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Using environmental radionuclides to elucidate sediment sources within a small drainage basin in the Polish Flysch Carpathians

WOJCIECH FROEHLICH[1] **& DES E. WALLING**[2]

1 *Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organization, Polish Academy of Sciences,Frycowa 113, 33-335 Nawojowa, Poland*
wfroehlich@pro.onet.pl

2 *Department of Geography, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK*

Abstract The work reported in this contribution was undertaken in the Homerka instrumented catchment in the Polish Flysch Carpathians, where a combination of conventional methods of documenting sediment mobilization, transfer and deposition and sediment tracing techniques have been used over the past 30 years to investigate the sediment budget of the catchment. This contribution focuses on the use of environmental radionuclides, and more particularly ^{137}Cs, to trace the main sources of the suspended sediment exported from the study catchment. Unmetalled roads were identified as the main suspended sediment source, with the channels and active gullys also providing significant contributions. The findings of the source tracing investigations are consistent with the results of other conventional monitoring undertaken in the study catchment aimed at identifying the main suspended sediment sources.

Key words Carpathians; caesium-137; environmental radionuclides; Homerka catchment, Poland; sediment budget; suspended sediment sources; source tracing; unmetalled roads

INTRODUCTION

The sediment budget concept provides a key to understanding the mechanisms of sediment routing through the fluvial system. It is also important for interpretation of longer-term contemporary relief evolution and the geomorphological effectiveness of fluvial processes operating within a drainage basin. In order to construct a sediment budget for a catchment, there is a need to obtain data on the primary sediment sources and the rates of sediment mobilization from those sources, on sediment transfer and storage within the catchment and on the sediment flux at its outlet (Walling, 2003). The high energy and active morphodynamic environments associated with mountain areas introduce important technical challenges to any attempt to assemble the data required to establish a reliable sediment budget for a catchment in such environments. The study reported in this contribution focuses on a long-term study of the sediment budget of a small (19.6 km^2) catchment in the Polish Flysch Carpathians and, more particularly, recent work aimed at exploring the potential for using environmental radionuclides to complement and extend the data provided by conventional measurements. This contribution places particular emphasis on identification of the main suspended sediment sources within the catchment, since identification of the sediment sources represents a fundamental requirement for establishing the sediment budget.

The Polish Flysch Carpathians comprise both low mountains and extensive foothills at an elevation of 300–1500 m a.s.l. The area is characterized by highly active fluvial erosion, transport and sedimentation processes, which in turn reflect the climate, the high relief energy, the erodible terrain, and the effects of poor land management. Much of the original forest cover has been cleared and at present only about 50% of the mountain area is under forest. Land disturbance by human activity is widespread. The present-day land-use change reflects the political and social changes of 1989 and the impact of the "free market". In general, arable cultivation is currently decreasing on steep slopes, with such areas being converted to permanent cover such as grassland or forest. Fluvial processes are dominant, but mass movements can locally assume considerable importance (cf. Starkel, 1972).

THE STUDY AREA

The 19.6 km^2 catchment of the Homerka stream lies at an altitude of 375–1060 m a.s.l. and is representative of the partly deforested landscape of the Polish Flysch Carpathians (Fig. 1). Extreme floods, with peak discharges in excess of 3 m^3 s^{-1} km^{-2}, exert an important control on the fluvial system and are highly significant as geomorphologically effective events. Fluvial processes are dominant, and the channel network is being actively deepened. The catchment has a mean discharge of 0.362 m^3 s^{-1}, a mean annual flood discharge of 9.15 m^3 s^{-1}, and a mean annual rainfall of 928 mm. The area is characterized by rapid flood generation, significant soil erosion, and high suspended sediment loads. The high annual suspended sediment yield of the Homerka catchment is approx. 550 t km^{-2} $year^{-1}$ and suspended sediment concentrations during floods may exceed 3×10^4 mg l^{-1}. The critical threshold for the widespread occurrence of dispersed overland flow is a storm rainfall of approx. 20 mm with a minimum intensity of approx. 1 mm min^{-1} (Słupik, 1981).

