Use of Chernobyl-derived radiocaesium to investigate contemporary overbank sedimentation on the flood plains of Carpathian rivers

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Abstract Evidence for recent incision is widespread along the channels of Carpathian rivers and because of the tendency for the relative height of the flood plain surface to increase, the contemporary importance of overbank sedimentation is uncertain. An attempt has been made to use measurements of Chernobyl-derived radiocaesium in flood plain cores to generate estimates of recent rates of overbank deposition at seven sites, representing rivers of different size, within the basin of the Dunajec River. The results obtained confirm the viability of the approach employed and indicate that overbank deposition at the study sites is currently proceeding at rates of the order of 1-5 cm year^{-1}. Deposition rates appear to be significantly higher for the smaller rivers due to the increased frequency of high magnitude flood events.

INTRODUCTION

Evidence for recent incision in response to gravel extraction, channel regulation and changes in runoff regime consequent upon changes in land use, is widespread along the channels of Carpathian rivers. Bedrock frequently outcrops in the channels and the general tendency for incision to advance upstream is marked by the upstream decrease in the depth of incision and in the width of the associated Holocene terrace (cf. Starkel, 1960). The incision appears to proceed intermittently, with periods of intensive downcutting being interspersed with periods of limited erosional activity and even slow aggradation. Estimates of current rates of channel incision have been derived from analyses of changes in minimum annual water levels at river gauging stations (cf. Froehlich, 1980; Klimek, 1987) and such estimates indicate values as high as 3 cm year^{-1}. Short-term incision rates are particularly high during high magnitude flood events (e.g. Froehlich, 1975; Soja, 1977).

The contemporary development of the flood plains of Carpathian rivers therefore reflects the complex interaction of channel deepening and overbank sedimentation during flood events. The process of channel deepening results in an increase in the relative height of the flood plain, which is in turn inundated and subject to overbank deposition less frequently. Progressively larger discharges are required to exceed the bankfull stage and the magnitude and frequency of overbank sedimentation will therefore decrease. For this reason, Carpathian rivers currently transport an increasing proportion of their suspended sediment load beyond the foothill region during floods, leading to increased rates of flood plain and reservoir sedimentation downstream.

Because of the tendency for the relative height of the flood plains of Carpathian rivers to increase, the contemporary intensity of overbank deposition of fine material is uncertain. Traditionally, rates of overbank deposition of fine sediment in mountain rivers has been assumed to be low, due to the high channel slopes and associated high flow velocities. Channel incision could be expected to further reduce rates of overbank deposition. Information on contemporary rates of overbank sedimentation on the flood plains of Carpathian rivers is needed to resolve these uncertainties and to provide an improved understanding of the contemporary development of the channel and flood plain systems.

Against this background, and because of the general lack of quantitative evidence concerning contemporary rates of overbank deposition on the flood plains of Carpathian rivers, the authors have attempted to exploit the potential for using Chernobyl-derived radionuclides, and more particularly radiocaesium, to provide a preliminary assessment of the rates involved. Attention has been directed to several subcatchments of different scale within the basin of the Dunajec River. This area lies some 700 km west of Chernobyl and received substantial levels of fallout derived from the disaster.

THE STUDY BASIN

The investigations were undertaken on the flood plains of the Dunajec River and its tributaries, which are located in the mid-Beskid portion of its basin in Poland (Fig. 1). In this area the river is representative of a typical mountain river flowing from the Tatra Mountains, and channel slopes range from more than 5% in the small tributaries to 0.4% on the main river. In order to obtain information for a representative sample of flood plain environments, seven sites were selected within drainage basins of different size (cf. Table 1). These included the Homerka stream (19.6 km^2), the Lososina River (407 km^2), the Poprad River (1977 km^2) and the main Dunajec River itself (1982 km^2). These sites embraced a representative range of channel conditions, flood event frequencies and suspended sediment concentrations, which could be expected to influence rates of flood plain sedimentation. This region is characterized by low stability alluvial channels, with gravel- and boulder-floored flood channels, and a tendency for braided patterns to develop within the incising flood-channel during extreme events (cf. Froehlich *et al.*, 1972). The flood plains are typically developed on a spread of coarse-grained channel deposits, covered with a thin layer of fine overbank deposits. Flood plain widths are generally limited (several metres) and heights range from *c.* 0.3-2.5 m above low water level. Figure 2 depicts the cross section of a typical flood plain location. In most cases, the flood plain surfaces support grasses and clumps of willow and are used for grazing. The zones occupied by willows are frequently higher and evidence greater thicknesses of fine sediment, which may be related to their greater flow resistance and therefore increased potential for deposition (cf. Froehlich *et al.*, 1972). The highest parts of the flood plains are sometimes occupied by arable fields.

