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The role of unmetalled roads as a sediment source in the fluvial systems of the Polish Flysch Carpathians

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Abstract This contribution presents results from a long-term study of the role of unmetalled roads as a sediment source in the fluvial systems of the Polish Flysch Carpathians. The study has employed both classical monitoring techniques and fallout radionuclide tracers and has investigated both agricultural and forested areas within the Homerka experimental catchment. In this environment, unmetalled roads greatly increase the effective drainage density and cause a major increase in sediment flux. They represent the main suspended sediment source in the study catchment. Most of sediment mobilized from the unmetalled roads is delivered directly to the stream channels and the downstream increase in suspended sediment concentration reflects the increasing input of sediment from the dense network of unmetalled roads. Most of the sediment mobilized from cultivated areas on the slopes of the catchment by surface wash and related processes is, in contrast, redeposited at the foot of the slopes as well as on the valley floors and does not reach the stream channels. The importance of unmetalled roads as a suspended sediment source is an important characteristic of drainage basins in the Flysh Carpathians.

INTRODUCTION

The Polish Flysch Carparthians are characterized by low mountains and extensive foothills at an elevation of 300-1500 m a.s.l. The area is underlain by sandstones and shales of varying resistance to weathering. The headwater zones are covered by thick regolith, whereas in the lower areas thick solifluction and slope wash deposits and aeolian sediments are found. 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 forest areas are intensively exploited and they are accessed by a dense network of unmetalled roads which are frequently using for log transport. In the headwater areas, logging greatly accelerates sediment flux to the channels because a high proportion of the mobilized sediment is delivered directly from the steep slopes to the channels which flow in narrow V-shape valleys (Froehlich, 1982, 1991; Froehlich & Slupik, 1986). In the lower areas, agricultural land use associated with small farms assumes increasing importance. This land is characterized by a mosaic of field plots of various sizes, separated by agricultural terraces, and intersected by networks of unmetalled roads, which frequently extend to the stream channels. The lower slopes and valley flood plains are occupied by meadows and pasture. In these areas, the valley side slopes are not directly coupled to the stream channels on the alluvial valley floors.

Unmetalled roads, including simple paths, cart tracks in the fields and forests, lumber tracks and sunken roads are therefore common throughout the area and must be seen as a characteristic feature of the region. They represent both an important sediment source and an important pathway for rapid sediment delivery to the stream channels. In the Beskidy Mountains, which represent the headwater areas of the Polish Flysch Carpathians, the average drainage density of unmetalled roads is 4 km km^{-2} whilst in the foothills it increases to 7 km km^{-2} (Soja & Prokop, 1996).

Existing information concerning the sediment yields of Carpathian rivers is restricted primarily to large basins. Annual sediment yields for such basins lie in the range 90-1000 t km^{-2} $year^{-1}$ (cf. Branski, 1968; Lajczak, 1989). Relatively little information is available on soil erosion and sediment sources in small drainage basins. Gil (1986) reports the influence of different crops on soil erosion rates. Rates of soil erosion under potato crops are as high as 22 t ha^{-1} $year^{-1}$, whilst typical values for winter crops, meadows and forest are 2.4, 0.1 and 0.03 t ha^{-1} $year^{-1}$ respectively. However, it is difficult to make direct comparisons between estimates of the intensity of erosion processes on the slopes and the downstream sediment yields of Carpathian rivers, because of the wide range of techniques of unknown accuracy and precision which have been used, the different periods of record involved and uncertainties regarding the degree of coupling between the slopes and the river channels. The study reported in this contribution aimed to establish the dominant sources of the suspended sediment transported by the local rivers, and more particularly to assess the importance of unmetalled roads as sediment sources within this environment.

STUDY AREA

Investigations focused on the small (19.6 km^2) Homerka drainage basin, but an attempt was also made to scale up the findings to the larger (4692 km^2) basin of the Dunajec river above Roznowski reservoir. The Homerka drainage basin (375-1060 m a.s.l.) is a typical partly deforested Carpathian basin. It is composed of two parts representing the montane headwater and the lower foothill zones (Fig. 1). In the foothill zone of the basin, the mean annual precipitation is about 900 mm, whereas in the montane headwaters it exceeds 1000 mm. The equivalent values of mean annual air temperature are 7.5° and 5°C respectively. 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 currently intensively exploited and are traversed 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 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 zone most of the river channels are not in direct contact with the slopes.

