# Quantification of the sediment budget of a river basin, based on reconstruction of the post-fallout redistribution of Chernobyl particle-bound $^{137}$Cs

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**Abstract** Quantitative assessment of the sediment budget of a fluvial system is a key approach to understanding its geomorphic behaviour and an essential tool for investigating the redistribution of particle-bound contaminants along the sediment cascade. Here, we present a study involving the application of several independent approaches for quantifying the post-fallout (1986–2009) redistribution of Chernobyl particle-bound $^{137}$Cs and the basin-scale sediment budget for the River Plava basin situated in the northern part of the Srednerusskaya Upland (Central European Russia). The techniques employed include $^{137}$Cs-based sediment tracing, two soil erosion models and the analysis of soil profile morphology. The results show that most of the sediment originating from human-accelerated soil erosion on cultivated slopes is redeposited on the uncultivated lower parts of the slopes or in the bottoms of infilled gullies, hollows and 1–3rd order valleys. The River Plava valley itself represents a system dominated by efficient transport, with very limited floodplain sediment storage. The $^{137}$Cs-contaminated sediment export from the River Plava basin outlet exerts a significant impact on the River Upa. Its floodplain sediment contamination by $^{137}$Cs downstream of the River Plava mouth increases by almost an order of magnitude.

**Key words** fluvial system; sediment budget; sediment sources and sinks; $^{137}$Cs; human-accelerated soil erosion; Central European Russia

## INTRODUCTION

Deforestation, agricultural development, urbanization, hydropower development, river regulation, mining and other human activities can profoundly affect the processes of erosion and deposition in river systems and may cause considerable changes, both in sediment redistribution within river basins and in sediment export into higher-order fluvial systems. In addition to causing changes of rates and patterns of geomorphic processes, intensive industrial and agricultural development during the last 150–200 years has resulted in significant contamination of various landscape components. It is now widely recognized that a significant proportion of the contaminants found in natural landscapes, such as radionuclides, heavy metals, toxic organic substances, etc., is redistributed in association with fine-grained sediment (Sterckeman *et al.*, 2002; Carter *et al.*, 2003; Walling *et al.*, 2003). Quantitative assessment of the sediment budget of a fluvial system is therefore a key approach for understanding both its geomorphic behaviour and the spatiotemporal patterns of particle-bound contaminant redistribution along the sediment cascade.

The artificial radionuclide caesium-137 ($^{137}$Cs) has long been employed as a tracer of soil and sediment redistribution (Ritchie *et al.*, 1974; Walling *et al.*, 1999; Belyaev *et al.*, 2003, 2005, 2009, 2011; Golosov *et al.*, 2008, 2010). Due to specific features of its environmental behaviour, the tracer can also be effectively employed for modelling the fate of other contaminants preferentially fixed by clay minerals in the fine fraction of sediment. This paper presents the results of applying several independent approaches for quantifying the post-fallout (1986–2009) redistribution of Chernobyl $^{137}$Cs and the basin-scale sediment budget for the River Plava basin situated in the northern part of the Srednerusskaya Upland (Central European Russia). The study was based on detailed investigations of sediment redistribution within three selected key sub-catchments of different size and sedimentation on the River Plava floodplain.

## STUDY SITE

The River Plava (with a drainage basin area of about 1856 km$^2$, and a main river length of ~87 km) is one of the main left bank tributaries of the River Upa (within the Upper River Oka basin). It drains the most elevated area of the northern part of the Srednerusskaya Upland, characterized by rolling hill topography, densely and deeply dissected by valleys and gullies (elevation up to 290 m ASL, elevation range up to 80–90 m). The headwaters of the basin are situated in the southern part of the Tula Region (Fig. 1). The underlying geology is characterized by relatively resistant sedimentary bedrock (limestones and marls of the Lower Carboniferous), overlain by a thin (up to a few metres) mantle of Late Quaternary loess. The general flow direction of the River Plava is from the south to the north. It flows into the River Upa near the town of Krapivna. The basin gradually widens in the same direction and is asymmetric in planform. All left bank tributaries are substantially longer than the respective right bank tributaries, as the main river valley is significantly shifted towards the east from the geometric axis of the basin (Fig. 1).