Rivers in the Dunajec basin attain bankfull discharge almost every year during floods caused by the spring melt or summer rainfall. Only a narrow zone of the flood plain, a few metres wide and close to the channel, is commonly inundated during the annual rainfall floods (cf. Fig. 2). Extreme floods resulting from several days of

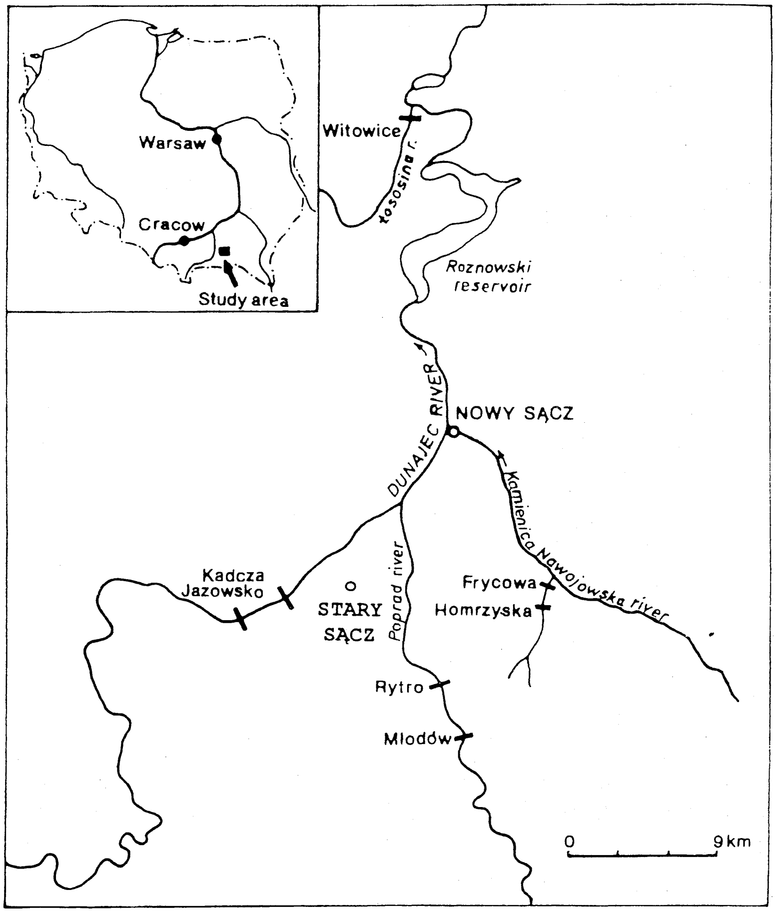

Fig. 1 The study area and the location of the flood plain study sites.

continuous rainfall, which will inundate the whole flood plain of the Poprad and Dunajec Rivers, occur with a frequency of 20-30 years. Such floods attain discharges of *c.* 800 m^3 s^{-1} and 2500 m^3 s^{-1} at the gauging stations at Stary Sacz (2065 km^2) and Nowy Sacz (4341 km^2) respectively. In the smaller tributary drainage basins, flash floods caused by localized intense rainfall occur almost every year and inundate large areas of the flood plain. The frequency of extensive flood plain inundation is thus substantially

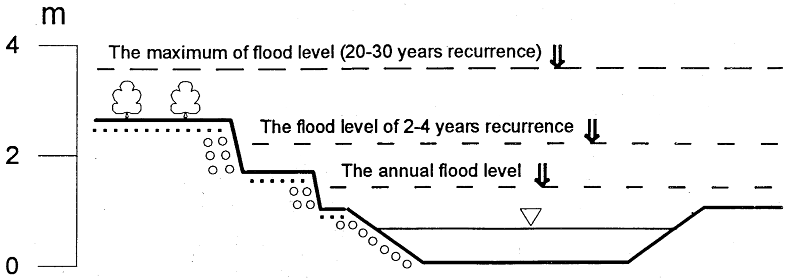

Fig. 2 A typical schematic cross section of the flood plain of a Carpathian river.

