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The history and assessment of effectiveness of soil erosion control measures deployed in Russia

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Abstract

Research activities aimed at design and application of soil conservation measures for reduction of soil losses from cultivated fields started in Russia in the last quarter of the 19th century. A network of "zonal agroforestry melioration experimental stations" was organized in the different landscape zones of Russia in the first half of the 20th century. The main task of the experiments was to develop effective soil conservation measures for Russian climatic, soil and land use conditions. The most widespread and large-scale introduction of countermeasures to cope with soil erosion by water and wind into agricultural practice supported by serious governmental investments took place during the Soviet Union period after the Second World War. After the Soviet Union collapse in 1991, general deterioration of the agricultural economy sector and the absence of investments resulted in cessation of organized soil conservation measures application at the nation-wide level. However, some of the long-term erosion control measures such as forest shelter belts, artificial slope terracing, water diversion dams above formerly active gully heads survived until the present. In the case study of sediment redistribution within the small cultivated catchment presented in this paper an attempt was made to evaluate average annual erosion rates on arable slopes with and without soil conservation measures for two time intervals. It has been found that application of conservation measures on cultivated slopes within the experimental part of the case study catchment has led to a decrease of average soil loss rates by at least 2.5 – 2.8 times. The figures obtained are in good agreement with previously published results of direct monitoring of snowmelt erosion rates, reporting approximately a 3-fold decrease of average snowmelt erosion rates in the experimental sub-catchment compared to a traditionally cultivated control sub-catchment. A substantial decrease of soil erosion rates on arable slopes has been equally reflected in a corresponding decrease of aggradation rates in the main valley bottom and tributaries.

Key Words: Soil erosion, Soil conservation, Sediment redistribution, ^{137}Cs, European Russia

1 Introduction

The Russian Federation is one of the largest agricultural countries in the world with vast areas of highly productive soils. Most of the cultivated lands of the country are located in steppe and forest-steppe zones which are dominated by very fertile zonal soil types – chernozems and grey forest soils. Both zones occupy the southern part of European Russia and also a relatively narrow belt within Southern Siberia. These territories of intensive agricultural land use consequently became areas with the highest intensity of human-accelerated soil erosion among the landscapes of the Russian (Eastern European) Plain and Western Siberia Lowland. Water erosion in these regions is mainly associated with intensive spring snowmelt runoff and relatively frequent heavy rainstorms during the warm part of the year (mainly July – August). In contrast, areas occupied by cultivated land within the mixed and boreal forest (taiga) zones have decreased considerably since the former Soviet Union collapse. Low productivity of zonal soil types represented by sod-podzolic and podzolic soils is the main reason for such a tendency. However, some parts of the forest zone are still characterized by a relatively high percentage of cultivated land and, subsequently,

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high intensity of human-accelerated erosion processes, in particular within the Kama River basin.

Development and implementation of various soil erosion control measures, including those aimed to control or prevent water erosion, was given serious attention in Russia since the last quarter of 19th century (Dokuchaev, 1892). The most widespread and large-scale introduction of countermeasures to cope with soil erosion by water and wind into agricultural practices supported by serious governmental investments took place during the Soviet Union period after the Second World War. After the Soviet Union collapse in 1991, general deterioration of the agricultural economy sector and the practical absence of investments resulted in a cessation of organized soil conservation measures application at the nation-wide level. However, some of the long-term erosion control measures such as forest shelter belts, artificial slope terracing, water diversion dams above formerly active gully heads have survived. Some other erosion-preventive approaches are still being implemented by individual farmers or larger agricultural enterprises without governmental support or legislative control simply because those are economically sound and beneficial in terms of agricultural production. Those include various types of soil-protective crop rotations, cultivation practices aimed at decreasing spring snowmelt runoff by increasing infiltration, different types of non-rotational and minimal tillage, etc. Therefore, the present paper is logically divided into two parts. The first part deals with the history of development and application of the soil erosion countermeasures in Russia. The second part of the paper presents example of the quantitative assessment of soil erosion control measures effectiveness for one of the typical small agricultural catchments in Central Russia.

