Overbank sedimentation rates on the flood plains of small rivers in Central European Russia

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Abstract The spatial variation and temporal dynamics of overbank sedimentation rates were studied on the flood plains of five rivers located in different parts of the Central Russian Plain. The radioactive isotope ^{137}Cs was used as a tracer for quantification of sedimentation rates. At least two morphologically typical flood plain segments were investigated along each of the rivers studied, with one sediment section sampled depth-incrementally at each of the studied segments to determine the ^{137}Cs depth distribution. Both bomb-derived (1963–1964) and Chernobyl-derived (1986) ^{137}Cs peaks could be reliably identified in most of the sections investigated. Thus, the vertical distribution of ^{137}Cs in flood plain deposits permits the sedimentation rates for two relatively equal time intervals: 1964–1986 and 1986–present to be estimated. A clear trend of decreasing deposition rates is apparent for the last two decades. This can be attributed to recent land-use changes and climatic fluctuations.

Key words overbank sedimentation; flood plain; small rivers; drainage basin; ^{137}Cs; European Russia

INTRODUCTION

Flood plain sedimentation represents an important component of the sediment budget of most river basins (Walling *et. al.*, 1998). Studies of flood plain sedimentation rates also provide a good basis for evaluating the intensity of erosion processes within a basin. Information on changes in sedimentation rates over time can be used to assess the impact of various anthropogenic and natural factors in influencing the intensity of erosion rates and the variation of this impact in different sections of a fluvial system sediment cascade. For example, by measuring both the ^{137}Cs and unsupported ^{210}Pb ($^{210}Pb_{ex}$) content in flood plain sediment cores, Walling & He (1999) were able to derive estimates of deposition rates over the last 33 years (^{137}Cs) and 100 years ($^{210}Pb_{ex}$) for 21 sites on the flood plains of British rivers (Walling & He, 1999). After the Chernobyl incident in 1986 vast areas of Europe were contaminated by different radionuclides, including ^{137}Cs. As a result it is frequently possible to define two peaks of ^{137}Cs content in its vertical distribution curve in flood plain sediment profiles for rivers in Europe. One peak is related to the maximum bomb-derived ^{137}Cs fallout in 1963–1964 and the other to Chernobyl-derived fallout in May 1986. Hence, sedimentation rates for two relatively equal time intervals (1963–1986 and 1986–present) can be estimated based on application of the ^{137}Cs technique.

The most detailed study of overbank sedimentation rates for rivers in European Russia undertaken to date was carried out in the Kama and Middle Volga river basins. It was shown that the total depth of sediment attributable to the entire period of intensive cultivation for rivers in the Udmurtiya Region (right bank tributaries of the Kama River) varied within the range 30–120 cm (Perevozchikov, 1997). Annual overbank sedimentation rates were subsequently estimated as 2–6 mm year^{-1}, with some increase with increasing stream order. Direct monitoring of overbank sedimentation rates over a period of 11–13 years on some rivers in the Tatarstan Region (the Middle Volga River basin) produced results which showed a strong negative relationship with the percentage of forested area in the upstream drainage basin. Measured rates varied within the range 0.3–22.0 mm year^{-1} for river basins with forested areas ranging from 63% to 2%, respectively (Kurbanova, 1996). The duration of the entire period of intensive cultivation in the Tatarstan Region is 220 years and the total thickness of the associated deposition on river flood plains is 20–160 cm, with increases in some cases of up to 300–400 cm. Estimated mean annual rates of overbank sedimentation over the entire period of intensive cultivation ranged from 1.0–20.0 mm year^{-1}, which is comparable with recent rates documented using direct monitoring.