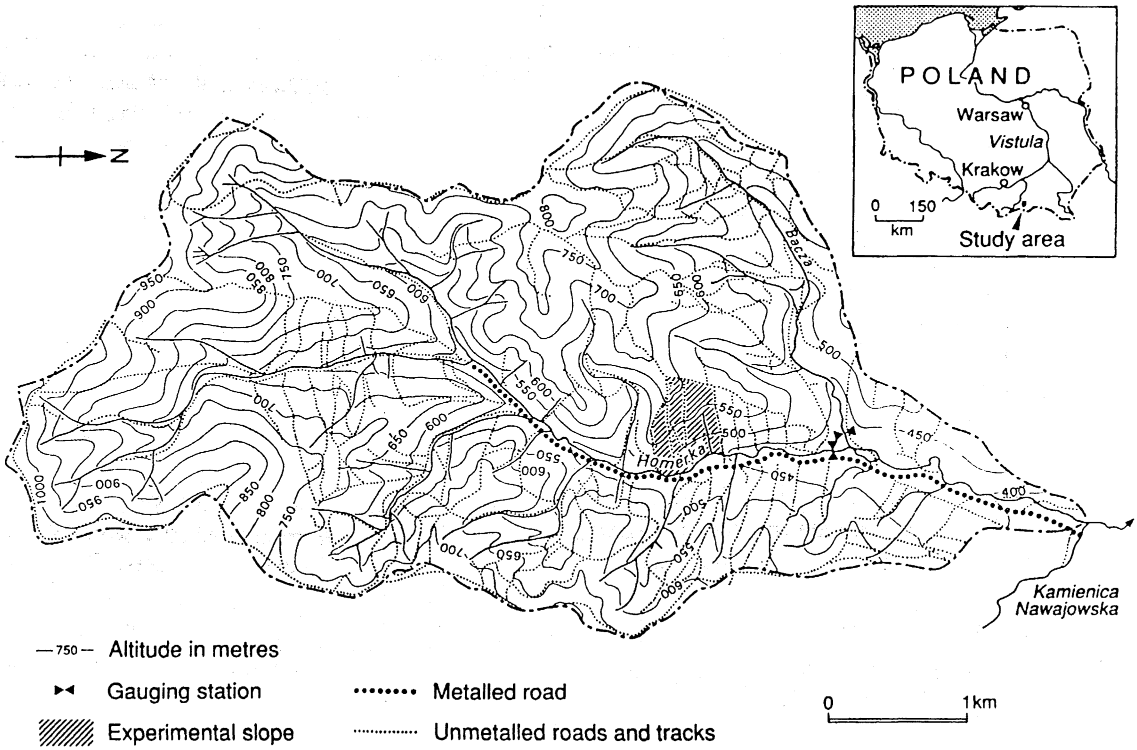

Fig. 1 The Homerka drainage basin and the location of the study area in Poland.

Detailed investigations of sediment mobilization and transfer to the channel network in the Homerka catchment have been undertaken both on an experimental slope representative of the cultivated zone in the lower part of the basin and within the forested headwater area (Fig. 1). The 500-700 m long convex-concave experimental slope covers an area of 26.5 ha at an altitude of 458-608 m a.s.l. The slope is subdivided into numerous field plots which are cultivated across the slope. The field plots are of various sizes and are separated by terraces and furrows and by the unmetalled roads which traverse the area from the watershed to the stream channel. In many places these roads are deeply incised into the slope and bedrock is exposed along their floors. The length of the unmetalled roads traversing the experimental slope is 3.3 km. This represents a density of 11.9 km km^{-2}, whereas the density for the whole basin is 5.3 km km^{-2}.

The experimental slope has been subdivided into several sub-areas representing the main potential contributing areas for runoff and sediment. These areas comprise:

(a) the catchment area of a Holocene gully;
(b) the unmetalled roads; and
(c) the interchannel areas under different crops.

Each of these areas was instrumented. In the headwater area attention focussed on:

(a) the unmetalled roads and
(b) the forested interchannel areas.

The sediment derived from these source areas reach the stream channel quickly in the case of concentrated flow along unmetalled roads, the Holocene gully or drain pipes, and slowly in the case of overland or subsurface flow.

FIELD AND LABORATORY METHODS

Each of the contributing areas investigated within the Homerka study basin was instrumented to measure the sediment load delivered to its outlet. A comparison was also made between the suspended sediment concentrations observed above and below the points where runoff from the unmetalled roads entered the stream channels. Experimental plots were established to observe rainsplash erosion on both an unmetalled road surface and a ploughed field (Froehlich & Slupik, 1980).