The Homerka catchment comprises two main zones, representing the montane headwater and the lower foothill zones. The headwater areas, which are predominantly forested, are characterized by steep (15–35°) convex and straight slopes and shallow permeable skeletal soils. These forest areas, which account for 52% of the total basin area, are dissected by a dense network of unmetalled roads and lumber tracks. The foothill zone lies below 650 m a.s.l., and this part of the drainage basin is underlain by shale-sandstone flysch series and is characterized by more gentle slopes (5–15°). The silt-clay soils support small traditional farms and the associated mosaic of arable fields is bounded by agricultural terraces and crossed by a dense network of unmetalled roads, which are commonly sunken below the level of the surrounding land. The valley floors of the third order streams are flat, covered by alluvium and occupied by meadows and permanent pasture. In this lower zone of the catchment, most of the stream channels are not in direct contact with the slopes. Unmetalled roads are a characteristic feature of both the Carpathian landscape in general and the Homerka catchment in particular. They date back to the original clearing and cultivation of the land. The network of roads serving the fields is related to the field pattern. Major roads tend to be located along both watercourses and divides and are linked by a dense network of secondary roads, which run downslope or at an inclination to the

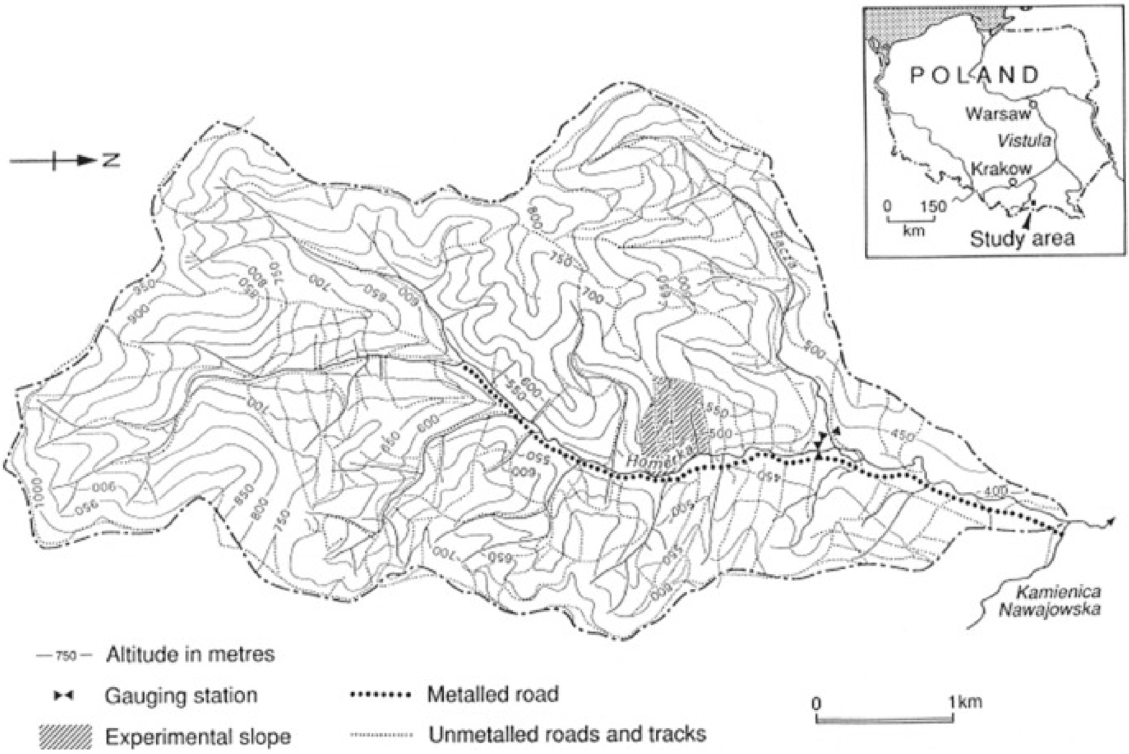

Fig. 1 The Homerka drainage basin and the experimental slope, and the location of the study area in Poland (based on Froehlich *et. al.,* 1993).

slope. In narrow valley bottoms, unmetalled roads often run along stream channels, which in forest areas are often used for log transport. The density of unmetalled roads within the catchment as a whole is 5.3 km km^{-2}.

In order to permit detailed investigation of erosion and sediment delivery from a representative cultivated zone in the lower part of the basin, an area of 26.5 ha located on the boundary between the forest and the agricultural areas has been designated an "experimental slope" (Fig. 1). The slope is 500–700 m long and convexo-concave in form. The silty clay soils increase in depth towards the base of the slope. The plots are separated by terraces and ditches and by the unmetalled roads, which traverse the area from the watershed to the stream channel. During times of heavy rainfall, these unmetalled roads act as channels for surface runoff and in many places they are deeply incised into the slope. The length of unmetalled road traversing the experimental slope is 3.3 km, equivalent to a density of 11.9 km km^{-2}.