In European Russia, the last 20 years have been characterized by a noticeable decrease of spring flood levels, mainly because of warmer and less snowy winters. Simultaneously, the area of cultivated land has shown a decrease during the period 1991–2005, resulting in reduced volumes of soil loss from the tributary catchments. The effects of the recent recovery of agriculture and re-occupation of previously abandoned fields during the period 2006–2009 are unlikely to be already reflected in flood plain sedimentation records. The main goals of the present study is to investigate changes in mean annual overbank sedimentation rates for two time intervals (1964–1986 and 1986–present) and to document the spatial variability of overbank deposition at different locations within typical flood plain reaches, based on the use of the ^{137}Cs technique

STUDY SITES

The investigations focused on the flood plains of five rivers (Fig. 1) draining the Srednerusskaya Upland, namely, the Chern, the Konopelka and the Vorobza rivers (of the Dnieper River basin); the Turdei River (of the Don River basin), and the Zhusha River (of the Volga River basin). All these river basins are located in areas affected by Chernobyl ^{137}Cs fallout. Four of the study rivers are 4–5 Hortonian-order streams, with mostly cultivated drainage areas. Only the Zhusha River has a relatively large basin area with diverse land-use characteristics (Table 1) upstream from the sampling locations. Ponds or small reservoirs are very typical in each of the studied river basins, but in the Vorobza River valley a large reservoir was constructed in the middle 1980s.

The underlying bedrock of the study basins is dominated by Devonian limestones in the Turdei and Zusha river basins, by interbedded terrigenous Cretaceous chalks, sandstones and sands in the Chern River, and by Carboniferous limestones in the Vorobza and Konopelka river basins. In all areas, the solid bedrock is overlain by Quaternary drift, dominated by loessial loams with thicknesses of up to 10–30 m. Mean annual precipitation across the region shows a