2 History of design and implementation of soil erosion control measures in Russia

Russia is a relatively young agricultural country in comparison with the rest of Europe. Until the second half of the 17th century, the area of cultivated land was relatively small because of low population density. The first historically documented wave of human-accelerated active gully erosion affected mainly the transition belt between the forest and forest-steppe landscape zones beginning at the end of the 17th century. It was triggered by a sharp increase in population in villages and towns accompanied by intensive agricultural development of surrounding areas and active unpaved road traffic. About 40% of anthropogenic gullies in this area were formed during the period 1730 – 1860 (Sidorchuk and Golosov, 2003). The area of cultivated land expanded after the middle of the 18th century to the south and south-east from Moscow. The area doubled during the 18th century.

However, the most dramatic growth of cultivated area was observed at the end of the 19th century, when large areas in the south and south-east of the Russian Plain became cultivated. Simultaneously the steepest slopes formerly considered unsuitable for ploughing were cultivated, especially in the forest-steppe zone. It was associated with the Land Tenure Reform in 1861, former serfs became “free peasants” but received ownership of small parcels of the worst-quality lands, usually on steeper parts of slopes with shallower and less fertile soils. This situation caused very intensive erosion, particularly gully growth along the parcel boundaries which were commonly oriented parallel to the slope in order to ensure that neighboring landowners would possess soils of similar quality. The increase of soil and gully erosion rates was so dramatic that eroded sediment entering the small river valleys caused intensive river channel siltation and valley bottom aggradation (Golosov and Panin, 2006).

In the late 19th century the Russian scientific community had already become aware of the emerging environmental problems. Discussion between experts of that time started, aimed at developing possible soil protection measures. V. Dokuchaev, who is well-known as the creator of the first soil classification, in his book “Our steppes in the past and at present” (1892) suggested that a complex approach be developed and employed for the entire river basin for reducing soil degradation because of soil erosion and droughts in the steppe zone of Russia. He noted that soil losses because of erosion lead to soil degradation, but in addition eroded sediment exerts a large negative impact on river bottoms, including the river channel. Thus, V. Dokuchaev was one of the first scientists to point out not only the direct onsite effects of soil erosion, but also its severe negative off-site impacts. He suggested the use of different agronomic and vegetative measures for reducing surface runoff and soil losses. Later, after the death of V. Dokuchaev, a network called the “zonal agroforestry melioration experimental stations” was organized in different landscape zones of Russia. The main task of the experiments conducted was to develop effective soil conservation measures for the given climatic, soil and land use conditions. The first agro-forestry melioration experimental station was founded in 1921 near Novosil, Orel region. Later a few other stations were organized in different parts of the former USSR. There are now seven agro-forestry experimental stations where different soil conservation measures are tested. One of the priority directions is the restoration of severely eroded lands, including land affected by gully erosion. Since the establishment of the first experimental station different measures have been developed and applied on agricultural lands.

Two national institutes in the former USSR were established for the development and testing of new soil conservation measures. These were the Institute of Agro-and Forestry Melioration and the Institute of Agriculture and Soil Protection from Erosion. In addition, some scientific groups from different universities and other institutes of the Academy of Agricultural Sciences also participated in experimental and theoretical investigations in different areas.

Soil erosion on arable lands in Russia are observed during spring snow-melting and during heavy rainstorms in the warm part of the year. However, much more attention during the Soviet period was given to the study of erosion rates during snow-melting, because of the opinion that the dominant soil losses occurred during spring snow-melting for most agricultural lands of the former USSR except for the southern part of the steppe zone. This is true for the gully erosion. According to the long-term observations of gully head growth in different parts of Russia, 80% – 90% of gully erosion sediment was produced during spring snow-melting (Myasoedov, 1981; Sirotkina, 1966; Korotina, 1981; Putilin, 1988; Rysin, 1998; etc.). However, observation results using similar methods found that sheet and rill erosion rates during snow-melting were usually in the same range or lower compared with erosion rates during rainstorm events. Most results of observations presenting in Table 1 were undertaken at the runoff plot scale.

