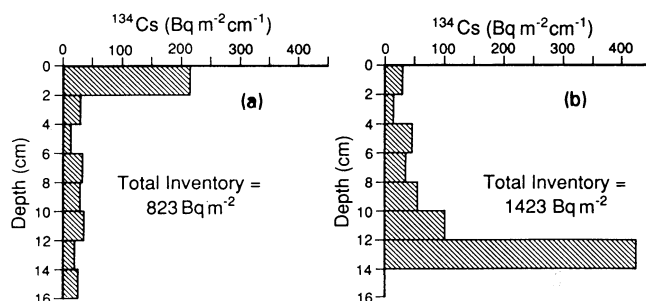


Fig. 5 Caesium-137 profiles associated with sediment cores collected from a flood plain site in the lower reaches of the Homerka basin. Profile A was collected from an area above the maximum flood level whereas profile B was collected from an area that is inundated during flood events.

have been exposed at the surface and would have received fallout of caesium-134. Subsequent deposition of caesium-134 bearing sediment eroded from the upstream drainage basin has buried the surface exposed in 1986 and the deposited sediment has increased the total caesium-134 inventory. Since these two cores were collected in 1989, annual deposition rates of *c.* 4 cm year<sup>-1</sup> may be estimated. Similar rates of deposition have been estimated for other flood plain locations within the Dunajec river system, indicating that flood plain accretion is widespread and that even in these high energy mountain environments, significant transmission losses may occur in association with flood plain deposition. Further work is, however, required to quantify the magnitude of the transmission losses involved.

## PERSPECTIVE

The results presented above indicate that radiocaesium measurements undertaken in the Homerka basin provide evidence relating to soil erosion on cultivated fields, the dominant suspended sediment sources, and sediment delivery which is consistent with the results of long-term labour-intensive classical monitoring techniques. The radiocaesium measurements were, however, undertaken during a short period and provide greater scope for investigating processes at the overall basin-scale. Thus, for example, the fingerprint technique can be used to assemble information on the relative importance of the potential sediment sources within the overall basin, whereas classical monitoring techniques can only document sources within small areas. Furthermore, the use of radiocaesium measurements to interpret sediment collected from the Roznowski reservoir and to estimate contemporary rates of flood plain sedimentation provides a means of extending the scale of investigation from the small Homerka basin to the much larger Dunajec basin. Radiocaesium measurements also afford valuable potential for extending the temporal base of process monitoring since the use of bomb fallout provides a

means of assessing sediment movement over the past 35 years. Further work, exploiting the potential afforded by both "bomb" and Chernobyl fallout, is planned in order to develop an improved understanding of erosion and sediment delivery within the Polish Flysh Carpathians.

**Acknowledgements** The support of the Polish Academy of Sciences and the University of Exeter for the work reported in this paper is gratefully acknowledged. Thanks are also extended to Dr David Higgitt for assistance with fieldwork, to Mr Jim Grapes for gamma spectrometry measurements, to Mr Rodney Fry for drawing the diagrams and to Dr Tim Quine for comments on the draft manuscript.