greater for the smaller drainage basins (e.g. Lososina River and the Homerka stream) than for the larger rivers (e.g. Dunajec and Poprad). There are also contrasts in the duration of inundation, since this is very short in the case of flash floods in the smaller basins (e.g. several minutes), whilst it may extend to several hours for the larger rivers.

Carpathian rivers transport relatively large amounts of suspended sediment during flood events (cf. Froehlich, 1982; Lajczak, 1989). In small drainage basins concentrations of suspended sediment during floods may exceed 20 000 mg l^{-1} because of the high rates of sediment mobilization associated with erosion along unmetalled roads and from gullies. In the larger Carpathian rivers, suspended sediment concentrations seldom exceed 10 000 mg l^{-1}. This contrast, coupled with that in the frequency of flood plain inundation noted above, exerts an important influence on the potential for overbank flood plain sedimentation, which will be further influenced by the microtopography and vegetation cover of the flood plain surface.

USE OF CHERNOBYL-DERIVED RADIOCAESIUM TO ESTIMATE RATES OF FLOOD PLAIN ACCRETION

The Chernobyl reactor accident that occurred on 26 April 1986, released large quantities of radioactive material, including radiocaesium, into the atmosphere, and this was subsequently deposited as fallout over many areas of Europe (cf. Dorr & Munnich, 1987). Deposition occurred primarily as wet fallout and was associated with the occurrence of rainfall at the time that the radioactive plume passed overhead. The spatial distribution of fallout deposition therefore reflected both air-mass trajectories and the incidence of precipitation during the period immediately after the accident. The study area received substantial inputs of radiocaesium, such that the existing inventories of caesium-137 in the soils of the area associated with bomb-derived fallout during the period extending from the late 1950s to the late 1960s were approximately doubled (cf. Froehlich *et al.*, 1993). Inputs of caesium-134, which was not present in the earlier bomb fallout, were also received and it has been suggested by many workers that the ratio of caesium-137 to caesium-134 activity in Chernobyl fallout was near-constant and approximately 1.6 (cf. Cambray *et al.*, 1987).

In most environments, radiocaesium reaching the soil surface is rapidly and strongly adsorbed by the fine fraction of the near-surface horizons (cf. Frissel & Pennders, 1983) and its subsequent transport occurs in association with sediment particles. It therefore provides a valuable tracer for erosion and sedimentation investigations (cf. Walling & Bradley, 1990). In the case of flood plain surfaces, Chernobyl-derived radiocaesium will have been adsorbed by the surface sediments and it provides a useful chronological marker for investigating rates of contemporary sedimentation. Sediment deposited after the Chernobyl incident may contain radiocaesium by virtue of its mobilization by erosion from surface areas of the upstream drainage basin, but the high concentrations associated with the surface existing at the time of the Chernobyl accident will commonly be clearly evident in the profile.

Figure 3 provides a typical example of the distribution of Chernobyl-derived caesium-134 in the soils and flood plain sediments of the study area, which clearly demonstrates its potential for estimating recent rates of overbank flood plain sedimentation. In this instance a comparison is made between a core collected from the flood plain of the Homerka stream near Frycowa and a core obtained from an adjacent area of