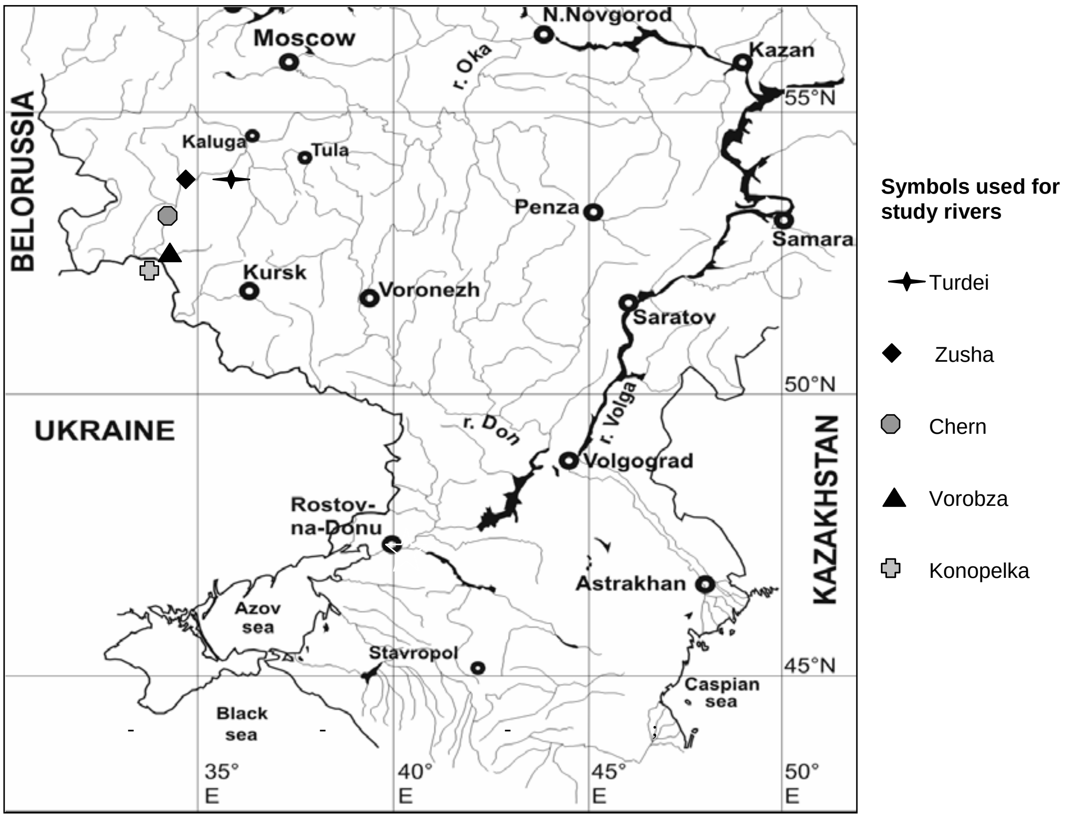

Fig. 1 Location of the case study river basins within European Russia.

Table 1 General characteristics of the study river basins.

River	Total basin area (km^2)	Maximum topographic range (m)	Area of cultivated land (%)		Number of reservoirs in main river valley	
			1964–1986	1986–2008	1964–1986	1986–2008
Turdei	420	≈100	65–75	55–60	1	1
Zusha	6793	≈150	54–60	40–50	0	0
Chern	435/133[(a)]	≈110	65–70	35–45	0[(b)]	0[(b)]
Vorobza	232	≈110	70–75	65–70	0	1
Konopelka	54	≈100	75–85	55–60	2	2

[(a)]Total drainage basin area and investigated drainage area upstream from the reservoir of the Mikhailovskiy iron ore mining and processing enterprise.

[(b)]Upstream from the reservoir of the Mikhailovskiy iron ore mining and processing enterprise.

slight decrease from about 600 mm for the Turdei River basin to about 500 mm for the Konopelka River basin (Fig. 1).

METHODS

The temporal variability of flood plain sedimentation rates and their local spatial patterns within different flood plain segments were assessed using ^{137}Cs of both bomb-derived and Chernobyl origin. ^{137}Cs is an artificial fallout isotope, which is strongly absorbed by surface soil particles immediately after its fallout from the atmosphere (Ritchie *et al*, 1990).

Depth-incremental samples (2–5 cm depth intervals from a 15 × 15 cm surface area) were collected from sediment sections dug at typical locations on each of the studied flood plain segments. In addition, from 6 to 10 bulk core samples were collected in order to document local variability of ^{137}Cs inventories, reflecting lateral variation of overbank sedimentation rates, from five flood plain segments of the Chern and Turdei rivers. The bulk samples were collected from depth intervals 0–30 and 30–60 cm (where possible) using an 8.2-cm diameter steel tube driven into the flood plain surface. The location of each sampling point and the microtopography of the flood plain segments were surveyed using a digital tacheometer (Leica Smart Station TPS 1200).

Subsequent laboratory treatment of the ^{137}Cs samples involved oven-drying, grinding, separation of the <2 mm fraction and homogenization of sub-samples for gamma-analysis. The ^{137}Cs activity was measured at 661.66 keV, using a high-resolution, low-background, hyperpure germanium coaxial gamma-ray detector (produced by the Institute of Physical and Technical Problems, Dubna, Russia).

Depth distributions of ^{137}Cs have been constructed for each of the studied flood plain segments basing on the gamma analysis of depth-incremental samples, in order to infer the recent sediment stratigraphy and to assess the variations in overbank deposition rates. It has been assumed that vertical migration of the ^{137}Cs has been negligible and that the peak with maximum ^{137}Cs activity corresponds to the flood plain surface in 1986 (the Chernobyl fallout). In the study area, the component of the total ^{137}Cs inventory attributable to Chernobyl fallout greatly exceeds that for bomb fallout. The approach developed by Walling and He (e.g. Walling & He, 1993) was used for converting ^{137}Cs inventories into estimates of accumulation rates for the bulk sampling points:

$$R_i = R_s \times \frac{A_i - A_{ref}}{A_s - A_{ref}} \tag{1}$$

where: R_i is accumulation rate at point of bulk sampling, cm year^{-1}; R_s is accumulation rate obtained from analysis of depth-incremental sampling core, cm year^{-1}; A_i is the ^{137}Cs inventory at point of bulk sampling, Bq m^{-2}; A_s is the ^{137}Cs inventory for the depth-incremental sampling core, Bq m^{-2}; and A_{ref} is the ^{137}Cs reference inventory for the specific flood plain study site, Bq m^{-2}.