FIELD AND LABORATORY METHODS

Each of the main subcatchments in the Homerka catchment and the catchment outlet are gauged and measurements of runoff and sediment load have been undertaken since 1971 (cf. Froehlich, 1982, 1986) These measurements have been complemented by other more targeted measurements, aimed at estimating erosion rates and slope–channel sediment transfer (see Froehlich, 1991, 1995). The application of caesium-137 (^{137}Cs) and other environmental radionuclides to studying sediment sources, soil erosion and sediment redistribution, sediment delivery dynamics and sedimentation began in the catchment in 1984 (see Froehlich & Walling, 1992, 1997; Higgitt *et al.*, 1992; Froehlich *et al.*, 1993).

Information about suspended sediment sources within the Homerka catchment has been assembled using the "fingerprinting" approach advocated by Peart & Walling (1986, 1988) and Walling & Woodward (1992, 1995), with ^{137}Cs providing the primary source fingerprint. In order to "fingerprint" potential sediment sources, samples of material were obtained from a range of potential sources, including the surface of areas of forest, pasture and arable cultivation, unmetalled roads, gully walls and channel banks. These samples were collected from the surface of an area of 1 m^2, using a steel frame. In order to take account of grain size effects and to permit direct comparison with suspended sediment samples, the <0.063 mm fraction of the source materials was separated by sieving prior to analysis by gamma spectrometry. Bulk samples of suspended sediment for source ascription were also 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-l and 180-l plastic containers using an electromagnetic pump. The suspended sediment was recovered from the bulk samples by sedimentation and centrifugation and the >0.063-mm fraction of these samples was separated by wet sieving. The separated fractions were dried at 105°C and 100-g sub-samples were packed into Marinelli beakers for gamma-ray spectrometry.

Gamma spectrometry analysis was undertaken both in the Environmental Radionuclide Laboratory at the Department of Geography, University of Exeter, UK, and the Homerka Laboratory of Fluvial Processes, Institute of Geography and Spatial Organization, Polish Academy of Sciences. All samples were analysed using ORTEC HPGe coaxial detectors calibrated with Standard Reference Materials (IAEA Soil-6, IAEA Soil-375 and IAEA Soil-327). Since soil and sediment sampling and associated measurements of ^{137}Cs activity were undertaken both prior to, and after, the Chernobyl accident, it is important to recognize that ^{137}Cs activities for the pre-Chernobyl period reflected only bomb-derived inputs of ^{137}Cs, whereas those for the subsequent period were generally higher and reflected both bomb- and Chernobyl-derived inputs.

INVESTIGATING SUSPENDED SEDIMENT SOURCES

Using environmental radionuclides

Measurements of the ^{137}Cs content of the <0.063-mm and >0.063-mm content of suspended sediment collected from the main flow gauging station at the outlet of the Homerka catchment during the pre-Chernobyl period indicated a range of activity between 6.3 and 22.6 Bq kg^{-1} for the <0.063-mm fraction. Activities for the coarser >0.063-mm fraction were much lower and consistently approx. 1–2 Bq kg^{-1}. These activities have been plotted against the discharge at the time of sampling in Fig. 2. The discharges in the main stream associated with the threshold for the initiation of surface runoff as linear flow on unmetalled roads and in gullies, ditches and furrows, and as overland flow from cultivated plots, pasture areas and forest areas, derived from conventional monitoring, have also been defined on Fig. 2. These thresholds show that linear flow from unmetalled roads and in gullies, ditches and furrows occurs above a relatively low threshold discharge in the main channel, but that at higher flows overland flow from cultivated areas, pasture areas and forest areas progressively occur, with overland flow from forest areas only occurring when flows in the main channel exceed approx. 4 m^3 s^{-1}. The range of ^{137}Cs activities associated with both suspended sediment and potential source materials have also been plotted on Fig. 2.

Two key features of Fig. 2 are worthy of comment in relation to identifying the dominant sources of fine (suspended) sediment in the Homerka catchment. First, comparison of the range of ^{137}Cs activity associated with suspended sediment with the typical ranges associated with potential source materials suggests that this most closely matches that associated with material collected from the surface of unmetalled roads. Sediment eroded from the surface of forest and pasture areas is unlikely to represent an important sediment source, since its ^{137}Cs activity is substantially higher. If the contribution from this source was appreciable, the overall concentration in the suspended sediment would increase to levels considerably above those recorded. Material eroded from the surface of cultivated land and from gully and channel banks could represent a significant sediment source, but is thought unlikely to represent a major source, since the range of ^{137}Cs activities associated with these materials again extends well above that which is representative of suspended sediment. Secondly, there