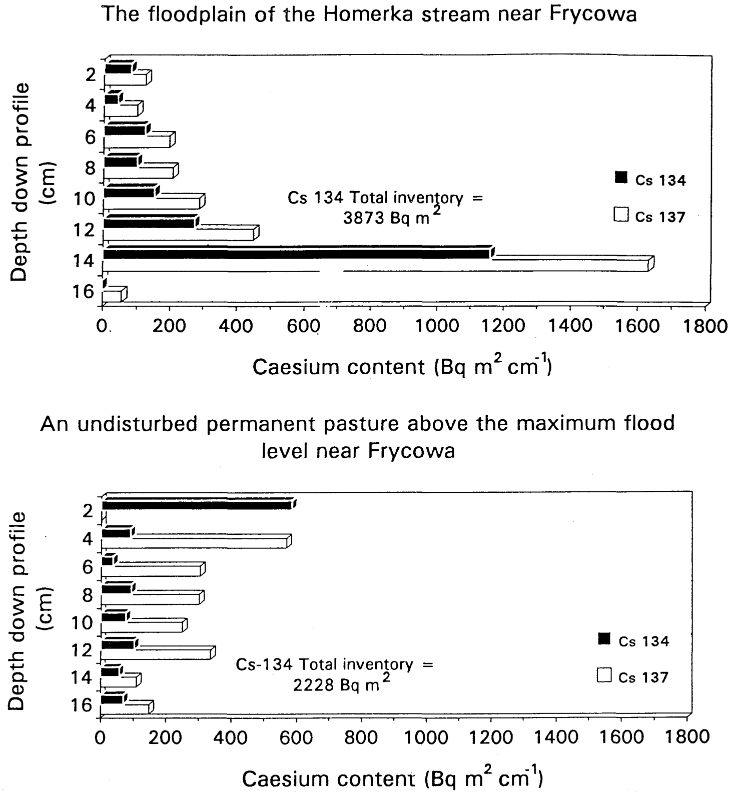

Fig. 3 The depth distribution of caesium-134 and caesium-137 in cores collected from the flood plain of the Homerka stream near Frycowa and an adjacent area of undisturbed pasture above maximum flood level.

undisturbed pasture above the maximum flood level. Both cores were collected in early 1989. In view of its short half-life (2.1 years), values of caesium-134 activity have been corrected to represent the levels that would have existed at the time of the Chernobyl accident in April 1986. In the case of the core collected from above the maximum flood level, the distributions of both caesium-137 and caesium-134 exhibit the typical exponential decline of activity with depth, which is characteristic of undisturbed pasture sites (cf. Walling & Quine, 1992). The ratio of the total inventory of caesium-137 to that of caesium-134 in this core (*c.* 2.7) confirms the presence of a substantial bomb-derived inventory within the profile. The significant downward migration of caesium-137 activity, which is probably associated with biological activity, reflects the substantial period of time (*c.* 30 years) that has elapsed since the main bomb-derived input. In the case of caesium-134, the majority of the inventory remains at the surface and some of the activity found at depth may reflect contamination associated with core retrieval, and counting errors associated with the low activity levels.

The depth distribution of radiocaesium in the core collected from the flood plain and illustrated in Fig. 3 differs greatly from that associated with the core collected from the pasture above the maximum flood level. The ratio of the total caesium-137 inventory to that of caesium-134 (*c.* 1.5) indicates that the radiocaesium is probably almost exclusively Chernobyl-derived and thus that the sediment is of very recent origin. This

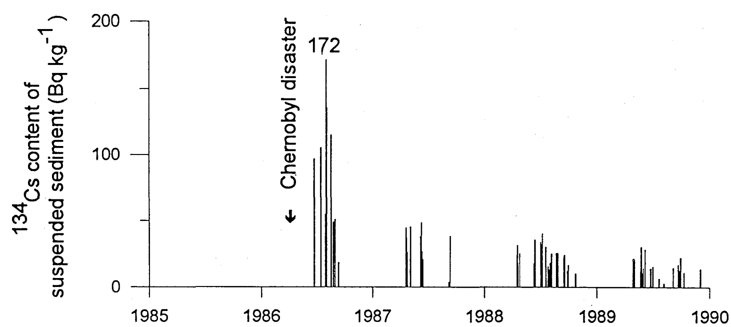

Fig. 4 Variation of the caesium-134 content of the (<0.063 mm) fraction of suspended sediment transported by the Homerka stream during the period 1985-1990. (Caesium-134 concentrations were zero prior to the Chernobyl disaster.)

is consistent with a relatively rapidly aggrading site, where the surface receiving bomb-derived fallout in the 1960s is now at a depth below that sampled by the core. The depth distribution of caesium-134 further confirms this interpretation. The maximum caesium-134 activity which exists at a depth of 12-14 cm can be interpreted as representing the surface exposed to fallout in April 1986 that has been subsequently buried by sediment deposited since that date. The exponential upward decline in both caesium-134 and caesium-137 activity above this level is consistent with the known decline in the concentrations of Chernobyl-derived radiocaesium in suspended sediment transported by the Homerka stream during the period following April 1986 (cf. Fig. 4). Most of the radiocaesium occurring above a depth of 12 cm therefore reflects the deposition of sediment-associated radiocaesium eroded from the upstream catchment and transported as suspended sediment by the Homerka stream.