The natural landscape represents the transition zone between the deciduous (broad-leaved) forest and forest-steppe landscape zones. The soil cover is therefore represented by a complex alternation of grey forest and chernozem soils. The latter are dominant, particularly within the River Plava basin. Cultivated land represents the predominant land use within the River Plava basin. Forested areas are limited in extent and scattered over the basin area. Documentary evidence indicates that intensive cultivation of the area began in the 17th century, with the area of arable land exceeding 60% of the total basin area around 1690 (~360 years ago). The maximum percentage of arable land was reached during the 1970s, when up to 80% of the basin area was cultivated. The period of economic disorder following the collapse of the former Soviet Union was

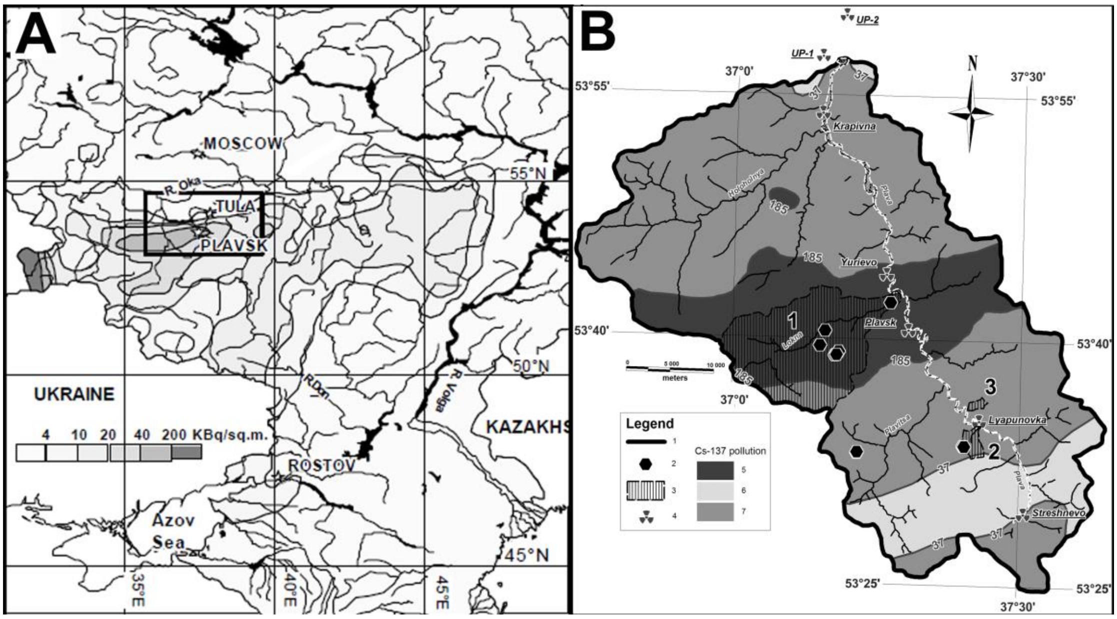


**Fig. 1** (A) Location of the study area within European Russia and a generalized map of Chernobyl-derived $^{137}$Cs contamination (based on Izrael, 1998). (B) Map of the River Plava basin showing the initial Chernobyl-derived fallout $^{137}$Cs (based on Izrael, 1998) and the location of the study sites. Legend: 1) the River Plava basin boundary; 2) $^{137}$Cs baseline fallout reference sampling sites; 3) the key sub-catchments (1 – the River Lokna; 2 – the Lyapunovka dry valley; 3 – the Sviatoy Istochnik dry valley); 4) the floodplain sampling sites. Levels of initial $^{137}$Cs fallout: 5) <37 kBq m$^{-2}$; 6) 37–185 kBq m$^{-2}$; 7) >185 kBq m$^{-2}$.