Table 1 Relationship between sheet and rill erosion rates for snow-melting and rainstorms in different landscape zones of Russia (long-term field observation) (Litvin, 2002)

Zone	Method	Period of observation	Mean erosion rate ($t\ ha^{-1}\ yr^{-1}$)		References
			During snow-melting	Rainstorms	
Forest	Runoff plot	1968 – 1970	3.5	6.3	Skryabina and Korotaev, 1971
	Slope catchment	1982 – 1996	1.8	4.1	Litvin et al., 1998
Forest-steppe	Runoff plot	1935 – 1969	3.2	2.1	Gonchar, 1981
	Rill measurements	1982 – 1991	8.7	2.2 – 20.9	D'yakov, 1994
	Runoff plot	1968 – 1979	8.1	17.1	Khmelev and Tanasienko, 1983
Steppe	Runoff plot	1980 – 1982	8.7	23.4	Pabat, 1984
	Runoff plot	1972 – 1988	1–2.1	2.1–4	Medvedev and Shabaev, 1991

Another approach was used for evaluation of soil losses during rain-storms and snow-melting. Total sedimentation volumes in small ponds located in the lower parts of cultivated fields above the gully heads were measured. Lifetimes of ponds and their catchment areas were known, so it was possible to calculate the total (snow-melting plus rainstorm) mean erosion rates for slope catchment with different area and morphology (Table 2). Than soil losses for each catchment were evaluated based on application of the modified version of the State Hydrological Institute model for snow-melting and a modified version of the Universal Soil Loss Equation (USLE) for rainstorm events (Larionov, 1993). In most cases total erosion rates derived from the models calculation overestimated actual total soil losses (Table 2). However input of soil losses during snow-melting were considerably lower than soil losses during rainstorms. More attention was directed to development of soil conservation measures for the period of snow-melting because it would solve three problems: reducing sheet and rill erosion rates, preventing gully growth and retaining moisture in the soil. The latter is especially important, because the soil moisture for forest-steppe and steppe zones is one of the limiting factors for high crops harvest, because of the high repeatability of droughts.

There were three main groups of soil conservation measures applied in the former USSR: agronomic, vegetative and structural measures. The latter is the most expensive but the most effective in case of proper engineering design and compliance technology of construction and operation.

A dam in dry valleys is the most widely used structural conservation measure in the forest-steppe and steppe zones of the former Soviet Union. Most sediment transported from cultivated fields to valleys of 1 – 4 orders, Horton system, accumulate in ponds and reservoirs. A detailed study of small reservoirs in the agricultural regions of Russia, undertaken by Prytkova (1982), found that almost 100% of sediments delivered from the catchment area were detained in the reservoir. It was found that because of sedimentation small reservoirs of the forest-steppe and steppe zones of Russia lose 0.9% per year and 1.8% per year of their useful volumes respectively. Construction of dams prevented sediment transport to the river channel and bottom gully development. Water from ponds is used for irrigation and as cattle drinking water. Construction of the section dams above the gully or ravine head in combination with trees along the edges of the ravine is the most effective method for prevention of slope ravines and bank gullies growth. Conservation measures were widely used in 1970, recently there are not many active bank and slope gullies and ravines in the central part of European Russia. For the most part, erosion forms have stabilized and are covered by grass and brush under the trees. However, dispersal of runoff in combination with changing landuse above a gully head from tillage to grassland is the cheaper approach for preventing bank gully growth. Filling and flattening is the other conservation measure widely used in areas with a high density of gullies.

Table 2 Comparison of soil erosion rates estimated using erosion models with observed soil erosion rates derived from measurements of the volume of sedimentation in small ponds of Central Russian Upland (Litvin, 2002)

No.	Catchment area (ha)	Relief		Observed soil erosion rates ($t\ ha^{-1}\ yr^{-1}$)	Estimated soil erosion rates ($t\ ha^{-1}\ yr^{-1}$)		
		Slope length (m)	Mean slope gradient (%)		During rain-storms	During snow-melting	Total
1	27	500 – 600	3.4	4.9	4.8	0.18	4.98
2	6.75	200 – 300	5.8	22.3	24	0.6	24.6
3	14.75	400 – 500	3.0	5.7	5.6	0.12	5.72
4	6.25	400 – 450	6.5	3.2	4.6	1.3	5.9
5	5.5	300 – 400	4.5	2.0	3.9	0.32	4.22
6	10.0	350 – 450	6.5	6.8	7.25	1.16	8.41
7	8.5	700 – 750	8.5	10.6	9.82	2.24	12.06
8	20.75	200 – 700	5.5	4.6	4.08	0.84	4.92
9	6.5	500 – 600	6.5	4.3	6.09	1.39	7.48
10	12.0	500 – 600	6.5	4.2	6.5	1.04	7.54

Agronomic and vegetative conservation measures are mostly used in steppe and forest-steppe zones. The system of forest-shelter belts for reduction of wind erosion was organized around 1970 for cultivated fields in the steppe and the southern part of the forest-steppe zone. In the forest-steppe zone, system of forest-shelter belts planted along contour lines of the slope are used for reduction of soil and water losses. Different types of soil cultivation were developed for reduction of water runoff and soil losses during snow-melting, in particular for the long cultivated slopes within the uplands.