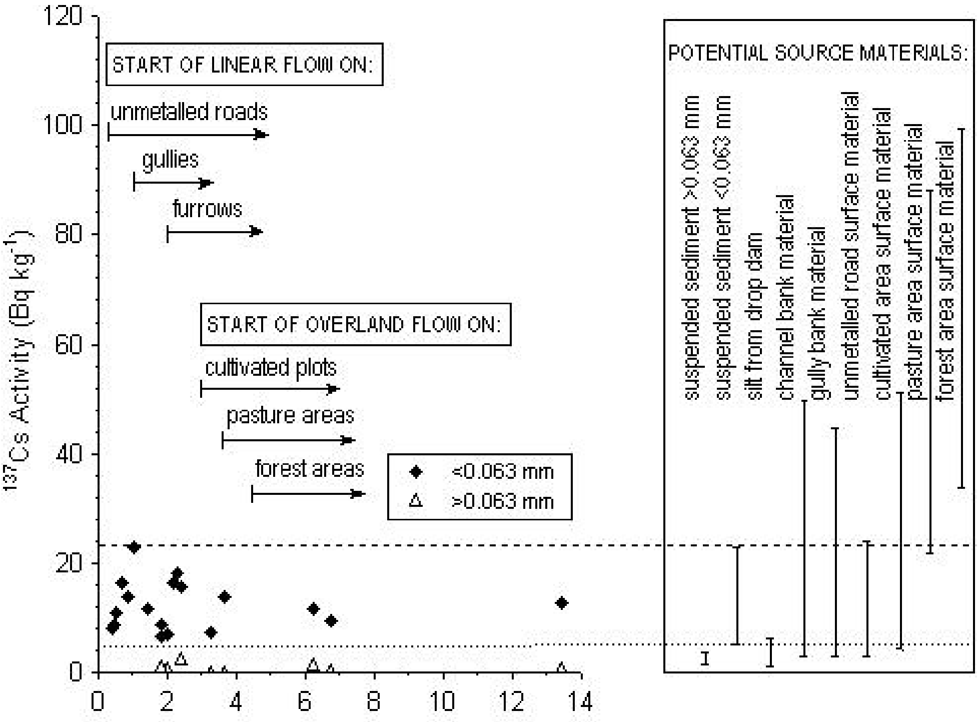

Fig. 2 The relationship between the ^{137}Cs content of suspended sediment and discharge, the discharge thresholds associated with the occurrence of storm runoff from various sources within the basin, and the range of ^{137}Cs concentrations associated with suspended sediment and potential source materials (based on Froehlich & Walling, 1992).

is no evidence that the dominant sediment sources change significantly during storm runoff events of different magnitude. The ^{137}Cs activity of the suspended sediment remains essentially similar across a wide range of flows, despite crossing a range of thresholds for surface runoff generation within the catchment. This suggests that unmetalled roads represent the main suspended sediment source within the catchment over the entire range of flows.

Figure 3 provides a longer-term perspective on sediment sources in the Homerka catchment, by plotting the values of ^{137}Cs activity recorded in suspended sediment over the entire period of sediment sampling, from its inception in 1984 through to 1997. This plot clearly shows the impact of the Chernobyl accident and the associated fallout of ^{137}Cs in 1986, since ^{137}Cs activities in suspended sediment increased by ~20 times during the immediate aftermath of the Chernobyl accident to reach nearly 400 Bq kg^{-1}. The rapid decline of ^{137}Cs activity in suspended sediment, to reach a new "equilibrium" after 3–4 years is consistent with unmetalled roads representing the dominant source, since Chernobyl fallout accumulating on these source areas could be expected to be rapidly removed by erosion of the road surface, so that after ~10 years, the ^{137}Cs activities are of a similar magnitude to those found before the Chernobyl accident, taking account of radioactive decay. If the catchment surface more generally was the main source, ^{137}Cs activities could be expected to remain higher for an extended period, since ^{137}Cs activities in catchment soils were significantly increased by Chernobyl fallout and still remain substantially higher than those recorded prior to the Chernobyl event.