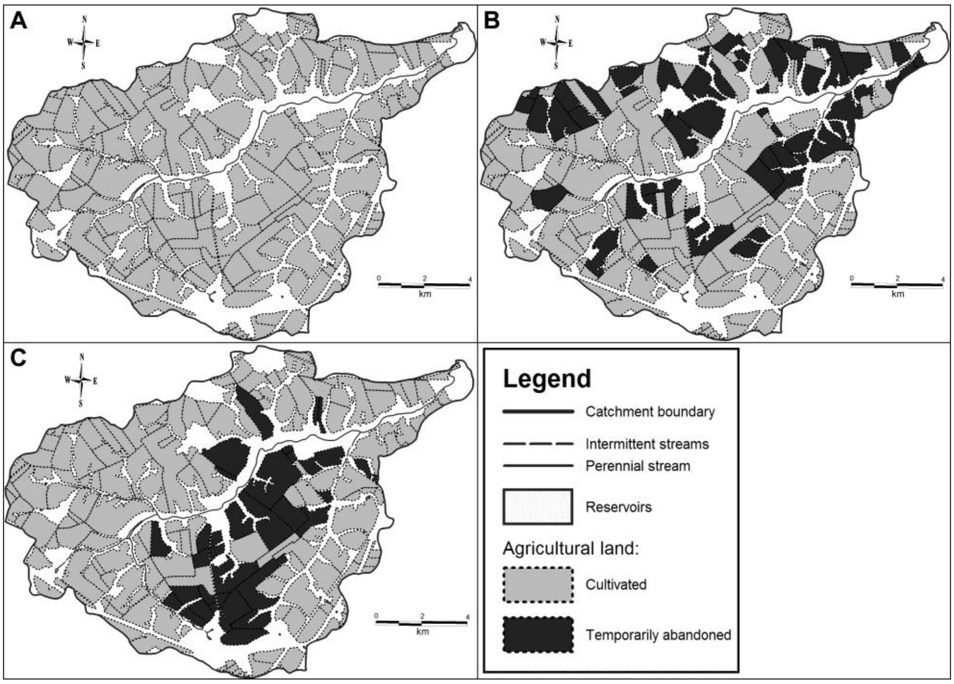


**Fig. 2** Reconstruction of the area of cultivated and abandoned land in the River Lokna basin during the period 1990–2009: (A) no abandoned fields in 1990; (B) cultivated and abandoned fields in 2002 (from Landsat ETM satellite images); (C) cultivated and abandoned fields in 2009 (direct field observations).

**Table 1** General characteristics of the River Plava basin and the three sub-catchments selected for detailed investigation of contemporary sediment and sediment-associated $^{137}$Cs redistribution.

| Basins, number on Fig. 1(B) | Drainage area ($km^2$) | Main river length (km) | Max Hortonian order | Cultivated area, $km^2$ / % | | |
|---|---|---|---|---|---|---|
| | | | | 1990 | 2002 | 2009 |
| Plava | 1856.0 | 87.0 | 7 | 1399.4 / 75.4 | 979.6 / 52.8 | 1080.2 / 58.2 |
| Lokna (1) | 177.1 | 18.2 | 5 | 126.6 / 71.5 | 87.8 / 49.6 | 98.6 / 55.7 |
| Lyapunovka (2) | 6.2 | 0.0 | 3 | 4.9 / 79.0 | 3.5 / 56.5 | 4.9 / 79.0 |
| Sviatoy Istochnik (3) | 1.9 | 0.0 | 2 | 1.3 / 68.4 | 1.3 / 68.4 | 1.3 / 68.4 |

associated with abandonment of substantial areas of cultivated land, especially from 1991 to 2005. During the last few years, part of the previously abandoned land has been returned to cultivation. However, up to 10–15% of the area previously cultivated still remains abandoned. The dynamics of the changes in the area of cultivated land during the last decades have varied for different parts of the basin, as illustrated by examples from the case study catchments (Fig. 2, Table 1).

The central part of the basin near the town of Plavsk, the local administrative centre, was severely contaminated by $^{137}$Cs fallout following the Chernobyl nuclear power plant accident (the so-called Plavsk $^{137}$Cs hotspot). Especially high levels of initial contamination (up to ~600 kBq $m^{-2}$) were detected within the River Lokna basin – one of the main left bank tributaries that flows into the River Plava at Plavsk town (Fig. 1).

## METHODS

Three key sub-catchments were selected for detailed investigation of soil redistribution on arable hillslopes, sediment delivery to the fluvial network and sediment redistribution within 1–3 Hortonian order dry valley bottoms. The locations of the sub-catchments are shown on Fig. 1(B) and their general characteristics are presented in Table 1. Sedimentation on the River Plava floodplain was studied at five locations, also shown on Fig. 1(B). In addition, depth-incremental sampling of the River Upa floodplain sediment was carried out at two sections located several kilometres upstream and downstream from its junction with the River Plava, in order to evaluate the impact of severely contaminated sediment exported from the latter.

In the study area, the component of the total $^{137}$Cs inventory attributable to Chernobyl fallout greatly exceeds that of bomb fallout. The latter generally represents 1–10% of the total radiocaesium inventory for sampling sites within the River Plava basin (Golosov *et al*., 1999). Therefore, estimates of soil and sediment redistribution rates obtained using the $^{137}$Cs data were based on the assumption that the pre-Chernobyl fallout inventory was negligible and relates to the post-1986 period.

An integrated approach, involving a combination of several independent techniques, has been employed to investigate sediment and sediment-associated contaminant redistribution within the key sub-catchments. The field-based techniques employed included the use of $^{137}$Cs for sediment tracing (radiocaesium method – RCM) and comparison of soil profile morphology to estimate soil redistribution rates (SPM). Detailed descriptions of the techniques are available elsewhere (Walling *et al*., 1999; Belyaev *et al*., 2005, 2009; Golosov *et al*., 2008, 2010). It is important to note that, unlike RCM, the SPM technique provides estimates of long-term average soil redistribution rates for the entire period of cultivation, integrating the influence of all the processes involved, as reflected by the spatial variability of the soil profile structure caused by its truncation or aggradation. The $^{137}$Cs sampling program included: (1) the River Plava floodplain sampled at five main sites (15 detailed sectioned cores and 22 cores sectioned into coarser 10-cm depth increments, and 19 bulk cores; (2) the bottoms of the 1–3rd order dry valleys within the key sub-catchments (19 detailed sectioned cores and 51 cores sectioned at 10-cm intervals); (3) 12 hillslope transects within the key sub-catchments (10 detailed sectioned cores and seven cores sectioned at 10-cm intervals from depositional locations and 60 bulk cores collected from erosional locations); (4) six undisturbed reference locations within the Lokna and Lyapunovka key sub-catchments (six detailed depth-incremental profiles and 72 bulk cores). In addition, previously analysed data from five undisturbed reference locations and several hillslope transects within the Lokna catchment (Fig. 1(B)) (Panin *et al*., 2001; Belyaev *et al*., 2003) were also used in this study.

