Response of a small arable catchment sediment budget to introduction of soil conservation measures

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Abstract This paper presents reconstructions of sediment budgets for a small arable catchment for two time periods: before and after the introduction of soil conservation measures in its upper part. The catchment is ideal for such a reconstruction because an earthen dam was built at its lower reach at the same time as planting forest belts at the beginning of 1986, making it a completely closed sedimentary system. At the same time, the Chernobyl ^{137}Cs fallout occurred in European Russia, leaving an easily distinguishable concentration peak in the sediment stratigraphy. A USLE-based modelling approach was employed for calculating soil loss from arable slopes before and after changes of management practice. A ^{137}Cs-based sediment stratigraphy provided information about volumes and average rates of valley aggradation above the dam for time intervals 1954–1986 and 1986–2006. Soil losses from the cultivated part of the catchment decreased by at least a factor of 2.8 after the introduction of soil conservation practices in 1986.

Key words sediment budget; soil conservation measures; ^{137}Cs technique; erosion model

INTRODUCTION

The Chernozem zone in European Russia is a very productive agricultural area due to the high organic carbon content in local soils. The Kursk Region is, in turn, one of the main agricultural areas of the Russian Chernozem zone, with a high percentage of row crops in crop rotation. Land-use, high intensity of rainstorms, and relative steepness of cultivated slopes cause soil erosion rates ranging from 15 to 20 t/ha/year. Highest erosion rates are observed during high intensity rainstorms falling on the fields under fallow or row crops. For example, a rainstorm of 192 mm fell on the fields under winter wheat and fallow during the night of the 20–21 August 1976, in the Sovetsky District of the Kursk Region. The resulting soil loss for that single rainfall event was 200 t/ha (Gerasimenko & Rozkov, 1976). Erosion during spring snowmelt period is observed in about 50% of springs, according to the 20-year long monitoring. Its rate is mostly dependent on the depth of the seasonally frozen topsoil layer and varies within a range of 0.5–10 t/ha with a mean value of 2.76 t/ha (Zdorovcev & Doschechkina, 2003). A system of soil conservation measures was especially designed for this area in order to protect soil from water erosion and was applied for the test catchment. The effectiveness of the application can be evaluated using indirect methods of soil redistribution assessment, allowing us to obtain estimates of mean annual erosion rates for different time intervals.

STUDY AREA

A small catchment with a total area of 1.98 km^2 was chosen for a detailed study of sediment redistribution for different time intervals. The Gracheva Loschina Catchment is located about 20 km south-southeast from the regional centre of Kursk, and lies within the territory of an experimental station belonging to the Russian Scientific Institute of Agriculture and Soil Protection from Erosion (Fig. 1). The area is characterized by temperate continental climate with relatively cold winters and warm summers. Average annual precipitation is 585 mm (for a 100-year period of observation) with variations in a range of 400–800 mm. Only 30% of precipitation falls during the cold months, mostly as snow. The most typical warm period precipitation events are rainstorms with total rainfalls of 10–40 mm commonly occurring from May to October. Thickness of the