The rate of incision of the unmetalled roads was documented by surveying at 55 transverse profiles using steel bench marks to an accuracy of ±2 mm. The profiles were established on different types of unmetalled road, reflecting the depth of incision, the nature of the regolith material, the slope inclination, the length of the eroded segment and the frequency of traffic. The small (2 m) distance between the individual cross sections also enabled the rate of incision along the longitudinal profile of the unmetalled roads to be determined. The cross sections were surveyed after each heavy rainfall event.

The use of fallout radionuclides measurements to investigate sediment sources and sediment delivery dynamics within the Homerka drainage basin began in 1984. Information of suspended sediment sources has been assembled using the "fingerprinting" approach advocated by Peart & Walling (1986, 1988) and Walling & Woodward (1992). Caesium-137 measurements were used to fingerprint the various potential sources. The Chernobyl reactor accident that occurred on 26 April 1986 produced a substantial increase in ^{137}Cs inventories in the area and introduced problems in making comparisons between samples collected before and after the disaster, but measurements of the ^{134}Cs activity can be used to apportion the total ^{137}Cs activity between bomb and Chernobyl-derived fallout. Most of the results presented in this study, however, relate to the period prior to the Chernobyl incident in order to simplify the interpretation.

In order to "fingerprint" potential sediment sources, samples of surface material were obtained from a range of potential sources, including areas of forest, pasture and arable cultivation, unmetalled roads, gully walls and channel banks. These samples were collected from 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 gamma spectrometry analysis. Bulk samples of suspended sediment 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 and 180 l plastic containers using an electromagnetic pump. The suspended sediment was recovered from the 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.

The Homerka drainage basin is a tributary of the Dunajec River which flows into the Roznowski reservoir. Sediment cores were collected from the delta area of the reservoir in order to establish the dominant source of the sediment entering the reservoir.

Gamma spectrometry analysis of suspended sediment and source material samples was undertaken at the Department of Geography of the University of Exeter using an ORTEC HPGe coaxial detector calibrated with Standard Reference Materials and radionuclide standards. The activities of ^{137}Cs and ^{134}Cs were determined from the photopeaks produced at 662 and 605 keV respectively. Count times were typically 30 000 s, providing an analytical precision of *ca.* ±10% and ±5% for ^{134}Cs and ^{137}Cs respectively.

DIRECT MONITORING OF SEDIMENT SOURCES

Using classical monitoring techniques, Froehlich (1982) suggested that unmetalled roads and active Holocene gullies represent the major suspended sediment source in the Homerka catchment. The unmetalled roads increase the overall drainage density and since the permeability of the road surface is low, their response to rainfall is rapid. The effective drainage areas of the unmetalled roads are relatively constant, but they may expand and contract in response to storm period, seasonal and annual variations in precipitation and traffic. Flow was observed on the unmetalled roads during almost all rainfall events. The abundance of poorly consolidated material capable of being transported is responsible for high suspended sediment concentrations in runoff collected from the unmetalled roads (Fig. 2). The maximum recorded suspended sediment concentration from the unmetalled roads was *ca.* 1.5×10^5 mg l^{-1}. During rising stages, the suspended sediment concentration was always greater on the unmetalled roads than in the channel of the Homerka stream. Concentrations of suspended sediment evidenced significant differences between different types of unmetalled road (Fig. 3).

Rapid formation of a surface detention layer on an unmetalled road surface results in an increased intensity of soil splash. The results from the experimental studies of soil splash on plots simulating a ploughed field and unmetalled road indicate that the intensity of the process in question can be 30 times greater in the case of an unmetalled road than for a ploughed field (Froehlich & Slupik, 1980). This promotes greater mobilization of suspended sediment from unmetalled roads compared to other potential sediment sources. Each flood is characterized by a specific relationship between discharge and suspended sediment concentration (Froehlich, 1982).