The ^{137}Cs inventory associated with that part of the sediment profile extending downwards from the 1986 flood plain surface (including the Chernobyl fallout peak) to the base of depth-incremental sampling at each flood plain study site was used to represent the reference inventory. Use of this value may result in overestimation of the initial ^{137}Cs atmospheric fallout input and consequent underestimation of sedimentation rates, because it includes both total ^{137}Cs fallout (bomb- and Chernobyl-derived) and additional ^{137}Cs input associated with sediment deposition during the pre-Chernobyl period. However, as indicated above, all our study areas are characterized by substantial inputs of Chernobyl-derived fallout and a low proportion of bomb-derived ^{137}Cs (generally less than 10%). Thus, the discrepancies associated with using reference inventory values obtained from the flood plain ^{137}Cs depth distributions are likely to be negligible. On the other hand, potential sources of overestimation of sedimentation rates include vertical migration of the ^{137}Cs peaks and general difficulties of locating precisely the 1964 bomb fallout ^{137}Cs peak in some of the sediment depth profiles under consideration.

RESULTS AND DISCUSSION

Analysis of the ^{137}Cs vertical distribution curves for the studied flood plain sediment depth profiles allowed reliable identification of the ^{137}Cs peaks related to both 1964 (maximum bomb-derived fallout) and 1986 (Chernobyl fallout) in most cases. Russian observations indicate that, as in other areas of the Northern Hemisphere, the maximum bomb-derived ^{137}Cs fallout occurred in 1963. However, the difference between the fallout out in 1964 and 1963 was relatively small (about 15%). Taking into consideration that the winter of 1963 experienced snow cover from the end of October until the spring flood in April 1964, most of the fallout during that period would not have reached the soil until spring 1964. Furthermore, most overbank deposition occurs during the spring flood and only limited deposition is likely to have occurred between the spring flood of 1963 and that of 1964. For these reasons the bomb fallout peak in the flood plain sediment cores has been ascribed to 1964. It is interesting to note that for most of the study rivers values of peak activity concentration for the 1964 peak are around 20 Bq kg^{-1} (Fig. 2), confirming the relatively uniform global ^{137}Cs fallout over European Russia (Silantiev & Shkuratova, 1983). The only exception is provided by the Turdei River, where the 1964 ^{137}Cs peak activity concentration is about 40 Bq kg^{-1}, which can probably be explained by a regional increase in bomb-derived fallout. The variability of the ^{137}Cs activity concentration associated with the Chernobyl peak is substantially higher (Fig. 2), as one would expect. This reflects the high spatial variability of the Chernobyl radioactive fallout, which was largely associated with one or two rainfall events during the period extending from the end of April to the first half of May, 1986 (Izrael, 1998).

The depth distributions of ^{137}Cs in the flood plain sediment depth profiles were used to estimate overbank sedimentation rates at each sampling point for the two time intervals (Table 2). The average rate of sedimentation ($R_0(t)$, mm $year^{-1}$) for the period 1986 to present was calculated following (He & Walling, 1996):

$$R_0(t) = \frac{M_{1986}(t)}{T_{1986}} - V \quad (2)$$

where: $M_{1986}(t)$ is depth of the 1986 ^{137}Cs peak, mm; T_{1986} is time from 1986 to the present, year; and V is vertical migration rate, mm $year^{-1}$.