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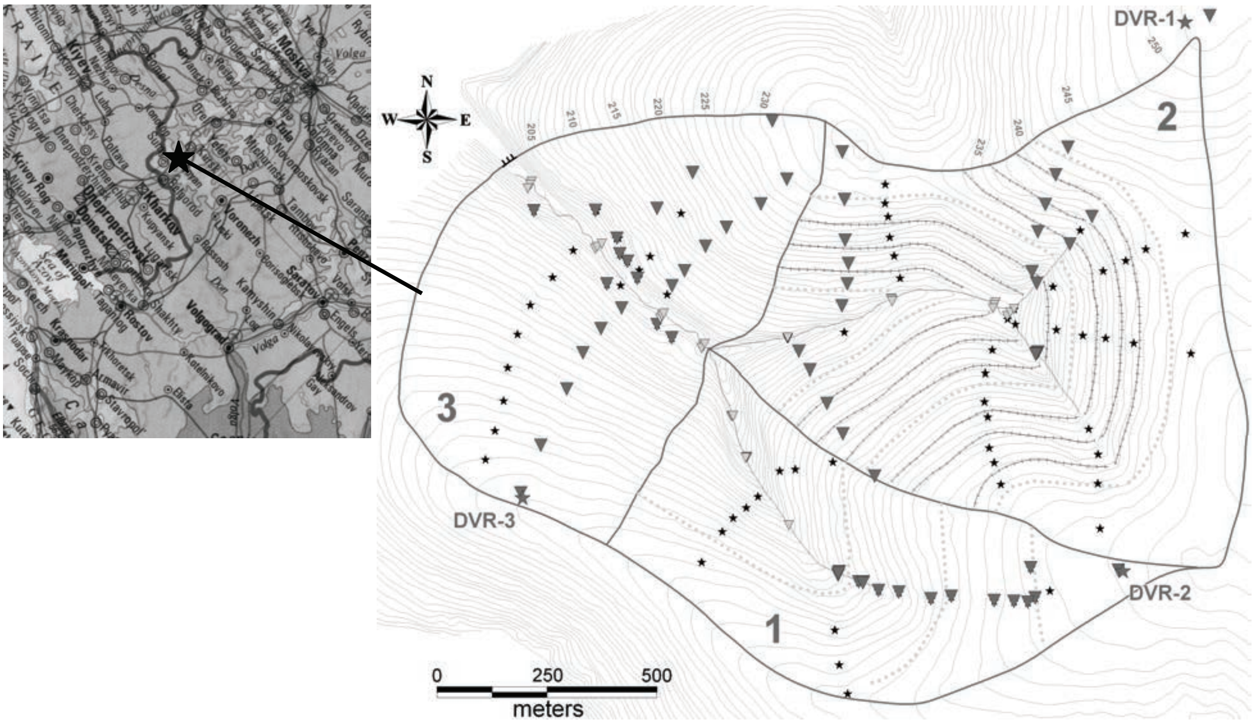

Fig. 1 Approximate location of the study catchment within the Russian Plain and location of sampling points within the Gracheva Loschina catchment. Legend: (1) DVR-1–DVR-3 and larger stars designate reference point locations (DVR-4 is located outside the map, about 1 km to the northwest of the study catchment); (2) grey triangles designate soil survey sections in the bottoms of the main valley and its two upper branches; (3) black triangles designate soil survey sections along slope transects; (4) smaller stars designate ^{137}Cs integral sampling points along slope transects; (5) dotted lines designate forest shelter belts; (6) hatched lines designate contour terraces; and (7) large digits designate subcatchment numbers as referred to in the text below. Topography contours are drawn at 1 m intervals.

winter-frozen topsoil layer varies from year to year in a range of 0–150 cm. This parameter controls the runoff coefficient during the spring snowmelt period and hence the associated erosion rates. The catchment occupies an area with typical and leached chernozem soils formed mostly on loess deposits. However, underlying parent bedrocks also have some influence on soil properties at different parts of slopes. Catchment topography is characterized by gradually rolling interfluve areas and a predominance of convex slopes with maximum gradients up to 5–10°. Only a few hollows dissect slopes in the upper parts of the catchment (Fig. 1). Most of the catchment area has been cultivated (Fig. 2(b)). Recently, the lower parts of slopes and tributary hollow bottoms have been converted to pasture (Fig. 2(b), (c)).

In the beginning of 1986 a system of soil conservations measures was introduced on 70% of the catchment area within two hollows/sub-catchments in the upper part of the catchment (Figs 1, 2(c)). Different sets of soil conservation measures were applied within the two sub-catchments. Two-rowed forest shelter belts were planted parallel to the contour lines and grassed waterways along hollow bottoms were introduced within both sub-catchments. Water retention ditches with depths of about 1 m were dug within each forest shelter belt between the two rows of trees. The hollows bottoms were sown by perennial grasses and used as erosion-protected and sediment-intercepting pathways for surface runoff. In addition, contour terraces parallel to the contour lines with relative heights of about 1 m were constructed between forest shelter belts within sub-catchment 2 (Figs 1, 2(c)). Runoff along those terraces is diverted at a very low gradient towards the grass-covered waterways in hollow bottoms. Simultaneously, an earthen dam was constructed at the main valley outlet. The rest of the catchment slopes remained cultivated in a traditional manner (Fig. 2(c)).