3 Evaluation of effectiveness of soil erosion control measures for a small catchment in the Kursk region

3.1 *Study area*

The Gracheva Loschina Catchment (catchment area 1.98 km^2) is located about 20 km south-south-east of the regional centre Kursk within the experimental station of the Russian Scientific Institute of Agriculture and Soil Protection from Erosion (Fig. 1). The territory is characterized by a temperate continental climate with a relatively cold winter and a warm summer. Average annual precipitation is 585 mm (for a 100-year period of observation) with variation in a range of 400 – 800 mm. Only 30% of precipitation falls during cold months, mostly as snow. The most typical warm period precipitation events are rainstorms with total rainfall of 10 – 40 mm occurring commonly from May to October. Thickness of the winter-frozen topsoil layer varies from year to year in a range of 0 – 150 cm. This parameter influences runoff during the spring snowmelt period and hence the associated erosion rate. The catchment occupies an area with typical and leached chernozem soils formed mostly on loess deposits. However, underlying parent bedrocks also apparently have some influence on soil properties at different parts of slopes. Catchment topography is characterized by gradually rolling interfluve areas and predominance of convex slopes with maximum gradients up to 5° – 10°. Only a few hollows dissect slopes in the upper part of the catchment (Fig. 1). Most of the catchment area has been cultivated (Fig. 2b). Recently lower parts of slopes and tributary hollow bottoms have been converted to pasture land (Fig. 2b, Fig. c).

Early in 1986 a system of soil conservations measures were introduced on 70% of the catchment area within the two hollows sub-catchment in the upper part of the catchment (Fig. 1, Fig. 2c). Different sets of soil conserva-