Where the 1964 peak could be identified in the ^{137}Cs vertical profile, the average rate of sedimentation ($R_1(t)$, mm $year^{-1}$) for the period 1964–1986 was also calculated as:

$$R_1(t) = \frac{M_{1964}(t) - M_{1986}(t)}{T_{1964-1986}} \quad (3)$$

where: $M_{1964}(t)$ is depth of the 1964 ^{137}Cs peak, mm; $T_{1964\text{-}1986}$ is time from 1964 to 1986, year.

It has been assumed that vertical migration rates of ^{137}Cs remained relatively uniform for both time intervals. Based on direct observations of the vertical migration of ^{137}Cs, Shagalova *et al.*

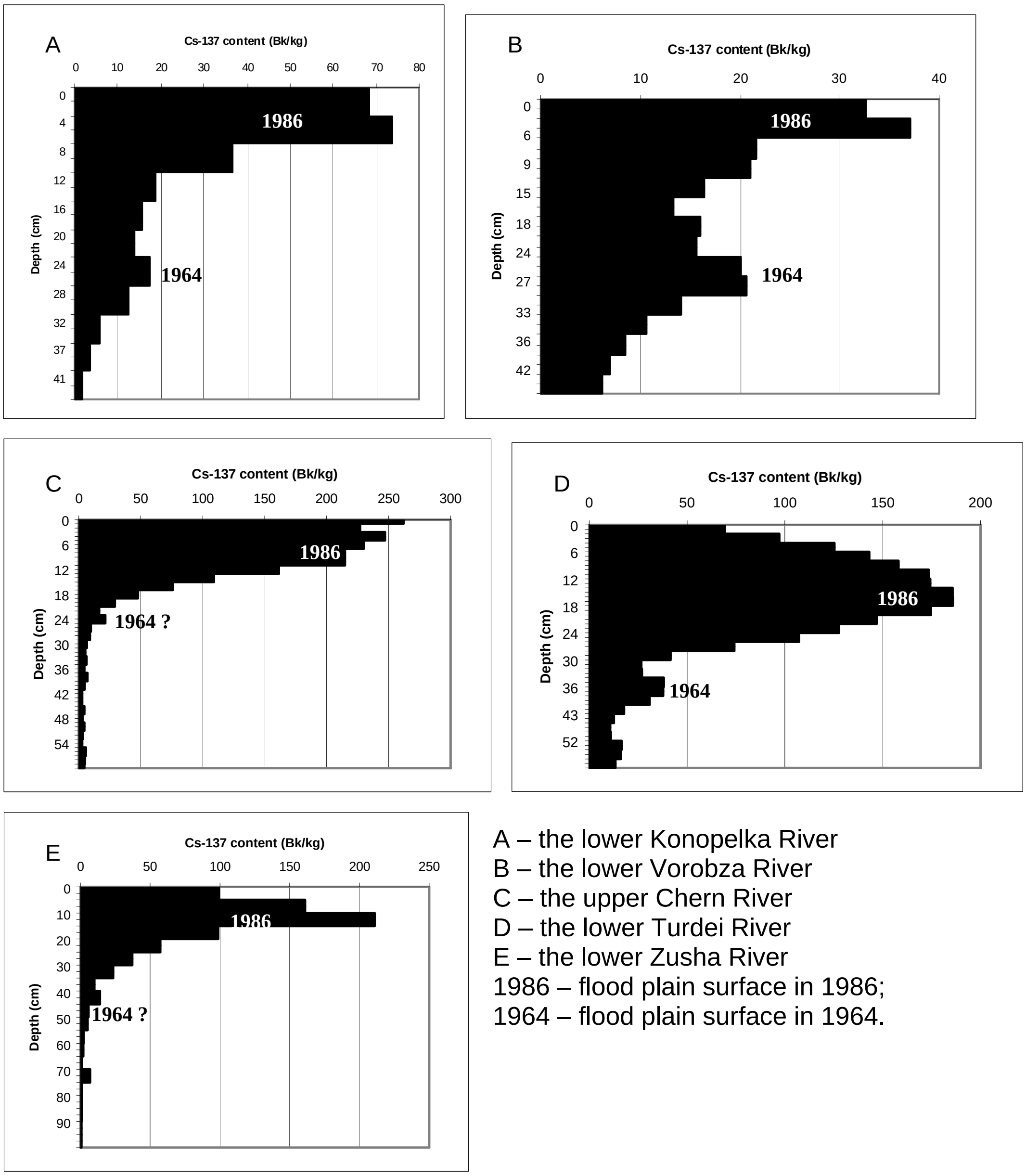

Fig. 2 Depth distributions of ^{137}Cs for the sectioned flood plain sediment cores.