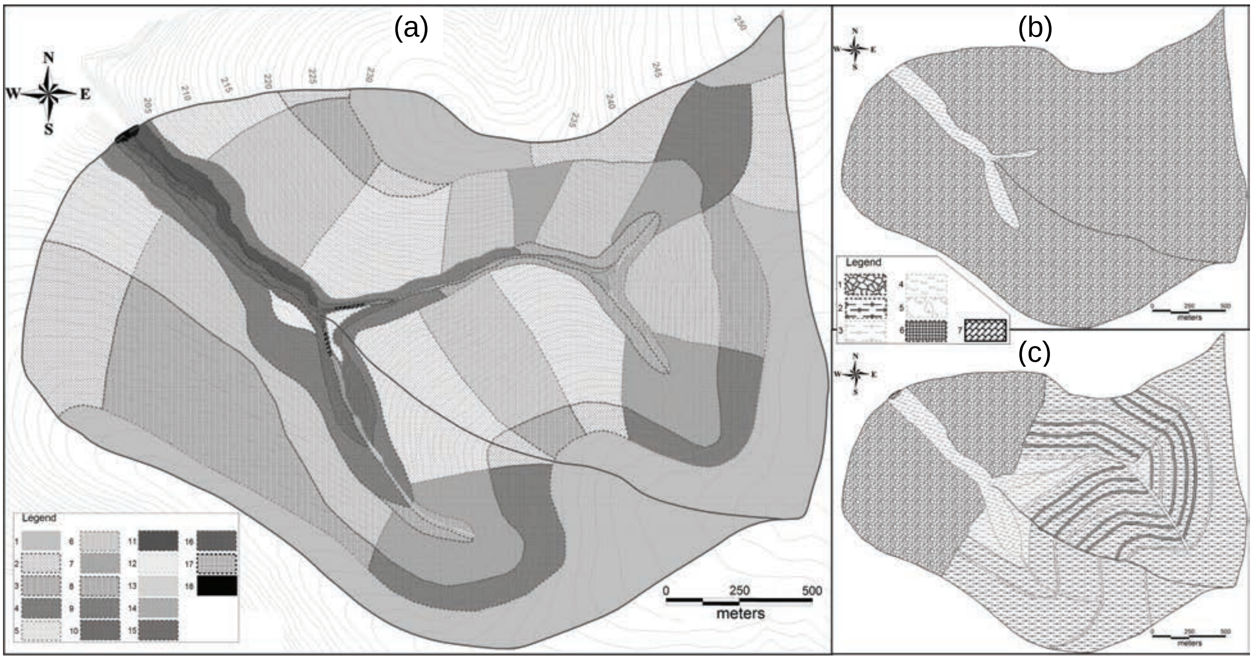

Fig. 2 (a) Geomorphic map of the case study catchment (topography contours are drawn in 1 m intervals). Legend: (1) Rolling interfluve surfaces with dominant gradients <2°; 2–4) Gradual slopes, 2–3° (2), divergent; (3), straight; (4), convergent; (5–7), moderate slopes, 3–5° (5, divergent; 6, straight; 7, convergent); (8), moderately sloping sides of tributary hollows, 3–5°; (9), relatively steep slopes and sides of tributary hollows, 5–10°; (10), moderately sloping main valley sides, 5–10°; (11), relatively steep main valley sides, >10°; (12), main valley terrace surfaces, 2–5°; (13), bottoms of slope depressions; (14), bottoms of tributary hollows; (15), main valley bottom; (16), aggraded reservoir bottom; (17), concrete troughs at sites of former gauging stations at outlets of tributary hollows; (18), earthen dam. (b) Land use before 1986. (c) Land use after 1986. Legend: (1), traditional cultivation; (2), soil-protective cultivation; (3), soil-protective cultivation parcels left under perennial grasses; (4), pasture and hay-mowing lands in valley bottoms and along grass-covered waterways; (5), forest shelter belts; (6), contour terraces; (7), earthen dam.

Crop rotations changed several times during the second half of the 20th century. The 6-field crop rotation with equal proportions of winter wheat, summer wheat, row crops, annual grasses and fallow was used until *c.* 1960. The proportion of maize seriously increased after 1960. During 1970–1980s sugarbeet increased to about 40% of total area of arable lands. The following 6-field crop rotation has been used during the last two decades within the soil-conservation experiment area: maize, summer barley, annual grass, winter wheat, sugarbeet and pea. The 5-field crop rotation has been used for the rest of catchment slopes, which included annual grass, winter wheat, maize, barley and buckwheat. The normal depth of soil cultivation is 25–27 cm.