Sediment inputs to the Homerka channel from the system of unmetalled roads originate primarily from the road itself. Some sediment mobilized from cultivated fields during periods of overland flow may be transported to the unmetalled roads directly or via a system of furrows. However, the magnitude of the suspended sediment concentrations in the furrows was always less those associated with the unmetalled roads (Fig. 2). The sediment flux from the unmetalled roads to the Homerka channel varies depending on the rainfall duration and intensity. It has been estimated that during storm events not generating overland flow, unmetalled roads

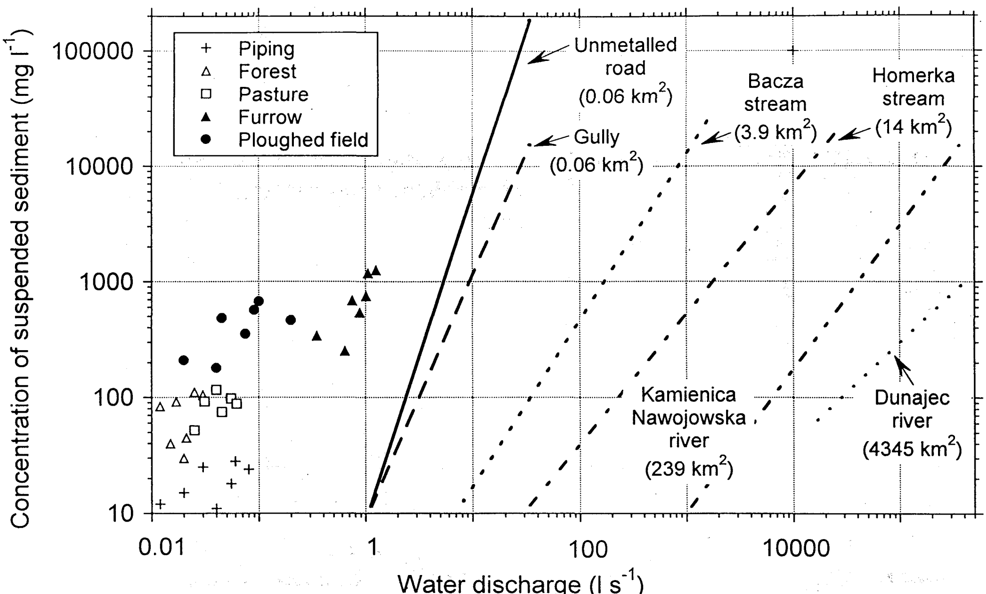

Fig. 2 The relationship between suspended sediment concentration and discharge for drainage basins of different scale and for potential sediment sources drained by dispersed overland flow and linear flow (source: Froehlich, 1995).

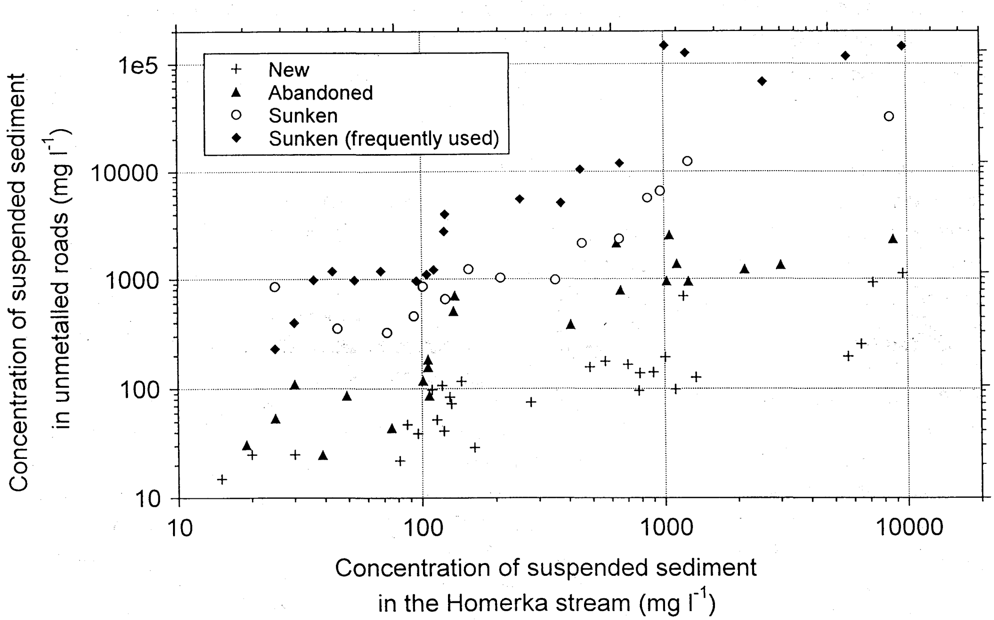

Fig. 3 The relationship between concentration of suspended sediment in the Homerka drainage basin and concentration of suspended sediment in runoff from different types of unmetalled road (source: Froehlich, 1995).

account for *ca.* 98% of the sediment input to the stream, whereas during annual floods this source accounts for *ca.* 60-70 % of the load (Froehlich, 1982).