Subsequent laboratory processing of the $^{137}$Cs samples involved oven-drying at 105°C, grinding, sieving to <2 mm 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 with a maximum relative error of the isotope activity determination of ±5–10%. Sample preparation, treatment and $^{137}$Cs activity measurements were carried out at the Laboratory of Soil Erosion and Fluvial Processes, Faculty of Geography, Lomonosov Moscow State University.

Information for the SPM-based assessment of soil and sediment redistribution rates within the key sub-catchments was obtained from detailed descriptions of soil pits located in most cases adjacent to the $^{137}$Cs sampling points (70 pits within the 1–3rd order dry valleys, 71 pits on hillslopes and 6 pits at undisturbed reference locations). In order to facilitate reliable extrapolation of the results from individual slope transects covered by field-based techniques to larger areas, two erosion models have been applied. The LANDSOIL model (Landscape design for Soil conservation under soil use and climate change model) represents an upgraded version of the STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management) model, which is an expert-based runoff and erosion model that operates at the small catchment scale (0.1–1000 km$^2$) and can generate rates of water erosion (transport-limited), soil translocation by tillage within the cultivated area (based on the approach developed by Govers *et al*., 1994) and sediment redeposition both within slopes and in the bottoms of small valleys (Cerdan *et al*., 2002a,b,c; Souchère *et al*., 2003; Evrard *et al*., 2009, 2010). The empirical-mathematical model (EMM) utilizes a combination of the USLE-based approach for estimating rainfall-induced sheet erosion (Wischmeier & Smith, 1965; Renard *et al*., 1994) and the model developed by the Russian State Hydrological Institute for estimating sheet erosion from snowmelt runoff (Bobrovitskaya, 2002). It was specially designed for application under Russian conditions and is provided with a large spatially distributed dataset of coefficients (Larionov *et al.*, 1998; Belyaev *et al.*, 2005). This model, however, cannot estimate within-slope sediment redeposition and cannot be applied to valley bottoms.

## RESULTS AND DISCUSSION

### Soil redistribution on arable hillslopes and sediment delivery to valley bottoms

The initial Chernobyl-derived $^{137}$Cs fallout contamination of the River Plava basin is characterized by high spatial gradients over limited distances, caused by the pattern of air mass transport and rainfall during the several days after the power plant explosion (Fig. 1). Hence it was necessary to have several undisturbed reference sites for assessment of the variability and spatial trend of local fallout. In total, information from 11 reference locations has been used, six of which were sampled specially for this project in 2011, and the other five sampled previously during earlier studies (Fig. 1B). It has been found that the local coefficient of variation for each of the reference sites does not exceed 20% and mean values of the $^{137}$Cs baseline fallout are in close agreement with the map of Chenobyl fallout produced by airborne survey (see Fig. 1 in Izrael, 1998).

A summary of the estimates of soil erosion rates on arable hillslopes, within-slope redeposition and sediment delivery into the adjacent valley bottoms is presented in Table 2. As can be seen, the values obtained are in reasonable agreement, despite the general overestimation of hillslope erosion by the EMM (due to its inherent inability to account for within-slope redeposition). Overestimation of the percentage of within-slope redeposition by the LANDSOIL model (because of the DEM errors, such as closed depressions in thalwegs of hillslope-dissecting hollows) and by the RCM (because of the denser sampling in deposition areas) for the Lokna catchment is likely. To construct the provisional sediment budget, the mean values provided by combining the results of the independent techniques used, with the exception of the erosion rates generated by the EMM, have been used.