METHODS

The introduction of soil conservation practices and dam construction were completed by spring 1986. This gave a very good opportunity to evaluate the entire catchment sediment budget using independent approaches. Firstly, a detailed large-scale geomorphic map was created based on a combination of topographic data and our DGPS and laser tacheometer surveys. The map shows different morphological units of the studied catchment as distinguished from the DEM analysis and field geomorphic survey (Fig. 2(a)). The following sampling program was based on that map and aimed to characterize all important morphological units in terms of the sediment fluxes between them. Evaluation of sediment redistribution was carried out for a few different time intervals on the basis of the following approaches: (i) ^{137}Cs budget; (ii) combination of the USLE-based erosion model and vertical distribution of ^{137}Cs in deposition zones; (iii) soil morphological method, buried soils and method of magnetic spherules (Olson *et al.*, 2002).

Four reference locations in different parts of the study area were chosen to determine the mean value of the ^{137}Cs fallout. All of them were located on non-eroded tops of rolling cultivated interfluves. At each reference site, 12 integral samples were taken at 0–30 cm depth intervals. In addition, several bulk samples for radionuclide analysis were taken from each of the slope morphological units within the two experimental sub-catchments and the remaining parts of catchment slopes with traditional cultivation. A total of 18 geological sections were dug in the main valley bottom and the bottoms of both tributary hollows (Fig. 1). In addition, at least two soil survey cores were drilled at each bottom cross-section where pits were dug. Depth-incremental samples were taken from seven depositional sections for the determination of ^{137}Cs concentration to a depth of 60–80 cm. The resulting ^{137}Cs vertical distribution curves at each sampled section were used to calculate sediment volumes deposited within valley bottoms over different time intervals. Both bomb-derived and Chernobyl fallouts of ^{137}Cs were observed at the study area. Thus, it is possible to evaluate deposition rates for at least two time intervals: 1954–1986 and 1986–2006. In a few cases it was also possible to define the 1964 peak.

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 along the 661.66 keV channel using a high-resolution, low-background, low-energy, hyperpure n-type germanium coaxial gamma-ray detector (EG&G ORTEC LOAX HPGe) coupled to an ORTEC amplifier and multichannel analyser. The gamma counting period for each sample was not less than 12 h.

The applied soil morphological method is based on an evaluation of the relative decrease or increase of topsoil thickness (A+AB soil horizons) in soil sections on arable slopes compared to undisturbed reference soil sections within interfluve areas. A reference value of A+AB soil horizons thickness was determined as a mean between those observed at several individual sections. A given value was used for estimation of the total soil loss or gain at slope sections for the entire period of cultivation. In total, 64 pits were used for analysis of soil redistribution on the catchment slopes. Evaluation of sediment deposition within the main valley bottom and the hollow bottoms for the entire period of cultivation was done on the basis of detailed description of 18 pits and 8 cores uniformly distributed along the bottoms. The buried soil method was applied for determination of total deposition depth for the entire period of cultivation. The age of the onset of intensive cultivation was defined using magnetic spherules vertical distribution curves (Olson *et al.*, 2002).

The empirical erosion model utilises a combination of: (i) the USLE-based approach for estimating rainfall-induced erosion, and (ii) a model developed in the Russian State Hydrological Institute for estimating erosion from snowmelt runoff. The combined model was used for assessment of soil losses from the cultivated area. The model was developed by Larionov (1993) especially for application in Russia, and supplied with a large spatially distributed data set of model parameters. Modifications from the initial USLE model include an improved set of equations for determining topographic factors (Larionov *et al.*, 1998), a novel approach calculating and mapping a rainfall erosivity index for European Russia (Krasnov *et al.*, 2001), as well as an adaptation of land-use factors and soil protection techniques specific to the Russian agricultural system. The model estimates sheet erosion rates from both rainfall- and snowmelt-generated overland flow. Data required for the model inputs include detailed topography of slope transects oriented along surface runoff flow lines, local soil properties, precipitation records, and land-use information. The output is generated as a series of points with values of soil loss, which can then be exported to various GIS tools for visual presentation and manipulation with other spatial data.