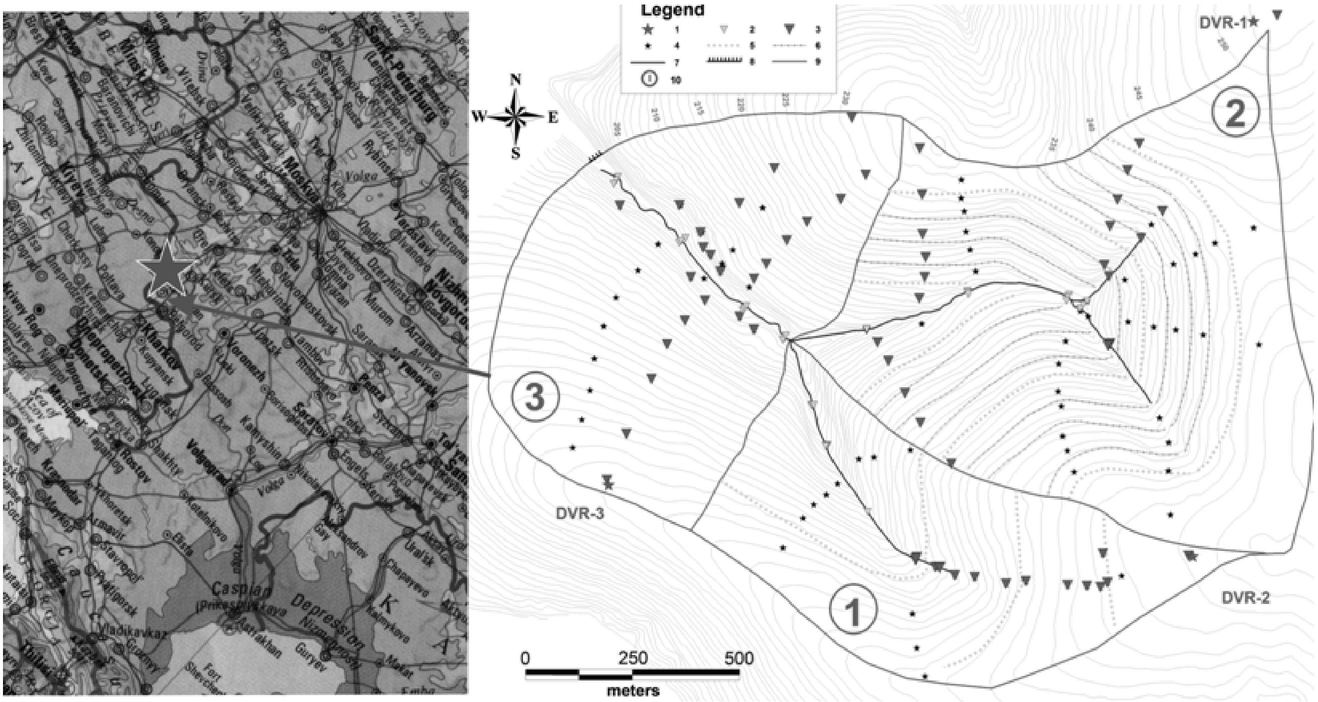

Fig. 1 Approximate location of the case study catchment within the Russian Plain and location of sampling points within the Gracheva Loschina catchment

Legend: 1) DVR-1 – DVR-3 reference point locations (DVR-4 is located outside the map about 1 km to the northwest from the study catchment); 2) soil survey sections in bottoms of the main valley and its two upper branches; 3) soil survey sections along slope transects; 4) ^{137}Cs integral sampling points along slope transects; 5) forest shelter belts; 6) contour terraces; 7) thalweg lines; 8) earthen dam at the catchment outlet; 9) catchment and sub-catchments boundaries; 10) sub-catchments numbers as referred to in the text below. Topography contours are drawn in 1 m intervals.

tion measures were applied within the two sub-catchments. Two-row forest shelter belts planted parallel to the slope topography contour lines and grassed waterways along hollow bottoms were introduced within both sub-catchments. A water retention ditch with depth about 1 m was dug within each forest shelter belt between the two rows of trees. Bottoms of hollows were sown to perennial grasses and used as erosion-protected and sediment-intercepting pathways for surface runoff. In addition, contour terraces parallel to the contour lines with a relative height of about 1 m were constructed between forest shelter belts within sub-catchment 2 (Fig. 1, Fig. 2c). Runoff along those terraces is diverted under 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 are cultivated in the traditional manner (Fig. 2c).

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

The objective of the study is the evaluation of the effectiveness of complex soil erosion control measures using indirect methods of soil redistribution assessment allowing us to obtain mean annual erosion rates for different time intervals.

3.2 *Methods*

The introduction of soil conservation practices and dam construction were completed by spring 1986. That gave a very good opportunity to evaluate the entire catchment sediment budget by independent approaches. First, a detailed large scale geomorphic map was created based on a combination of initially available topographic data and our Differential Global Positioning System (DGPS) and laser theodolite surveys. The map shows different mor-