**Table 2** Rates of soil erosion from arable hillslopes, sediment redeposition within arable hillslopes and in uncultivated buffer zones located between the arable hillslopes and the valley bottoms (forest belts, grassed buffer strips and uncultivated steep valley sides) and the resulting sediment delivery into adjacent valleys as estimated by the different techniques employed.

| Key sub-catchment (no. in Fig. 1B) | Techniques | Mean erosion rate (t ha$^{-1}$ year$^{-1}$) | [1)]Redeposition within arable hillslopes, t ha$^{-1}$ year$^{-1}$ / % | [1)]Redeposition within buffer zones, t ha$^{-1}$ year$^{-1}$ / % | SDR (%) |
|---|---|---|---|---|---|
| Lokna (1) | RCM | 9.2 | 1.7 / 18.5 | 0.9 / 9.8 | 71.7 |
| | SMM | 5.5 | 0.5 / 9.1 | 1.4 / 12.6 | 78.3 |
| | LANDSOIL | 3.6 | 0.8 / 22.2 | 1.0 / 13.7 | 64.1 |
| | EMM | 13.8 | - | - | - |
| Lyapunovka (2) | RCM | 11.9 | 1.5 / 12.6 | n/a | <87.4 |
| | SMM | 4.5 | 0.6 / 13.3 | n/a | <86.7 |
| | EMM | 14.5 | - | - | - |
| Sviatoy Istochnik (3) | SMM | 3.6 | 0.2 / 5.6 | n/a | <94.4 |
| | EMM | 12.1 | - | - | - |
| Mean values (discarding EMM) | | 6.4 | 0.9 / 14.1 | 1.1 / 8.5 | 77.4 |

[1)] Recalculated for the entire area of arable hillslopes;
[2)] Recalculated for the area of buffer zones.

### Sediment redistribution along the 1-3rd order dry valley bottoms

Rates of post-1986 sedimentation within the bottoms of small dry valleys within the three key sub-catchments have been quantified by locating the 1986 peak in the $^{137}$Cs depth distributions and correcting its depth to take account of the sampling depth increment and the vertical migration of the peak established using $^{137}$Cs profiles from non-cultivated reference locations, based on the method described by Walling & He (1997) for floodplain aggradation. As can be seen in Fig. 3(A)–(C), the $^{137}$Cs concentration peak attributed to Chernobyl fallout in 1986 was easily identifiable for most of the sediment profiles. However, its depth varies substantially, depending on the valley order, catchment land use, the arable hillslope connectivity, the morphological type of the valley cross-section and the long profile shape. As the $^{137}$Cs measurements have not yet been completed for the Sviatoy Istochnik key sub-catchment, results are presented only for the Lokna and Lyapunovka sub-catchments (Table 3). There is an obvious general trend of decreasing mean deposition rates with increasing valley order for both of the sub-catchments. However, in terms of the percentage of sediment stored within the bottoms of valleys of different order, the situation mainly depends on the structure of the valley network within each catchment and valley bottom widths and gradients. Thus, for example, in the much simpler Lyapunovka sub-catchment there are only three 2nd-order valleys, which are characterized by relatively high bottom gradients. Therefore, their importance as sediment sinks is less than that for the Lokna sub-catchment. For the 3rd-order valley (a single main valley in the case of the Lyapunovka sub-catchment) the situation is reversed, probably as a result of increased hillslope connectivity in the small Lyapunovka sub-catchment.

**Table 3** Mean deposition rates and associated sediment storage (as a percentage of catchment-scale sediment production from arable hillslopes).

| Key sub-catchment (number on Fig. 1B) | 1st-order valleys | 2nd-order valleys | 3rd-order valleys |
|---|---|---|---|
| Lokna (1) | ≈6.0 mm year$^{-1}$ / 43.0% | ≈4.0 mm year$^{-1}$ / 13.2% | ≈2.0 mm year$^{-1}$ / 6.8% |
| Lyapunovka (2) | ≈8.0 mm year$^{-1}$ / 31.0% | ≈3.0 mm year$^{-1}$ / 7.3% | ≈2.7 mm year$^{-1}$ / 13.2% |