Similar behaviour was documented for the unmetalled roads in the forested part of the Homerka drainage basin. As is generally known, wash processes in forested areas of the lower subalpine region are quantitatively unimportant (cf. Gerlach, 1976; Gil, 1986). It can therefore be expected that the majority of the suspended sediment is derived directly from unmetalled roads.

During the last 20 years the average rate of incision of the unmetalled roads was estimated to be 6.6 mm $year^{-1}$ (1975-1995), with values ranging from 0 on the bedrock surface up to 370 mm on permeable cover as a result of catastrophic floods.

FINGERPRINTING SUSPENDED SEDIMENT SOURCES

The results presented above, obtained using classical methods, are only representative of small areas and are based on relatively short periods of record. In consequence, it is difficult to produce meaningful assessments of the relative contribution of sediment mobilized from unmetalled roads for drainage basins of different scale. The use of ^{137}Cs as a source tracer affords a valuable alternative means of investigating suspended sediment source and its spatial variability. Information on suspended sediment source was assembled using the "fingerprinting" approach described by Peart & Walling (1986, 1988) and Walling & Woodward (1992). The caesium-137 content of suspended sediment samples collected from the main gauging station on the Homerka stream during each flood event was compared with the ^{137}Cs content of samples representative of potential source materials.

Measurements of the ^{137}Cs content of the <0.063 mm fraction of suspended sediment collected from the Homerka stream at the main gauging station during the pre-Chernobyl period, indicated a range between 6.3 and 22.6 mBq g^{-1}, with a mean of 11.9 mBq g^{-1} and a standard deviation of 4.4. Comparison of these values with typical values for potential source materials measured during the pre-Chernobyl period (Table 1, Figs 4, 5) suggests that they most closely match those associated with material collected from the surface of unmetalled roads. Sediment eroded from the surface of forest and pastures areas is very unlikely to represent an important sediment source, since its ^{137}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}Cs levels associated with these materials extends well above that

Table 1 Caesium-137 concentrations associated with suspended sediment, silt deposited in the silting basin above a drop structure, and potential suspended sediment sources within the Homerka drainage basin (source: Froehlich & Walling 1992).

Samples	Mean concentration (mBq g^{-1})	Standard deviation (mBq g^{-1})
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

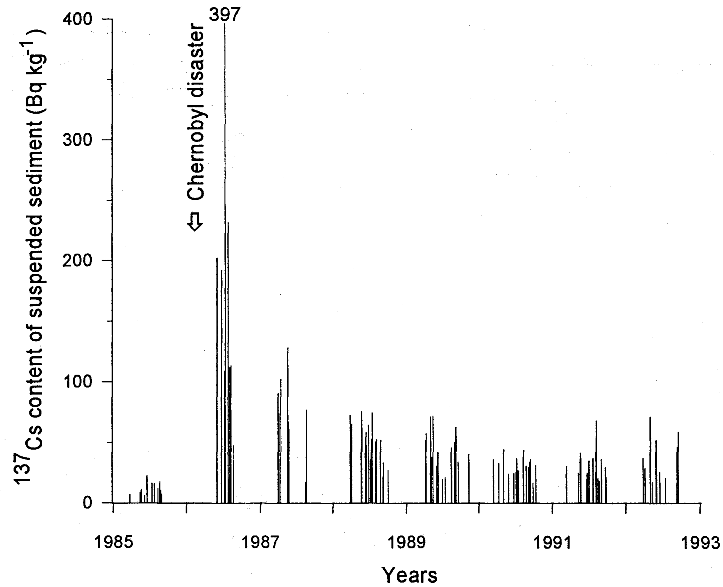

Fig. 4 Variation of the ^{137}Cs content of the <0.063 mm fraction of suspended sediment transported by the Homerka stream during the period 1985-1993.

representative of suspended sediment (Froehlich & Walling 1992; Froehlich *et al.*, 1993). The evidence provided by the radiocaesium fingerprints 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.

Existing evidence relating to the generation of storm runoff within the Homerka drainage basin indicates that the frequency of occurrence of surface runoff on unmetalled roads and in gullies and the furrows between cultivated fields is considerably greater than on the cultivated areas. This is further emphasized by Fig. 5 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 linear flow on the cultivated plots and within the areas of pasture and forest are shown. The relationship between the ^{137}Cs content of suspended sediment and the discharge of the Homerka stream shown in Fig. 5 shows no evidence of shifts associated with the incidence of overland flow contributions from the cultivated fields and pasture and forest areas of the drainage basin or 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 suspended sediment transported by the Homerka stream.