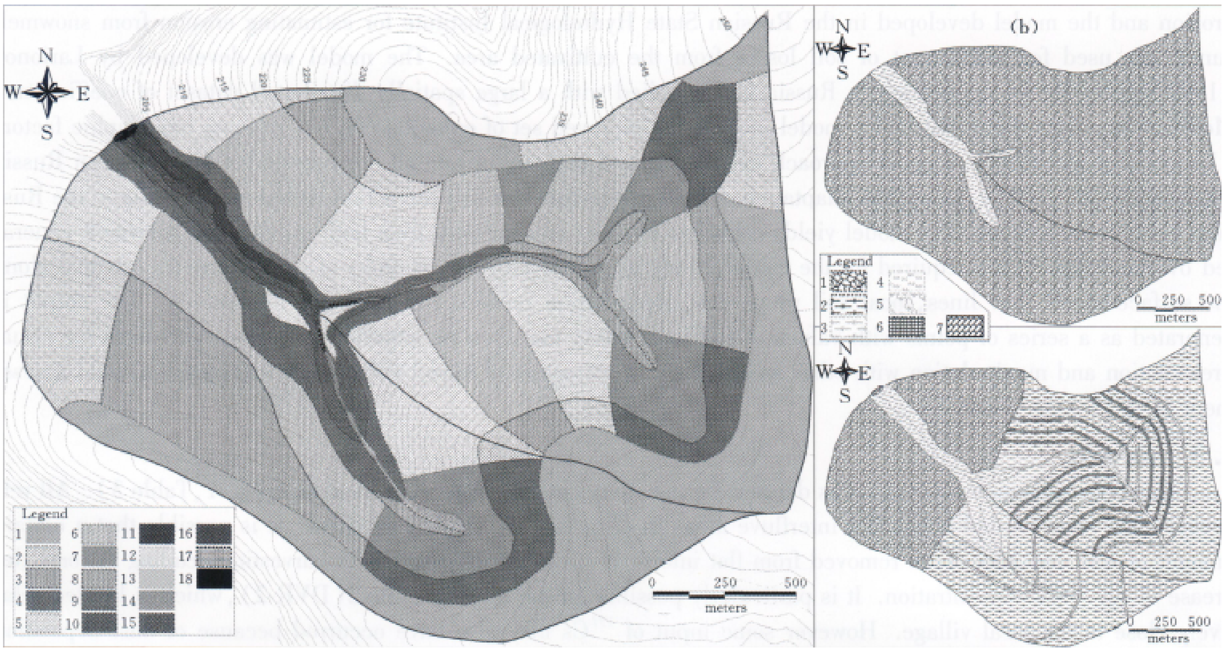

Fig. 2 Geomorphic map of the case study catchment

(a) topography contours are drawn in 1 m intervals; (b) land use before 1986; (c) land use after 1986

Legend: (a): 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. (c): 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.

phological units of the studied catchment distinguished from the DEM analysis and field geomorphic survey (Fig. 2a). The following sampling program was based on that map and aimed to characterize all important morphological units distinguished in terms of sediment redistribution between them. Evaluation of sediment redistribution was carried out for two time intervals on the basis of application 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.

Four reference locations in different parts of study area were chosen for determination of mean value of the ^{137}Cs fallout (Fig. 1). All of them were located on non-eroded tops of rolling cultivated interfluves. At each reference site 12 integral samples from the 0 – 30 cm depth intervals were taken along the spiral. In addition, several bulk samples for radionuclide analysis were taken from each of the slope morphological units within the 2 experimental sub-catchments and the remaining parts of catchment slopes with traditional cultivation. There were 18 geological sections dug along the main valley bottom and bottoms of the 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 7 depositional sections for determination of ^{137}Cs concentration to the depth of 60 – 80 cm. The resulting ^{137}Cs vertical distribution curves at each sampled section were used for calculation of sediment volumes deposited within valley bottoms over different time intervals. Both bomb-derived and Chernobyl fallout of ^{137}Cs were observed at the study area. Thus it is possible to evaluate deposition rate for at least two time intervals: 1964 – 1986 and 1986 – 2006. In a few cases it was also possible to define the year 1958 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 analyzer. Gamma counting period for each sample was not less than 12 hours.

The empirical erosion model using a combination of the USLE-based approach for estimating rainfall-induced erosion and the model developed in the Russian State Hydrological Institute for estimating erosion from snowmelt runoff 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 dataset of coefficients. 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 adaptation of land use factors and soil protection techniques specific to the Russian agricultural system. The model yields estimates of 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 the 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. Verification of model calculation was based on field assessment of soil losses (Table 2).

3.3 *Results*

The ^{137}Cs reference inventory was defined for the study catchment for four locations (Fig. 1, Table 3). All reference sites were located at the flat interfluve areas in or nearby the study catchment. It is possible that a certain amount of soil may have been removed from flat interfluve areas during sugar-beet harvesting, leading to some decrease of the ^{137}Cs concentration. It 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 ground roads. It is most likely for the reference site 1 (DVR-1) with two relatively busy ground 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 and Quine, 1990). No notable spatial trend of the ^{137}Cs inventory have been determined when analyzing the 4 reference locations together, as it 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 (8, 600 Bq/m^2) obtained from the whole set of reference samples from the 4 sites for calculations of the total ^{137}Cs budget.

Table 3 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)
1	2	3	4	5	6
DVR – 1	12	9, 289	5, 219 – 11, 476	22	2, 062
DVR – 2	12	7, 537	6, 298 – 10, 209	16	1, 209
DVR – 3	12	9, 063	7, 206 – 11, 021	13	1, 186
DVR – 4	12	8, 517	6, 346 – 10, 150	13	1, 112

Total ^{137}Cs budget was evaluated using mean values of ^{137}Cs inventory for each individual morphological unit for three sub-catchments (Table 4). Uncertainty is associated with a presence of bomb-derived ^{137}Cs, which redistribution prior to introduction of soil conservation measures was not accounted for in budget calculations.