Table 2 Mean overbank sedimentation rates (mm year^{-1}) for the two time intervals considered based on ^{137}Cs vertical distribution curves.

River	Turdei		Zhusha		Chern		Vorobzha		Konopelka	
Time interval	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986	1986–2008	1964–1986
Upper cross-section	1.6–2.0	Not available	4.3–4.7	17.9–18.3	2.1–2.5	7.5–7.9	1.2–1.6	Not available	2.0–2.4	7.0–7.4
Extent of decrease	–		4.0		3.3		–		3.3	
Lower cross-section	6.8–7.2	7.9–8.3	4.3–4.7	13.4–13.8	2.2–2.6	7.9–8.3	1.2–1.6	10.7–11.1	1.6–2.0	8.9–9.3
Extent of decrease	1.15		3.0		3.4		7.8		5.0	

(2000) reported that migration rates decreased from an initial value of 0.4 mm per year to 0.2 mm per year after 15 years and subsequently stabilized. This is consistent with the convection-diffusion model of vertical ^{137}Cs migration proposed by Prokhorov (1982).

For the 1964–1986 period the highest sedimentation rate was found for the Zusha River flood plain. This can be explained by the larger size of both the Zusha River itself and its drainage basin. The values of sedimentation rate for this time interval for all the other rivers studied are relatively similar, with a maximum for the Vorobza River, where the percentage of arable land area was highest (Table 1). For the time period extending from 1986 to the present, sedimentation rates for all the flood plain segments studied showed a significant decrease, in most cases by 3–4 times. The main reasons for this decrease relate to the following: (a) warmer and less snowy winters with a decrease in the thickness of the winter-frozen topsoil layer promoting lower spring snowmelt runoff and associated flood levels; (b) the gradual increase of flood plain levels caused by continuous surface aggradation due to overbank sedimentation over the preceding period since the onset of intensive cultivation; and (c) the abandoning of a significant percentage of previously cultivated land during the period of general economic disorder following the collapse of the former USSR (Table 1). The construction of the comparatively large reservoirs in the middle reach of the Vorobza River in 1987 is considered to be the main reason for the sharp decrease of overbank sedimentation rates on its flood plain (by 7.8 times between 1964–1986 and the 1986–present time periods, Table 1).

The decrease of sedimentation rates for the middle reach of the Turdei River over the periods considered is the smallest for all the rivers studied. It is likely that the large-scale road works carried out during the last five years associated with major refurbishment of the adjacent Moscow-Don motorway, which crosses the river basin, became a significant additional source of sediment. Its contribution could have been sufficiently large to compensate for the effect of decreased soil losses from the abandoned cultivated lands. In addition, long and active bottom gullies are very typical of small dry tributary valleys in the Turdei River basin. Their presence substantially increases the effective connectivity of the slope runoff and stream network sections of the fluvial sediment cascade. Sediment directly derived from the growth of such gullies also provides an important additional contribution to the sediment load of the main river. The delivery of gulley-derived sediment into the main river valley bottom is much more efficient in comparison to the delivery of soil particles eroded from cultivated slopes. These suggestions are confirmed by the significant decrease of ^{137}Cs activity concentrations in the upper layers (above the Chernobyl peak) of the Turdei River flood plain deposits (Fig. 2D). It must also be borne in mind that the Turdei River basin is the most northeastern of those considered in this study (Fig. 1). As such, it is likely that the decrease of winter-frozen topsoil layer thickness is not so marked in that area. The decrease of cultivated land percentage is smallest in this basin, when compared with the other river basins (Table 1).