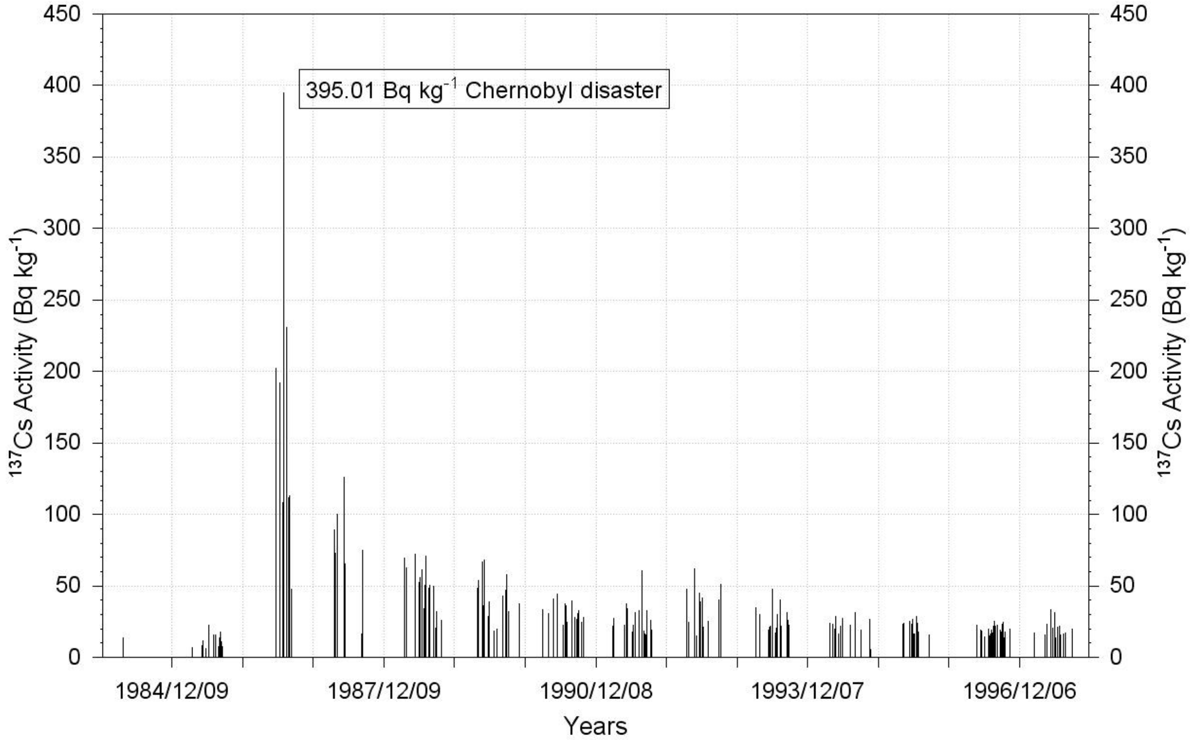

Fig. 3 Variation of the ^{137}Cs content of the <0.063 mm fraction of suspended sediment transported by the Homerka stream during the period 1984–1997.

Figure 4 introduces a spatial dimension to the identification of the dominant sediment sources in the catchment, by comparing the ^{137}Cs activity associated with fine (<0.063 mm) sediment collected from deposits at various locations along the channel of the Homerka stream after a flood in July 2003. The low ^{137}Cs activities associated with the sediment are again indicative of the dominance of unmetalled roads as a sediment source. However, although this plot evidences significant scatter, it still shows a trend for ^{137}Cs activities to decrease downstream, in passing from the upper reaches of the catchment to the lower reaches. This is consistent with the progressive increase in the importance of unmetalled roads as a sediment source in the agricultural areas towards the lower part of the catchment, where road densities are frequently greatest, and the associated reduction in the relative importance of channel and gully erosion. This trend could also suggest that although unmetalled roads are the dominant source, there is some limited contribution from the catchment surface more generally. Since pasture and forest areas dominate in the upper part of the catchment, any surface contribution from this area is likely to have a higher ^{137}Cs activity than sediment contributed from the catchment surface in its lower areas, where cultivated areas are more important and the forested area is very limited.

Figures 5 and 6 provide further information on sediment source dynamics within the Homerka catchment, by considering variation of the ^{137}Cs content of suspended sediment during individual events. The two examples provided relate to a snowmelt event occurring during March 2003 (Fig. 5) and a "flash flood" resulting from an intense summer rainstorm occurring in August 2004 (Fig. 6). The pattern of variation