RESULTS AND DISCUSSION

The ^{137}Cs reference inventory was defined for the study catchment for four locations (Fig. 1, Table 1). All reference sites were located at the flat interfluve areas in or nearby the study catchment. A certain amount of soil may have been removed from flat interfluve areas during

Table 1 General characteristics and ^{137}Cs inventory (Bq/m^2) statistics for the reference sites.

Reference site	Number of samples	Mean value (Bq/m^2)	Range (Bq/m^2)	Cv (%)	Standard deviation, (Bq/m^2)
DVR-1	12	9289	5219–11476	22	2062
DVR-2	12	7537	6298–10209	16	1209
DVR-3	12	9063	7206–11021	13	1186
DVR-4	12	8517	6346–10150	13	1112

Table 2 ^{137}Cs budget for different sub-catchments within the study catchment.

No.	Sub-catchment	Total area (ha)	^{137}Cs loss, KBq / % / Eroded area, ha	^{137}Cs gain, KBq / % from ^{137}Cs loss / Deposition area, ha		Residual KBq / %
				Within cultivated areas (including grassed waterways)	In tributary hollow bottoms and main valley bottom	
1	Sub-catchment with forest shelter belts and grass waterways	52.8	189606 / 100% / 42.3	154620 / 82% / 55.2	7954 / 4% / 0.3	–27032 / 14%
2	Sub-catchment with forest shelter belts, grass waterways and contour terraces	88.1	926885 / 100% / 73.3	834195 / 90% / 9.5	24650 / 3% / 0.95	-68040 / 7%
3	Area without soil conservation measures and the main valley bottom	56.9	236786 / 100% / 48.6	22061 / 9% / 1.4	200508 / 85% / 1.4	–14217 / 6%

sugarbeet harvesting, leading to a decrease of the ^{137}Cs concentration. This is particularly possible for the reference site 2 (DVR-2), which is located relatively close to the local village. However, some input of ^{137}Cs may also have occurred because of dust deposition from adjacent earth/gravel roads. This is most likely for the reference site 1 (DVR-1) with two relatively busy earth/gravel roads located nearby. The ^{137}Cs inventory Cv varies in a range of 13–22%, which are typical for the bomb-derived ^{137}Cs (Walling & Quine, 1990). No notable spatial trend of the ^{137}Cs inventory was determined when analysing the four reference locations together, as has been the case in some other areas with substantial input of the Chernobyl-derived fallout (Belyaev *et al*., 2007). Hence it is possible to use the single mean value of ^{137}Cs inventory (8600 Bq/m^2) obtained from the whole set of reference samples from the four sites for calculations of the total ^{137}Cs budget.

The total ^{137}Cs budget was evaluated using mean values of ^{137}Cs inventory for each individual morphological unit for the three sub-catchments (Table 2). Uncertainties associated with the presence of bomb-derived ^{137}Cs, which redistributed prior to introduction of soil conservation measures, were not accounted for in our budget calculations. According to *The Atlas of Radioactive Contamination* (Yu, 1998), the proportion between the Chernobyl-derived and bomb-derived ^{137}Cs inventory (corrected for radioactive decay) for the case study area is about 6:1–5:1. Moreover, it can be assumed that parts of the bomb-derived ^{137}Cs inventory were removed through the catchment outlet before the dam construction in 1986. This can explain the differences between ^{137}Cs losses from eroded areas and ^{137}Cs accumulation within depositional areas. However, it is also clear from Table 2 that most of the Chernobyl-derived ^{137}Cs has been delivered into the main valley bottom from catchment areas without soil conservation. Mechanical soil removal at contour terraces during tillage operations in the experimental area can be held responsible for noticeable ^{137}Cs redistribution within the cultivated area of sub-catchment 2. In sub-catchment 1, most of the ^{137}Cs redistribution within slopes can be attributed to limited erosion and subsequent sediment redeposition within grassed waterways.

Combined application of erosion model calculations with evaluation of sedimentation rates based on analysis of the ^{137}Cs vertical distribution in different parts of the main valley bottom and two main tributaries, can be used to evaluate within-catchment sediment redistribution for the two time intervals (1964–1986 and 1986–2006). Soil losses for these two time intervals were evaluated using the model calculations along 72 transects. It was found that total soil loss has decreased by 2.8 times between the periods considered (Table 3). The erosion model used for calculation does not take into consideration within-slope sediment redeposition, so it is very likely that the model calculation overestimates soil losses.