Examples of local lateral variation of overbank deposition rates over the individual flood plain segments studied are shown on Figs 3 and 4. For the Turdei River middle reach, the highest deposition rates (9.8 mm year^{-1}) were recorded in the deepest part of the depression marking the former channel location and situated in the middle of the studied flood plain segment (Fig. 3). High variability of deposition rates (2.4–9.8 mm year^{-1}) is observed within this flood plain segment.

The local spatial variability of overbank sediment deposition rates in the upper reaches of the Turdei River valley bottom is illustrated in Fig. 4. This flood plain segment is characterized by much less variable topography than that represented on Fig. 3. A comparatively strong negative correlation between overbank sedimentation rate and relative flood plain elevation is observed. The point located in the middle of the segment (6.9 mm year^{-1}) represents a single exception. It is likely that this reflects an additional sediment input derived directly from the adjacent sideslope, which is cultivated in the upper part and used as permanent pasture in the lower part. Similar relationships between overbank deposition rates and flood plain microtopography have been observed for the three flood plain segments studied for the Chern River.

Mean overbank deposition rates are relatively uniform along the small rivers studied in this investigation (Table 3). It confirms that soil loss and sediment delivery from cultivated slopes is the main source of the suspended sediment load for river basins with a high percentage of arable land.

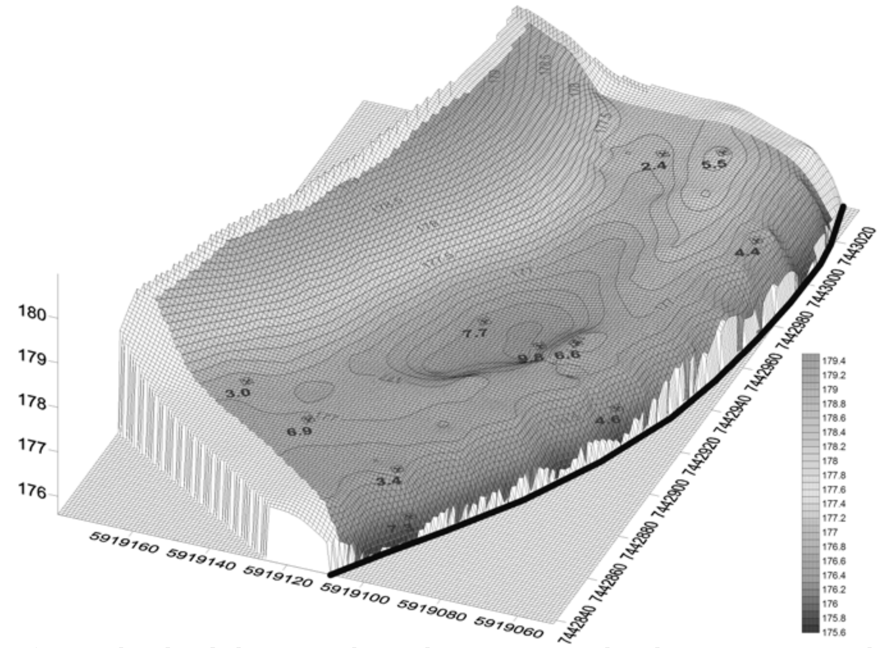

Fig. 3 The detailed topography and point-estimated sedimentation rates obtained from the ^{137}Cs measurements for the middle reach of the Turdei River.