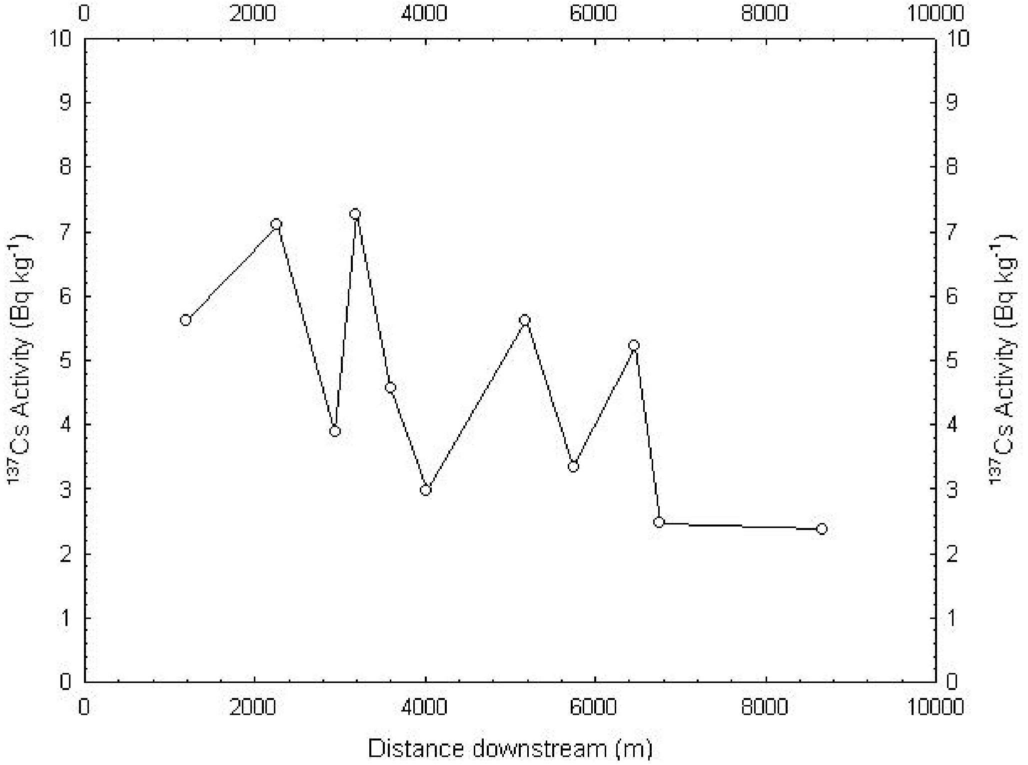

Fig. 4 Downstream changes in the ^{137}Cs content of the <0.063-mm fraction of fine sediment deposits in the main channel of the Homerka catchment sampled after the flood of July 2003.

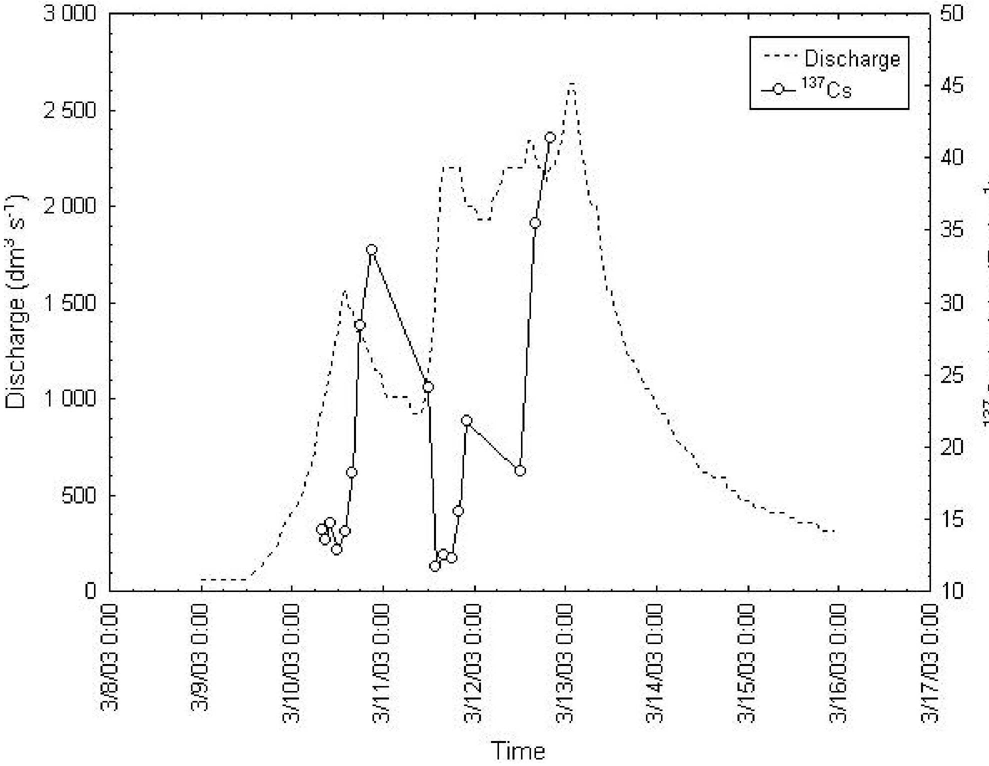

Fig. 5 Variation in the ^{137}Cs content of the <0.063-mm fraction of suspended sediment transported by the Homerka stream during a snowmelt flood in March 2003.