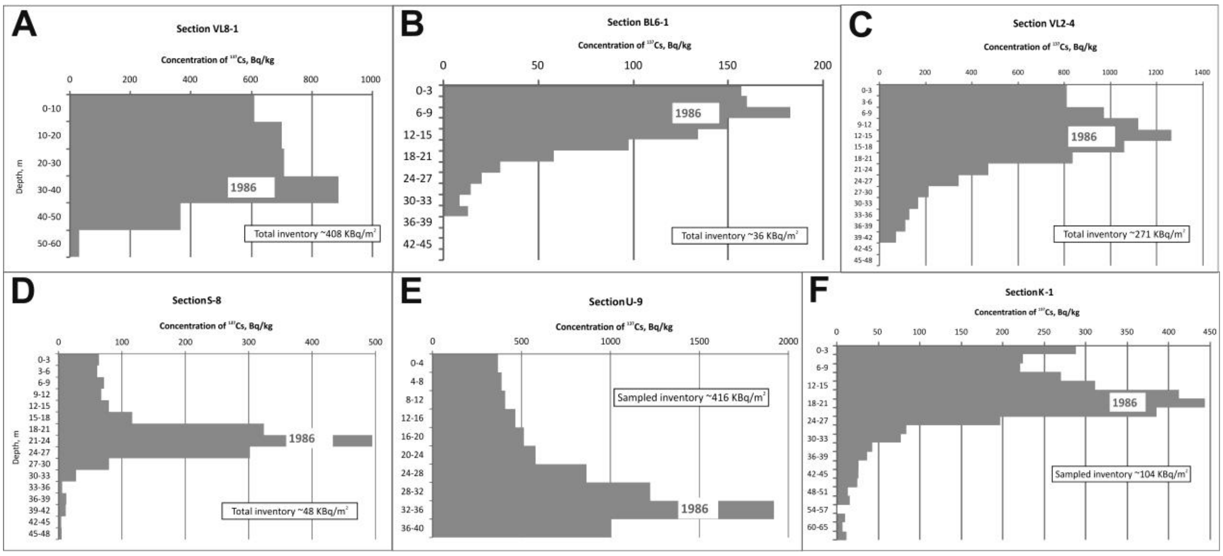


**Fig. 3** Examples of typical $^{137}$Cs depth distributions in sediment deposited in the bottoms of valleys of different orders: (A) Formerly cultivated head of the Upper Lokna dry valley tributary (1st order); (B) Transport reach of the Lyapunovka dry valley (2nd order); (C) the Upper Lokna dry valley (3rd order). The Plava River floodplain: (D) Streshnevo site (4–5th order transition); (E) Yurievo site (6th order); (F) Krapivna site (7th order).

## Sedimentation on the River Plava floodplain

Rates of post-1986 sedimentation for the key locations within the valley bottom of the River Plava (Fig. 1(B)) have been estimated by locating the 1986 $^{137}$Cs peak in the radiocaesium depth profiles, using a similar approach to that used for estimating aggradation rates in the bottoms of the dry valleys (Walling & He, 1997; Walling *et al.*, 1999). The examples provided by Fig. 3(D)–(F) show that the observed peak depths and associated deposition rates varied substantially, both along the river course (according to the downstream increase of stream order, discharge, floodplain width and flood levels), and within the individual floodplain sites according to geomorphic position (relative elevation and distance from the active channel), which influences inundation duration and frequency. Based on the estimated floodplain aggradation rates, geomorphic surveys of the floodplains to determine the areas occupied by different floodplain levels and measured sediment bulk densities, it has been possible to derive an approximate estimate of the total amount of sediment entering storage on the River Plava floodplain during the period 1986–2009. It was also possible to estimate the storage associated with the different floodplain levels. Local-scale variability of overbank deposition rates is evident at all five study locations, with aggradation rates for the lower level floodplain (6–14 mm year$^{-1}$) exceeding by 1.5–3 times the values for the middle (2–9 mm year$^{-1}$) and by 3–6 times the values for the upper (1–5 mm year$^{-1}$) level floodplains. The total volume of sediment entering storage on the River Plava floodplain during the period 1986–2009 period has been estimated to be approximately 30 000 t.

## A provisional sediment and associated $^{137}$Cs budget for the River Plava basin

Based on the sediment redistribution values presented above, it has been possible to construct sediment budgets for the Lokna and Lyapunovka sub-catchments, as well as to extrapolate the information obtained to provide a provisional sediment budget for the entire River Plava basin. Annual sediment budgets for the Lokna and Lyapunovka key sub-catchments are shown in Fig. 4(A)–(B). It can be seen that for the Lokna catchment two important components of the budget are still unknown, namely, sediment trapping by reservoirs and main river floodplain storage. These require further investigation.

The provisional River Plava sediment budget for the 1986–2009 period (Fig. 4(C)) has been constructed using mean values for sediment mobilization and storage determined for the key sub-