Sediment deposition has been evaluated on the basis of detailed analyses of ^{137}Cs vertical distributions in seven sections located in different parts of the main valley bottom and uncultivated low parts of the sub-catchment valley bottoms (Fig. 3), as well as ^{137}Cs concentration in the bulk samples taken from the bottom parts of the interfluve slopes. In this case, it was not possible to split deposition layers to two time intervals because of regular mixing of the soil plough layer during cultivation. The proportions of sediment redeposition within the main valley and tributary hollow bottoms, compared to the total soil loss, are similar for both time intervals (Table 3), despite the dam construction in 1986. However, the deposition rate has decreased by about 2.8 times after 1986. It is also very likely that a part of the sediment delivered into the main valley bottom during 1964–1986 was transported further downstream by temporary bottom incisions.

Application of the soil morphological method allows defining sediment redistribution for the entire period of cultivation. The vertical distribution of magnetic spherules in the deposition zone of the main valley bottom is about 150 years. The mean values of soil losses for the entire period of cultivation obtained from the soil survey data are in a good agreement with those provided by

Table 3 Sediment redistribution in the study catchment according to different methods.

Method	Time interval, year	Gross erosion, t / %	Deposition within cultivated field, t / %	Deposition within hollows and valley bottom, t / %	Output from the catchment, t / %
Soil Morphological Method	1857–2006	400375 / 100%	33650 / 8.4%	39220 / 9.8%	327505 / 81.2%
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1964–1986	66148 / 100%	6615 / 10%**	15757 / 23.8%	43776 / 66.2%
^{137}Cs budget*	1986–2006	50989 / 100%	33778 / 82.8%	8766 / 17.2%	0
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1986–2006	22606 / 100%	17050 / 75.4%	5556 / 24.6%	0

*With bomb-derived ^{137}Cs.