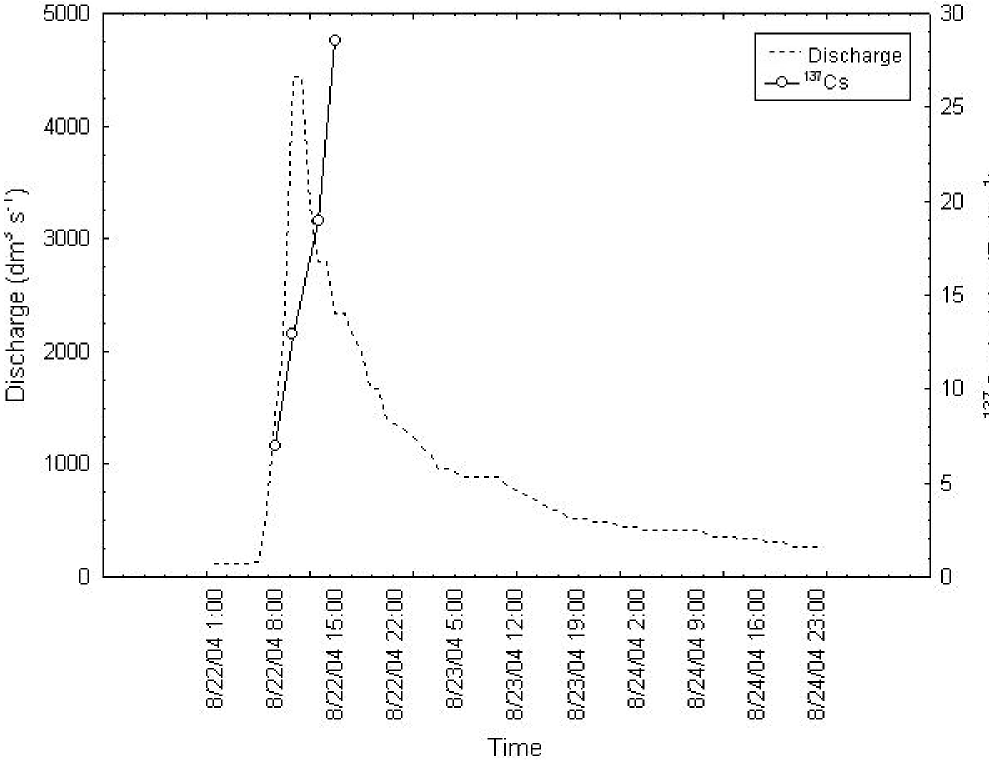

Fig. 6 Variation in the ^{137}Cs content of the <0.063-mm fraction of suspended sediment transported by the Homerka stream during a flash flood in August 2004.

of the ^{137}Cs content of suspended sediment during the snowmelt event of March 2003 shows an increase in ^{137}Cs activity during high flows, although there is considerable hysteresis in the relationship, with the increase in ^{137}Cs activity lagging the increase in water discharge by 6 h or more. Furthermore, there is a very rapid decline in ^{137}Cs activity associated with the second increase in water discharge that occurred around midday on 11 March. This behaviour is again consistent with unmetalled roads providing the main suspended sediment source in the Homerka catchment. During the early stages of storm events, runoff and sediment generation is likely to be primarily restricted to the network of unmetalled roads, and particularly those parts of the network close to the channel system. As the event proceeds and discharge increases, sediment from parts of the unmetalled road network further from the channel network, which may only contribute during higher magnitude events, will reach the channel system. Equally, during the period of peak runoff, increased sediment inputs are likely to be generated from active gullies and eroding channel banks, and also from cultivated areas connected to the channel system by furrows and ditches, either directly or via the unmetalled roads. These inputs will introduce sediment with a higher ^{137}Cs content, causing the ^{137}Cs content of the overall sediment load to increase. Similar behaviour is demonstrated by the flash flood which occurred in August 2004, and which is shown in Fig. 6. In this event, there is again an increase in the ^{137}Cs content of the suspended sediment as the event proceeds, and this increase also lags the peak in the water discharge. This increase in ^{137}Cs activity during the latter stages of the flood is again likely to reflect the delayed transmission of sediment from the outer parts of the network of unmetalled roads and from the smaller tributary channels and active gullies, which supply sediment less frequently, and also contributions from cultivated areas, linked to the unmetalled roads and channels by ditches and furrows. These contributions are all likely to be characterized by increased ^{137}Cs activity. It is however important to note that the peak ^{137}Cs activities recorded during both events depicted in Figs 5 and 6 are well below those that might be expected for sediment mobilized from the catchment surface more generally, particularly in view of the fact that such activities are likely to be substantially higher in 2003 and 2004 than shown in Fig. 2 for the pre-Chernobyl period. Surface soils from forest, pasture and cultivated areas are currently characterized by typical ^{137}Cs activities of around 224, 185 and 47 Bq kg^{-1}, respectively.