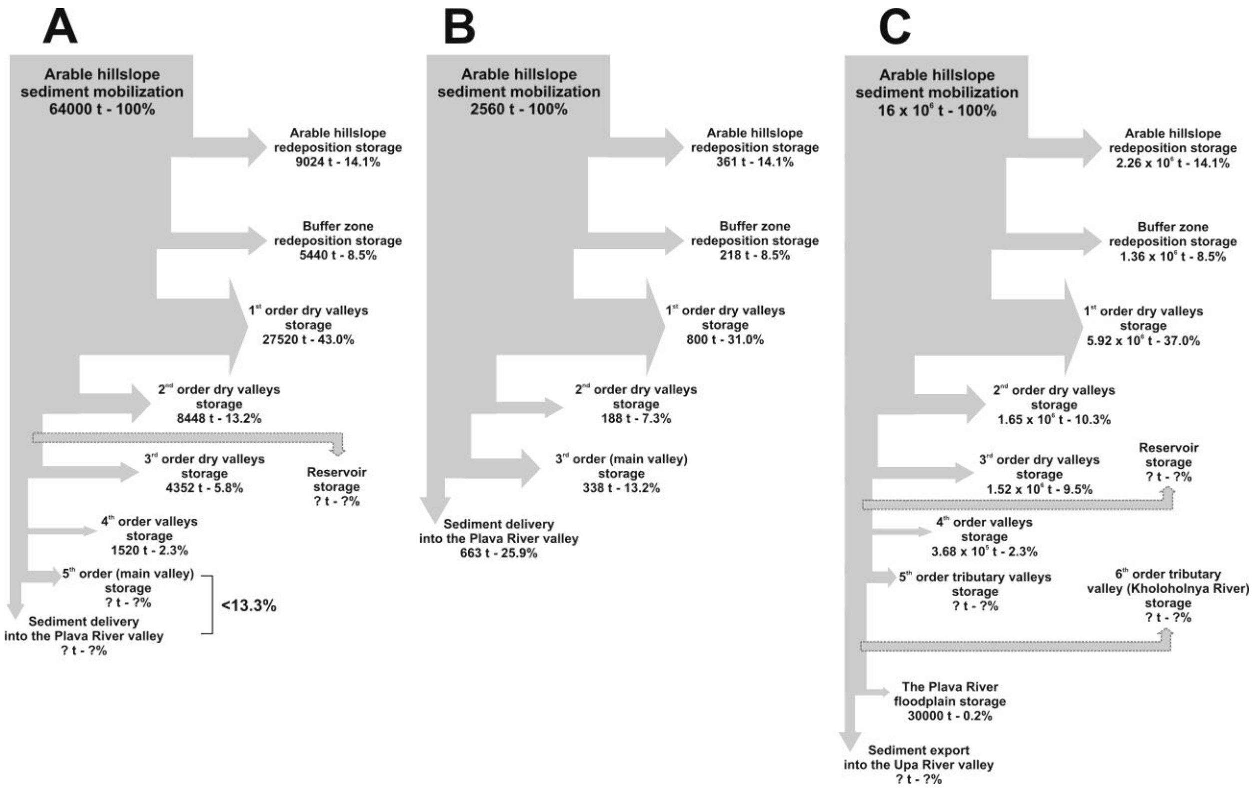


**Fig. 4** Provisional sediment budgets: (A) and (B) annual budgets for the Lokna and Lyapunovka key sub-catchments respectively; (C) sediment budget for the entire River Plava basin for the period 1986–2009.

catchments. A mean soil loss rate ~6.4 t $ha^{-1}$ $year^{-1}$ and hillslope sediment delivery ratio 78.4% have been determined by this study. These values are comparable with values provided by previous investigations carried out in the region (Golosov *et al.*, 1999; Panin *et al.*, 2001; Golosov & Ivanova, 2002; Belyaev *et al.*, 2003). Total sediment delivery from all arable slopes of the River Plava basin into the fluvial network over the same period has been estimated to be approximately ~$12.4 \cdot 10^6$ t. Furthermore, ~60% of this sediment has been stored within the bottoms of 1–3rd order dry valleys. There are two major unknown components of the Plava River sediment budget which require further investigation. These are the amounts of sediment trapped by reservoirs and sediment storage in the main tributaries (5–6th order tributary valleys). Based on the above estimates, we can conclude that the Plava River floodplain stores only about 0.2% of the total sediment export from the cultivated hillslopes of the basin. This supports the conclusions of Panin *et al.* (2001), that most of the sediment delivered from arable hillslopes remains stored in the bottoms of dry valleys of 1st–4th Hortonian order and that only <5% of the sediment reaches the small river valleys of 5th–6th order, such as the main left bank tributaries of the River Plava (i.e. the rivers Lokna, Plavitsa and Holoholnya; Fig. 1).

Several components of the sediment budget still remain unknown and it is difficult to infer what proportion of the sediment delivered to the main valley is stored on the floodplain and to evaluate the conveyance losses within the system, because information on suspended sediment yield at the basin outlet is unavailable. However, for small rivers with a drainage basin area $F >$ 200 $km^2$ in the Volga River basin the following empirical relationship has been established (Sidorchuk, 1996):

$$SDR = 0.25 \cdot F^{0.2} \qquad (1)$$

where *SDR* is the sediment delivery ratio (%) and *F* is the drainage basin area ($km^2$).