**Defined on a basis of application of 137Cs budget (Table 2, line 3) and soil morphological method.

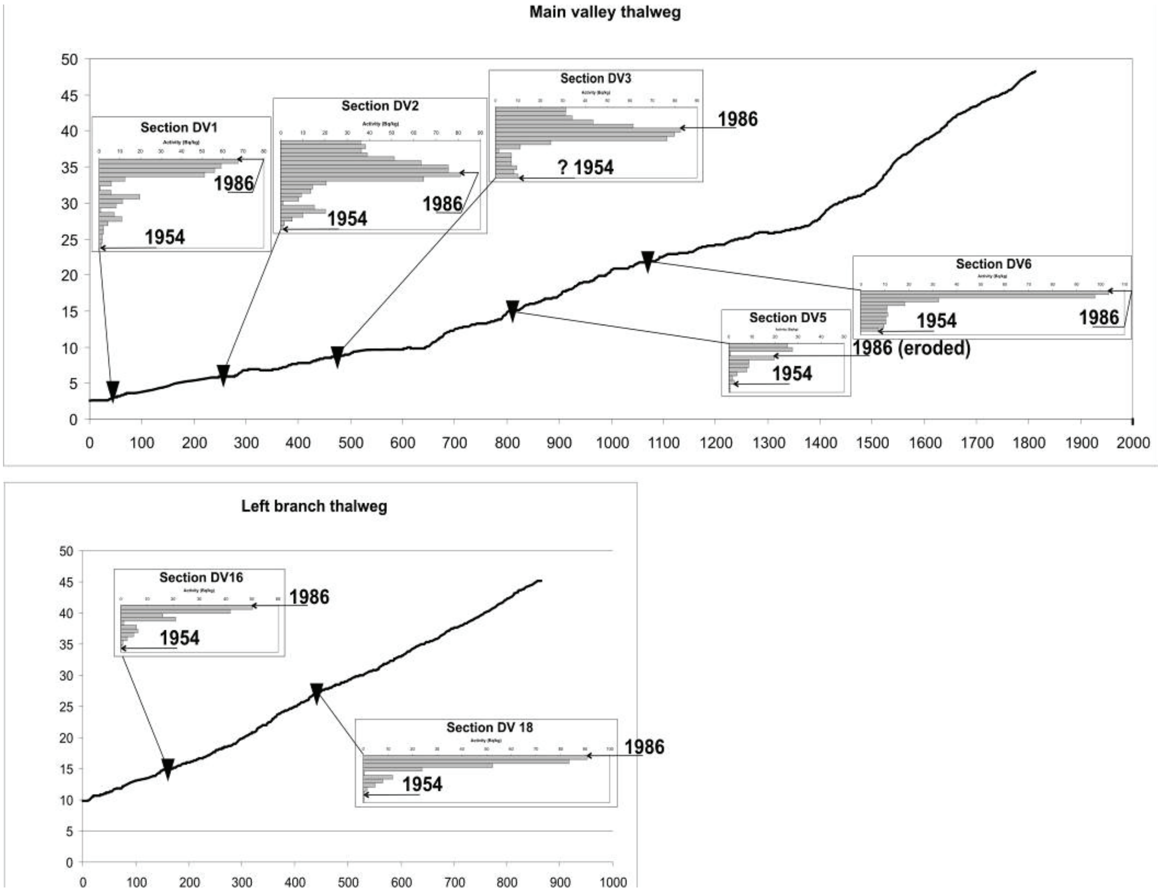

Fig. 3 Longitudinal profiles of the main valley and the right tributary hollow (upper graph) and of the left tributary hollow (lower graph) with vertical distribution of ^{137}Cs (scale exaggerated) in sampled sections (designated by black triangles).

Table 4 Evaluation of gross (bold characters) and net erosion rates for different time intervals based on different independent methods for the entire case study catchment.

Method	1857–2006	1964–1986	1986–2006
Soil Morphological Method	**15.7**		
Erosion model calculation		**15.3**	**6.0**
^{137}Cs budget			2,4
Sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)		3.7*	1.5

*Does not take into consideration possible sediment export through the catchment outlet.

the erosion model (Table 4). Sediment deposition along the lower parts of cultivated slopes is about 8% (Table 3), which is in good agreement with the value for the same morphological unit defined on the basis of the ^{137}Cs budget for the area without soil conservation measures (Table 2). Hence, it is possible to use this value to determine the sediment deposition along the lower parts of the cultivated slopes for the 1964–1986 period (Table 3).

It is possible to conclude that both erosion rates on cultivated slopes of the studied catchment and sediment redeposition in lower parts of slopes and valley bottoms decreased during the period after the Chernobyl incident. There are two main explanations of the observed tendency. Firstly, obviously the introduction of soil conservation measures in the upper half of the catchment since 1986 had a positive effect. The second factor relates to the changes of crop rotation, which took place since 1994, when the percentage of row crops decreased drastically. It is very likely that both reasons have significantly influenced sediment redistribution rates within the study catchment.

Application of experimental soil-conservation measures has promoted substantial decreases of soil loss rates. According to the long-term monitoring undertaken by scientists from Kursk at experimental catchments with soil conservation measures and another catchment with traditional cultivation (located about 1 km north), erosion rates during snowmelt periods are approx. three times lower on slopes with conservation measures and vary within a range of 0.5–1.5 t/ha from year to year (Zdorovcev & Doschechkina, 2003). Soil loss evaluation was based on direct rill measurements carried out immediately after cessation of the snowmelt period runoff. Unfortunately, no observations have been carried out during the warm season. However, the reported value of decrease of soil loss rates is in good agreement with the evaluation made by the indirect methods presented here.

CONCLUSION

Detailed study of sediment redistribution within a small cultivated catchment has allowed us to evaluate average annual erosion rates on arable slopes for three time intervals. It has been found that application of conservation measures on cultivated slopes within the experimental part of the study catchment has led to decreases of average soil loss rates by at least a factor of 2.5–2.8. The figures obtained are in good agreement with previously published results of direct monitoring of snowmelt erosion rates, reporting approx. 3-fold decreases of average snowmelt erosion rates in experimental catchments compared to traditionally cultivated control catchments. Substantial decreases of soil erosion rates on arable slopes have been equally reflected in corresponding decreases of aggradation rates in the main valley bottom as well as in its tributaries, despite the 100% sediment retention by the earthen dam constructed in 1986. A closed sediment budget with a zero output has been derived for the 1986–2006 period from calculations by two independent approaches (the ^{137}Cs budget and combination of erosion models with aggradation assessment by the ^{137}Cs vertical distribution in sediment sections).

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