Evidence from conventional measurements

The results from the radiocaesium measurements presented above, which emphasize the importance of unmetalled roads as the dominant suspended sediment source in the Homerka catchment, are consistent with other evidence provided by the more traditional monitoring techniques deployed in the study catchment and the adjacent region. Studies of surface runoff generation in forested areas of the Carpathians have emphasized that surface runoff rarely occurs (e.g. Gerlach, 1976) and it can therefore be inferred that direct supply of sediment from the forested areas to the stream channels and the network of unmetalled roads is of very limited importance. Similarly, measurements of suspended sediment concentrations in diffuse surface flow from pasture areas in the Homerka catchment have shown that values are typically in the range 25–65 mg l^{-1}, and were always an order of magnitude or more less than those measured in suspended sediment samples collected from the river at the catchment outlet. Although surface runoff and sediment mobilization have frequently been documented on the cultivated plots investigated within the experimental slope (see Froehlich, 1982), these areas have been shown not to represent a significant source for sediment transfer to the stream channel. In most locations, the slopes are poorly coupled to the stream channels and the existence of terraces and also pasture areas adjacent to most stream channels, which act as buffer strips, serve to reduce slope–channel connectivity. The evidence available from conventional monitoring undertaken within the Homerka catchment therefore provides a strong indication that the high suspended sediment concentrations found in the stream channel, and which sometimes exceed 3×10^4 mg l^{-1}, could not have been produced by sediment mobilized from the catchment slopes, but primarily reflect sediment mobilization from the dense network of unmetalled roads in the catchment. The magnitude of the suspended sediment concentrations measured in samples of surface runoff collected from unmetalled roads has been shown to reflect a number of characteristics of the roads, including their age, their degree of incision, and their frequency of use (Froehlich, 1995). Suspended sediment concentrations in excess of 15×10^4 mg l^{-1} have been recorded for samples collected from sunken roads that are frequently used. Attempts to document the rate of incision of such unmetalled roads have generated estimates of average rates of incision over the past 30 years of approx. 6–7 mm $year^{-1}$.

PERSPECTIVE

Caesium-137 measurements have been shown to provide an effective means of identifying the main suspended sediment sources in the Homerka catchment. Source tracing techniques possess many advantages over more conventional approaches to establishing sediment sources, since they overcome the sampling problems associated with monitoring individual sources. The measurements of ^{137}Cs activity undertaken on suspended sediment samples collected from the catchment outlet integrate the source contributions from the entire upstream catchment. Both approaches point to the importance of unmetalled roads as the primary suspended sediment source within the Homerka catchment. The overall density of the unmetalled roads within the catchment is 5.3 km km^{-2}, but this value increases to 11.9 km km^{-2} on the experimental slope, which is representative of much of the lower area of the catchment, where agricultural land-use is important. It is estimated that unmetalled roads contribute ~98% of the sediment yield during low magnitude storm events and about 60–70% during floods equivalent to the mean annual flood. Overall, the contribution of unmetalled roads to the mean annual sediment yield from the study catchment is ~70–80% of the annual suspended sediment yield. Most of the remaining sediment is contributed by channel sources and by active gullies.

These findings serve to emphasize the importance of human activity in modifying the sediment budgets of small catchments such as the Homerka catchment in the Polish Flysch Carpathians. Equally, they have important implications for the implementation of a sediment control and management strategies in this environment. It is clear that any attempt to reduce the sediment yield of the study catchment would need to target the network of unmetalled roads in the catchment, with a view to reducing surface runoff and sediment mobilization from these sediment sources and attenuating the transfer of sediment from the roads to the stream system, by, for example, diverting runoff to temporary sinks.

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