If the caesium-134 inventories of the two cores are compared, and the additional inventory associated with the flood plain core (i.e. 1645 Bq m^{-2}) is assumed to represent caesium-134 associated with the deposition of suspended sediment transported by the river, the mean activity of the deposited sediment can be estimated to be approximately 14 Bq kg^{-1} (assuming a deposition depth of 12 cm and a bulk density of 1.0 g cm^{-2}). This value is in reasonable agreement with the values of caesium-134 activity measured in suspended sediment and presented in Fig. 4, since the deposited sediment is likely to be coarser than the transported sediment and therefore characterized by lower activity (cf. Walling & Woodward, 1992). The evidence provided by the vertical distribution of radiocaesium in this flood plain core can therefore be used to estimate a total depth of deposition of 12 cm between April 1986 and the time that the core was collected in early 1989, and therefore a mean annual deposition rate of *c.* 4 cm $year^{-1}$. This approach to quantifying recent rates of flood plain accretion was used to obtain estimates of contemporary rates of flood plain sedimentation at the selected sites in the study area.

FIELD AND LABORATORY METHODS

At each study site, representative sediment cores were collected from the flood plain itself and from an adjacent area of undisturbed pasture above the maximum floodwater level. The flood plain cores were collected from the middle zone of flood plain represented in Fig. 2 (i.e. 2-4 years frequency of inundation). The cores were *c.* 16 cm long and were sectioned into 2 cm increments. All samples were dried at 60°C, disaggregated and sieved to pass a 2-mm mesh prior to analysis of their caesium-134 and caesium-137 activity by gamma spectrometry. Gamma assay 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, and the activities of caesium-137 and caesium-134 were determined from the photopeaks produced at 662 and 605 keV respectively. Count times were typically 30 000 s, providing an analytical precision of *c.* ±10% and ±5% for caesium-134 and caesium-137 respectively.

RESULTS

All of the flood plain cores collected from the seven study sites showed evidence of recent deposition of fine sediment similar to that shown by the core obtained from the flood plain of the Homerka stream near Frycowa (Fig. 3). In all cases the maximum caesium-134 activity occurred at a significant depth below the surface, and in all but one instance the caesium-134 inventory associated with the flood plain core was substantially greater than that associated with the reference core collected from an adjacent area. In