From this equation, it can be estimated that sediment delivery ratio for the entire Plava basin is about 1.1%. If we combine this result with the approximate value of sediment export from the basin cultivated slopes presented above, the hillslope-derived component of the Plava River sediment yield for the 1986–2009 period can be estimated as ~136 400 t, and the approximate value of floodplain storage (30 000 t) represents a conveyance loss within the main river system for the study period of about 20%, which falls within the range of values reported in similar studies, where actual suspended sediment yield monitoring data were available (Miller & Shoemaker, 1986; Walling & Quine, 1993; Campo & Desloges, 1994; Walling *et al.*, 1999). This value does not take into account local sediment sources such as bank erosion and valley side landslides, but our field investigations showed that their contributions are relatively small. It is also important to note, in terms of the redistribution of $^{137}Cs$ contamination, that, although most of the particle-bound contaminant still remains within the Plava basin, about 20 GBq (or 0.8 GBq $year^{-1}$) of $^{137}Cs$ (assuming ~100 000 t of sediment export with a mean $^{137}Cs$ activity of ~200 Bq $kg^{-1}$) have been already exported into the River Upa since 1986. Knowing the mean $^{137}Cs$ activities in different landscape components and geomorphic units, it is possible to estimate the basin-scale $^{137}Cs$ contaminant fluxes and to identify areas with a potential threat of secondary pollution enrichment on the basis of the constructed sediment budgets.

The results of sampling the River Upa floodplain sediment for $^{137}Cs$ concentration measurements upstream and downstream from the River Plava confluence presented in Fig. 5 provide additional confirmation of significant export of $^{137}Cs$-contaminated suspended sediment from the River Plava basin into the higher-order river system. It can be seen from comparison of the $^{137}Cs$ depth distributions and the very similar depths of the 1986 peak that floodplain aggradation rates at the two locations are essentially identical. However, the total $^{137}Cs$ inventory associated with section UP-1 (Fig. 5(B)) affected by the sediment output from the River Plava basin is almost an order of magnitude greater than that in section UP-2 (Fig. 5(A)) where only sediment from the less contaminated upper parts of the River Upa basin has been deposited.

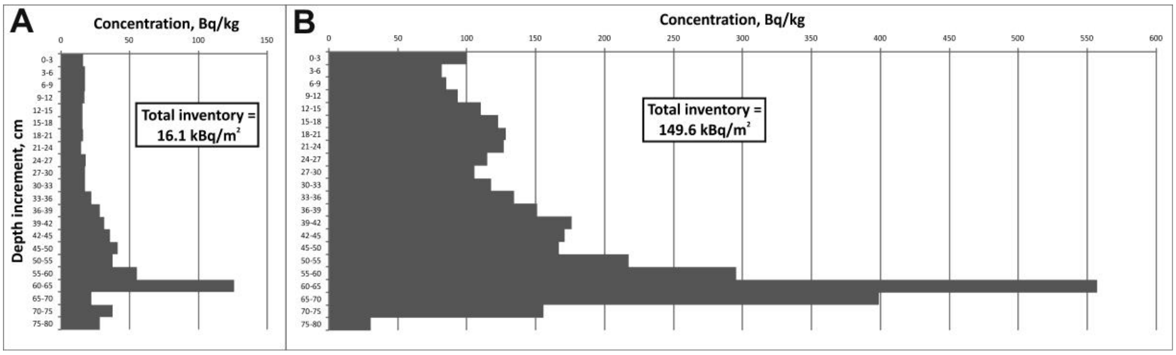


**Fig. 5** The $^{137}$Cs depth distribution curves (shown on the same X-axis scale to facilitate comparison) and inventories associated with the River Upa floodplain sediment upstream (A – section UP-2), and downstream (B – section UP-1) from the River Plava confluence. For precise section locations see Fig. 1(B).

## CONCLUSIONS

Application of the integrated approach combining several independent techniques has provided a quantitative assessment of soil and sediment redistribution rates within the key sub-catchments and a basis for reconstructing the sediment budget for the 1856 km$^2$ River Plava basin for the period 1986–2009. The mean soil loss rate from arable hillslopes is estimated to be about 6.4 t ha$^{-1}$ year$^{-1}$ and a hillslope sediment delivery ratio of 78.4% has been estimated by the study. These values are very similar to the results obtained by previous investigations carried out in the region. It is estimated that ~60% of the sediment delivered to the fluvial network is stored in the bottoms of 1–3rd order dry valleys. There are two major unknown components of the sediment budget of the Plava River which require further investigation. These are the amount of sediment trapped by reservoirs and sediment storage in the main tributaries (5–6th order tributary valleys).

In terms of the redistribution of $^{137}$Cs radioactive contamination, knowing the mean radio-caesium concentrations associated with different landscape components and geomorphic units, it is possible to estimate the basin-scale $^{137}$Cs contamination fluxes and determine areas with a potential threat of secondary contaminant enrichment, based on the constructed sediment budgets. Most of the particle-bound $^{137}$Cs still remains within the Plava basin. However, about 20 GBq (or 0.8 GBq year$^{-1}$) of radioactive $^{137}$Cs (assuming ~100 000 t of sediment export with mean isotope concentration of ~200 Bq kg$^{-1}$) have been exported into the River Upa basin since 1986.

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