## REFERENCES

- Campbell, B. L. (1983) Application of environmental caesium-137 for the determination of sedimentation rates in reservoirs and lakes and related catchment studies in developing countries. In: *Radioisotopes in Sediment Studies*, 7-29. IAEA-TECDOC-298.
- Campbell, B. L., Loughran, R. J. & Elliott, G. L. (1982) Caesium-137 as an indicator of geomorphic processes in a drainage basin system. *J. Austral. Geogr. Studies* **20**, 49-64.
- Campbell, B. L., Loughran, R. J. & Elliott, G. L. (1988) A method for determining sediment budgets using caesium-137. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 171-179. IAHS Publ. no. 174.
- Frissel, M. J. & Penners, R. (1983) Models for the accumulation and migration of  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$ ,  $^{239,240}\text{Pu}$  and  $^{241}\text{Am}$  in the upper layer of soils. In: *Ecological Aspects of Radionuclide Release* (ed. by P. J. Coughtrey), 63-72. Spec. Publ. British Ecol. Soc. no. 3.
- Froehlich, W. (1982) Mechanism transportu fluwialnego i dostawy zwietrzelin do koryt w gorskiej zlewni fliszowej. *Prace Geogr. IG i PZ PAN* **143**.
- Froehlich, W. (1991) Sediment production from unmetalled road surfaces In: *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation* (ed. by N. E. Peters & D. E. Walling) (Proc. Vienna Symp., August 1991), 21-29. IAHS Publ. no. 203.
- Gerlach, T. (1976) Wspolczesny rozwoj stokow w Polskich Karpatach Fliszowych *Prace Geogr. IG i PZ PAN* **122**.
- Gil, E. (1976) Splukiwanie gleby na stokach fliszowych w rejonie Szymbarku. *Dokum. Geogr. IG i PZ PAN* **2**.
- Gil, E. (1986) Ruissellement et érosion sur les versants du flysh d'après les résultats de parcelles expérimentales. *Bull. Assoc. Géogr. Français* **63**, 357-361.
- Lajczak, A. (1988) Impact of various land uses on the intensity of sediment runoff in the Polish Carpathians flysh catchments. In: *Proc. International Symp. Interpretation, Graz, 1988*, **3**, 131-165.
- Loughran, R. J., Campbell, B. L. & Elliott, G. L. (1982) The identification and quantification of sediment sources using  $^{137}\text{Cs}$ . In: *Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield* (Proc. Exeter Symp., July 1982), 361-369. IAHS Publ. no. 137.
- Oldfield, F., Rummary, T. A., Thompson, R. & Walling, D. E. (1979) Identification of suspended sediment sources by means of magnetic measurements. *Wat. Resour. Res.* **15**, 211-218.
- Pear, M. R. & Walling, D. E. (1986) Fingerprinting sediment sources: the example of a drainage basin in Devon, UK. In: *Drainage Basin Sediment Delivery* (ed. by R. F. Hadley) (Proc. Albuquerque Symp., August 1986), 41-55. IAHS Publ. no. 159.
- Pear, M. R. & Walling, D. E. (1988) Techniques for establishing suspended sediment sources in two drainage basins in Devon, UK: a comparative assessment. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 269-279. IAHS Publ. no. 174.
- Slupik, J. (1973) Zroznicowanie splywu powierzchniowego na fliszowych stokach gorskich. *Dokum. Geogr. IG i PZ PAN*.
- Sutherland, R. A. & de Jong, E. (1990) Estimation of sediment redistribution within agricultural fields using caesium-137, Crystal Prings, Saskatchewan, Canada. *Appl. Geogr.* **10**, 205-221.
- Starkel, L. (1972) Charakterystyka rzezy Polskich Karpat i jej znaczenie dla gospodarki ludzkiej. *Probl. Zagosp. Ziem Gorskich* **10**, 75-150.
- Tamura, T. (1964) Selective sorption reaction of caesium with mineral soils. *Nuclear Safety* **5**, 262-268.
- Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **69**, 209-237.
- Walling, D. E. (1990) Monitoring contemporary geomorphological processes. In: *Global Change Regional Research Centres: Scientific Problems and Concept Developments* (ed. by A.

- Breymeyer), 7-32. Polish Academy of Sciences, Warsaw.
- Walling, D. E. & Bradley, S. B. (1988) The use of caesium-137 measurements to investigate sediment delivery from cultivated areas in Devon, UK. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling)(Proc. Porto Alegre Symp., December 1988), 325-335. IAHS Publ. no. 174.
- Walling, D. E. & Bradley, S. B. (1990) Some applications of caesium-137 measurements in the study of fluvial erosion, transport and deposition. In: *Erosion, Transport and Deposition Processes* (ed. by D. E. Walling, A. Yair & S. Berkowicz)(Proc. Jerusalem Workshop, April 1987), 179-203. IAHS Publ. no. 189.
- Walling, D. E. & Quine, T. A. (1990) Use of caesium-137 to investigate patterns and rates of soil erosion on arable fields. In: *Soil Erosion on Agricultural Land* (ed. by J. Boardman, I. D. L. Foster & J. A. Dearing), 33-53. Wiley, Chichester, UK.
- Walling, D. E. & Quine, T. A. (1991) Use of caesium-137 measurements to investigate soil erosion on arable fields in the UK: potential applications and limitations. *J. Soil Sci.* **42**, 147-165.
- Walling, D. E., Quine, T. A. & He, Q. (1992) Investigating contemporary rates of floodplain sedimentation. In: *Lowland Floodplain Rivers: Geomorphological Perspectives* (ed. by P. A. Carling & G. E. Petts), 165-184. Wiley, Chichester, UK.