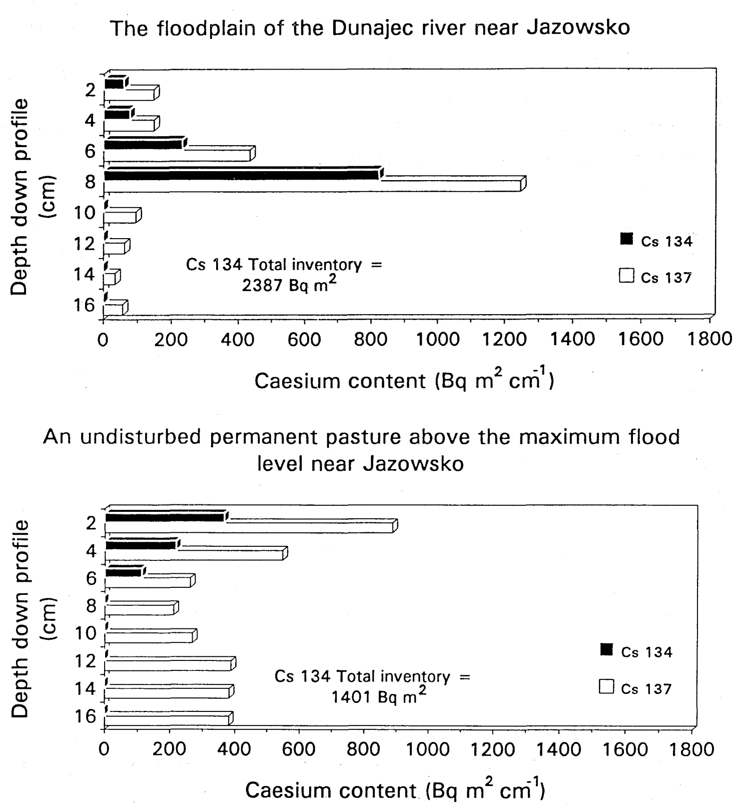

Fig. 5 The depth distribution of caesium-134 and caesium-137 in cores collected from the flood plain of the Dunajec River near Jazowsko and an adjacent area of undisturbed pasture above maximum flood level.

the one instance where this was not the case, the core failed to penetrate the entire depth of the caesium-134 profile and therefore did not represent the total inventory. Figure 5 illustrates the radiocaesium profiles associated with the core collected from the flood plain of the main Dunajec river near Jazowsko. In this case there is evidence of 6 cm of deposition since 1986, and a mean annual deposition rate of *c.* 2 cm $year^{-1}$ may therefore be estimated. The excess caesium-134 inventory associated with this core provides an estimate for the mean caesium-134 content of the deposited sediment of 16 Bq kg^{-1}, which is closely similar to the estimate presented above for the Homerka stream near Frycowa.

The estimates of mean annual deposition rates derived for the seven sites based primarily on the caesium-134 depth distribution, but also taking account of the magnitude of the excess caesium-134 inventory, are listed in Table 1. Although the limited number of cores collected precludes a definitive assessment of the relative rates of overbank deposition associated with the individual rivers, some tentative observations may be advanced. The highest rates of deposition are associated with the Homerka stream and Lososina River, which represent the two smallest rivers investigated. Both are known to have experienced extreme flash floods in 1986 and 1987 and these will have undoubtedly contributed to the high rates of deposition documented. In the case of the Poprad and Dunajec Rivers, which are similar in catchment area, the deposition rates are lower. This reduction may reflect the lower suspended sediment concentrations, as well as contrasts in the magnitude and frequency of overbank flooding. The reduced rates of deposition associated with the Poprad River, as compared to the Dunajec, is likely to reflect the lower frequency of significant overbank flood events that is associated with the former river.

Table 1 The study sites and the rates of recent overbank flood plain sedimentation estimated from radiocaesium measurements.

River	Location	Depth to 1986 surface (cm)	Average accretion rate (cm $year^{-1}$)
Homerka stream	near Homrzyska	2	0.7
Homerka stream	near Frycowa	12	4.0
Lososina River	near Witowice	>16	>5.0
Poprad River	near Mlodow	3	1.0
Poprad River	near Rytro	3	1.0
Dunajec River	near Jazowsko	6	2.0
Dunajec River	near Kadcza	5	1.7

PERSPECTIVE

The results presented in Table 1 and discussed above demonstrate that measurements of Chernobyl-derived radiocaesium in flood plain cores can provide a viable means of quantifying contemporary rates of overbank flood plain deposition in areas which received significant amounts of Chernobyl fallout. Because of its short half life (2.1

years), Chernobyl-derived caesium-134 will now be difficult, if not impossible, to detect and it will therefore also be impossible to apportion the total caesium-137 inventory into its Chernobyl- and bomb-derived components. However, the caesium-137 depth distribution should still provide a basis for identifying the level of the 1986 flood plain surface (cf. Figs 3 and 5) and there is considerable potential for applying this approach in future flood plain sedimentation investigations.

The results obtained for the study area are clearly limited by the small number of cores collected and the likely spatial variability of flood plain sedimentation in response to variations in microtopography, surface cover and local hydraulic conditions. A more intensive sampling programme would be required to provide a more rigorous assessment of recent rates of overbank sedimentation and of contrasts between individual rivers. Nevertheless, the data assembled serve to demonstrate that overbank flood plain accretion continues to represent a significant process in the contemporary development of the channel systems of Carpathian rivers, despite the evidence for recent incision. Overbank sedimentation must in turn also represent a significant conveyance loss in the transfer of suspended sediment from the headwaters to the lower reaches.

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 Mr Jim Grapes for undertaking the gamma spectrometry measurements.

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