The >0.063 mm fraction of suspended sediment is characterized by very low ^{137}Cs content, ranging from 0.0 to 2.5 mBq g^{-1}, with a mean value of 0.8 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. He & Walling, 1996) 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. 5).

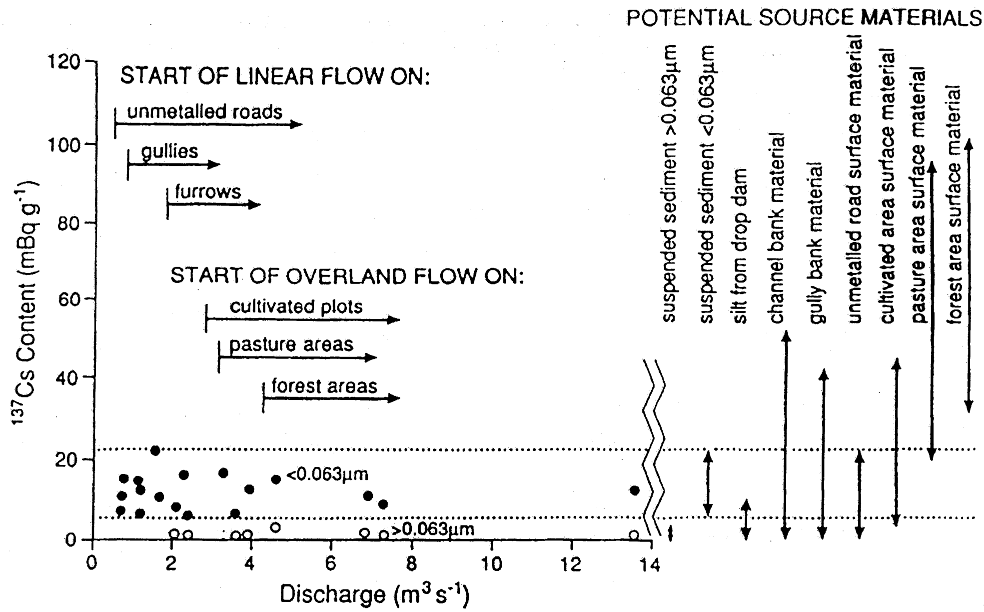

Fig. 5 The relationship between the ^{137}Cs content of suspended sediment and discharge, the discharge thresholds associated with the occurrence of storm runoff from various sources within the basin, and the range of ^{137}Cs concentrations associated with suspended sediment and potential source materials (source: Froehlich & Walling, 1992).

These were characterized by a relatively low ^{137}Cs content ranging from 0.1 to 10.7 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 further confirms the representativenes of the ^{137}Cs fingerprints of the suspended sediment samples.

The extremely low caesium content of fine channel deposits in the downstream reaches of the Homerka channel suggests that suspended sediment fluxes from the forested headwater areas of the Homerka catchment are relatively low compared to the contribution from unmetalled roads sources and that sediment with a relatively low caesium content is progressively added to the system downstream. This material is primarily derived from linear erosion of unmetalled roads and gullies, rather than extensive surface wash processes of the cultivated lands.

Sediment samples collected from the surface of alluvial deposits within the Roznowski reservoir in the period immediately prior to the Chernobyl disaster were characterized by ^{137}Cs concentrations in the range 9.1-9.8 mBq g^{-1}. These conform closely with the concentrations associated with suspended sediment from the Homerka stream and thus suggest that unmetalled roads and gullies represent the main sediment source throughout the Dunajec drainage basin.

PERSPECTIVE

Information on the dominant sediment sources operating within a drainage basin is important for improving land management, predicting sediment loads and reducing rates of reservoir siltation. Studies undertaken within the Homerka experimental catchment using traditional monitoring techniques have suggested that unmetalled roads are the dominant sediment source and that they contribute the majority of the suspended sediment transported by the stream. The significance of the unmetalled roads as sediment sources reflects both the efficient mobilization of sediment from their surfaces and their direct connection to the stream channels. In an attempt to establish the wider representativeness of the results from these small-scale investigations both within the overall Homerka catchment and for the Flysch Carpathians more generally, sediment source fingerprinting studies have been undertaken using ^{137}Cs as a tracer. The results obtained again emphasize the importance of unmetalled roads as a sediment source and thus underscore the importance of human activity in controlling sediment yields in this region.

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