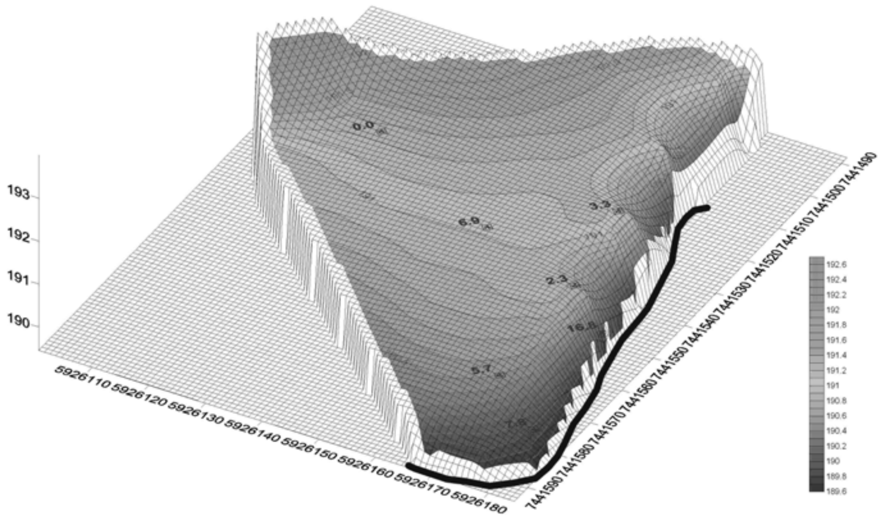

Fig. 4 The detailed topography and point-estimated sedimentation rates obtained from the ^{137}Cs measurements for the upper reach of the Turdei River.

Table 3 Mean and extreme values of overbank deposition rate (mm year^{-1}, for the 1986-present time period) for typical flood plain segments along the Chern and Turdei rivers.

	The Chern River			The Turdei River		
	Mean	Min	Max	Mean	Min	Max
Upper reach	1.9	0.4	4.3	6.1	2.3	16.9
Middle reach	2.3	1.2	4.3	5.6	2.4	9.8
Lower reach	2.2	0.3	5	–	–	–

DISCUSSION

Deposition of sediment-associated nutrients and contaminants in sediment sinks is a significant environmental problem in terms of both their storage and the potential for their subsequent remobilization (Walling, 1999). Since at least the 1950s, intensification of industrial and agricultural development has promoted active increase of overbank deposition on small river flood plains, simultaneously with increased pollution of their drainage basins. Application of ^{137}Cs measurements for dating recent flood plain sediments in areas contaminated by Chernobyl fallout can provide a means of quantifying aggradation rates and changes in sediment-associated pollutant loadings for the three time intervals: 1954–1964, 1964–1986 and 1986 to the present day. Most of the European territory of Russia experienced measurable contamination by ^{137}Cs after the Chernobyl incident. Selection of typical small river basins across Europe could provide the basis for a regional assessment of the dynamics of flood plain sediment storage and associated pollutant accumulation, involving the combined application of geomorphic mapping of river valley bottoms, dating of recent flood plain sediment using the ^{137}Cs technique, and geochemical sampling of overbank sediment layers belonging to different time intervals. The natural radionuclide tracer $^{210}Pb_{ex}$ can be potentially considered as an additional chronometer to cover a longer time period and thereby provide additional temporal markers.

CONCLUSION

Both bomb-derived and Chernobyl-derived ^{137}Cs can be applied to evaluate the dynamics of overbank sedimentation rates on small river flood plains in areas contaminated by Chernobyl fallout. However, in some cases it may not be possible to identify the 1964 ^{137}Cs peak because of the superimposition of the substantially larger inventories of Chernobyl-derived ^{137}Cs onto the previously deposited bomb-derived ^{137}Cs fallout. It has been found that overbank flood plain sedimentation rates have decreased considerably on most of the study rivers between the 1964–1986 and the 1986–present day periods. This trend can be explained as a combined effect of recent climatic fluctuations and the abandoning of a significant part of the previously cultivated land. It is difficult to quantify the relative contribution of each of the above influences. However, it is likely that the effect of warmer and less snowy winters with reduced snowpack and decreased thickness of the seasonally frozen topsoil layer occurring during the last two decades is more important.

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