Table 4 ^{137}Cs budget for different sub-catchments within the Gracheva Loschina catchment

No.	Sub-catchment	Total area (ha)	^{137}Cs loss (KBq) and 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 grass waterways and forest shelter belts	52. 8	189, 606/42. 3	154, 620/82/55. 2	7, 954/4/0. 3	–27, 032/14
2	Sub-catchment with contour terraces, grass waterways and forest shelter belts	88. 1	926, 885/73. 3	834, 195/90/9. 5	24, 650/3/0. 95	–68, 040/7
3	Area with traditional soil cultivation and the main valley bottom	56. 9	236, 786/48. 6	22, 061/9/1. 4	200, 508/85/1. 4	–14, 217/6

According to available information (Atlas.., 1998), 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. It can be suggested that certain part of the bomb-derived ^{137}Cs inventory was 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 4 that most of the Chernobyl-derived ^{137}Cs has been delivered into the main valley bottom from area without soil conservation. Mechanical soil removal to contour terraces during tillage operations in the experimental area can be held responsible for noticeable ^{137}Cs redistribution within the cultivated area of the sub-catchment 2. In the sub-catchment 1 most of the ^{137}Cs redistribution within slopes can be attributed to limited erosion and subsequent sediment redeposition within grassed waterways.

A 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 erosion model calculations along 72 transects. It was found that total soil loss has decreased by 2.8 times between the periods considered (Table 5). The Erosion model used for calculation does not take into consideration within-slope sediment redeposition, so it is very likely that model calculation overestimates soil losses.

Table 5 Sediment budgets in the case study catchment according application of different methods

Method	Time interval (year)	Gross erosion		Deposition within cultivated field		Deposition within hollows and valley bottom		Output from the catchment	
		t	%	t	%	t	%	t	%
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1964 – 1986	66,148	100	6,615	10 * *	15,757	23.8	43,776	66.2
^{137}Cs budget *	1986 – 2006	50,989	100	33,778	82.8	8,766	17.2	0	0
Erosion model calculation and sediment deposition in the valley bottom (vertical distribution of ^{137}Cs)	1986 – 2006	22,606	100	17,050	75.4	5,556	24.6	0	0

* With bomb-derived ^{137}Cs.

* * Defined on a basis of application of ^{137}Cs budget (Table 4, Line 3).

Sediment deposition has been evaluated on the basis of detailed analysis of ^{137}Cs vertical distribution in 7 sections located in different parts of main valley bottom and uncultivated low parts of hollows bottoms, 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 on two time intervals because of regular mixing of soil plough layer during cultivation. Proportions of sediment redeposition within the main valley and tributary hollow bottoms from the total soil loss are similar for both time intervals (Table 5) despite the dam construction in 1986. However deposition rate has decreased by about 2.8 times since 1986. It is also very likely that certain part of the sediment delivered into the main valley bottom during period 1964 – 1986 was transported further downstream by temporary bottom incisions.

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, it is obviously the influence of soil conservation measures introduced on 70% of the catchment area since 1986. Secondly, it is changes of crop rotation, which took place since 1994, when percentage of row crops decreased greatly. It is very likely that both have significantly influenced sediment redistribution rates within the case study catchment.

Application of experimental soil-conservation measures has promoted a substantial decrease of soil loss rates. According to the long-term monitoring undertaken by scientists from Kursk at the experimental catchments with soil conservation measures and another catchment with traditional cultivation (located in about 1 km north), erosion rates during snowmelt periods are approximately 3 times lower on slopes with conservation measures and vary within a range of 0.5 – 1.5 t ha^{-1} from year to year (Zdorovcev and 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 seasons. However the reported value of comparative decrease of soil loss rates is in good agreement with evaluation made by indirect methods presented here.

4 Conclusion

A detailed study of sediment redistribution within the small cultivated catchment has allowed the evaluation of average annual erosion rates on arable slopes for the two time intervals. It has been found that application of conservation measures on cultivated slopes within the experimental part of the case study catchment has led to a decrease of average soil loss rates by at least 2. 5 – 2. 8 times. The figures obtained are in good agreement with previously published results of direct monitoring of snowmelt erosion rates, reporting approximately 3-fold decrease of average snowmelt erosion rates in the experimental catchment compared to a traditionally cultivated control catchment. Substantial decrease of soil erosion rates on arable slopes has been equally reflected in correspondent decrease 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 obtained for the 1986 – 2006 periods from calculations by two independent approaches (the ^{137}Cs budget and combination of erosion model with aggradation assessment by the ^{137}Cs vertical distribution in sediment sections).

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