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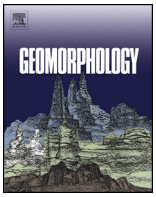

Influence of relief characteristics and landscape connectivity on sediment redistribution in small agricultural catchments in the forest-steppe landscape zone of the Russian Plain within European Russia

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ABSTRACT

Sheet, rill and gully erosion occurring in the snowmelt period (March–April) and rainfall season (May–September) is the main factor of soil degradation and mobilized hillslope sediment redistribution within cultivated lands of the Russian Plain. The evaluation of sediment redistribution for the period since 1986 within catchment sediment cascades was done based on an integrated approach for some representative dry valley catchments located in the western (the Plava River basin, Tula Oblast, Russian Federation) and eastern (the Temeva Rechka Creek catchment, the Myosha River basin, Republic of Tatarstan, Russian Federation) sectors of the forest-steppe landscape zone of the Russian Plain. All the catchments studied are characterized by a high proportion (within the range of 60–80%) of cultivated lands. The modified version of the Universal Soil Loss Equation (USLE), the Russian State Hydrological Institute's erosion model, and the LandSoil erosion model were applied to calculate soil losses within the cultivated lands. The morphological classification of interfluve slopes and hollow slope catchments, in combination with the sediment delivery ratio (SDR) assessment for slopes and hollow slope catchments of different configuration, were used to assess sediment transfer from the cultivated lands. The Chernobyl-derived ^{137}Cs isotope was applied as a chronomarker for sediment dating in different sediment sinks located along pathways from cultivated slopes to river valley bottoms. We found that the morphological features of the dry valley catchments, including a pattern of the dry valleys of different Hortonian orders, dry valley and hollow density, dry valley incision depth, and proportion of slopes and hollow slope catchments of different configurations are the main parameters that determined a proportional input of the different sediment sinks to the sediment interception along the pathways from the cultivated slopes to the river valley bottoms. The land use/cover features are mostly responsible for the pattern of buffer zones within the interfluve parts of the catchments. The quantitative assessment of the sediment budget allowed us to conclude that the mean SDR coefficients for the dry valley catchments of second, third, and fourth Hortonian orders are 0.56, 0.33, and 0.07 respectively. The extrapolation of the study results of sediment redistribution evaluation, obtained from the studied catchments located within the Plava River basin, to the entire basin of the river also allowed us to evaluate the mean value of hillslope-to-river-valley-bottom SDR = 0.27.

1. Introduction

The quantitative assessment of sediment delivery within different components of fluvial cascade systems is one of the key problems of fluvial geomorphology during the last decades (Walling, 1983; Bracken and Croke, 2007; Golosov, 2009; Hopp and McDonnell, 2009; Heckmann et al., 2010; Wainwright et al., 2011; Fryirs, 2013; Haregeweyn et al., 2013; Bisantino et al., 2015; etc.). In general, to solve the problem it is necessary to evaluate the amount of sediments eroded within a catchment area and redeposited along the pathways from catchment slopes to river mouths. The sediment delivery ratio (**SDR**) (the ratio between gross and net erosion for a particular area: slope, small catchment, or river basin) has been used to provide a first evaluation of the connectivity between different units of the fluvial cascade systems (Glymph, 1954; Walling, 1983; Brierley et al., 2006; Baartman et al., 2013; etc.). The topographic Index of Connectivity (IC) relying on topography derived from the Digital Terrain Model (DTM) is widely used to evaluate sediment redistribution in the different sediment sinks (Borselli et al., 2008). A large number of sediment storage and redistribution studies were undertaken in mountains in different parts of the European Alps (Schrott et al., 2003; Mao et al., 2009;

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Schlunegger et al., 2009; Tarolli and Dalla Fontana, 2009; Wichmann et al., 2009; Theler et al., 2010; Cavalli et al., 2013; Heckmann and Schwanghart, 2013; Santangelo et al., 2013; Messenzehl et al., 2014; etc.) and other regions of Eurasia (Borselli et al., 2008; D'Haen et al., 2013; Laute and Beylich, 2013; López-Vicente et al., 2013; Simoni et al., 2013; Ali et al., 2014; Foerster et al., 2014; etc.). High influence of topographic factors on sediment transport and storage is associated with steepness of mountainous areas and significant density of linear erosion landforms there.

Land use/cover characteristics mainly determine the SDR within plains (Gay et al., 2016). The use of IC exclusively based on topography may not reveal hot spots of connectivity because factors other than topography control the (dis)connectivity between the different points (Fryirs et al., 2007; Ali et al., 2014). Sediment delivery to slope catchment outlets is also strongly dependent on the spatial organization of land use/cover, as well as the connectivity between sediment-producing areas and catchment outlets (Steegen et al., 2001).

Sediment connectivity is a connected transfer of sediments from a source to a sink in geosystems via sediment detachment and sediment transport. It is controlled by how the sediment moves and partly or completely redeposits between all anthropo-geomorphic and natural relief units. These relief units control sediment yield in the hillslope-to-river-valley cascades within the agriculturally transformed landscapes (Verstraeten et al., 2009; Bracken et al., 2015). The plains of the temperate climate zone of Earth are mainly used as agricultural lands. Soil particles eroded from cultivated fields are the main sediment sources for the local rivers (Dedkov and Mozzherin, 1984; Lang et al., 2003; Golosov, 2006; Dotterweich, 2008; Trimble, 2008, 2010; Gusarov, 2015; etc.). Large masses of sediments, mainly originating from cultivated slopes, are deposited and stored within footslopes and dry valley bottoms, nearby their source areas (Golosov et al., 1992, 2013; Golosov, 1998, 2009; Larionov et al., 1998; Belyaev et al., 2008; Verstraeten et al., 2009; Smetanová et al., 2017).

The amount of sediments that may be delivered from basin (catchment) slopes to river valley bottoms within the upland and lowland areas of the temperate climate zone of Earth are mainly controlled by a proportion of arable lands area within the catchments and also by their locations within the river basins. It was established (Golosov, 1988) that only ~34% of cultivated hollow slope catchments are coupling to river valley bottoms in the Protva River basin (with total area of arable lands <40%) located in the forest landscape zone of European Russia. Mobilized hillslope sediments eroded from other slopes with different configurations in the Protva River basin are totally redeposited within the interfluve slopes. Moreover, drainage patterns of sediment transfer from cultivated lands to river valley bottoms determine the interfluve-hillslopes-to-river-valley-bottom connectivity for different landscapes (Brunsden and Thornes, 1979; Meade, 1982; Walling, 1983; Caine and Swanson, 1989; Phillips, 1992; Lang and Hönscheidt, 1999; Harvey, 2002; Michaelides and Wainwright, 2002; Hooke, 2003; Schrott et al., 2003; Golosov, 2006; etc.).

Soil erosion intensity in the Russian Plain increased owing to destruction of its natural vegetation cover about 300 years ago, since the beginning of the intensive cultivation period there (Sidorchuk and Golosov, 2003). The highest erosion rates within agricultural lands were observed during the second half of the nineteenth century after land reform in the Russian Empire in 1861, which promoted ploughing the steep valley sides in the region (Sidorchuk et al., 2006). The increase in sediment yield from arable areas led to intensive small river aggradation and a decrease in permanent stream network density, which has reduced to the middle of the twentieth century compared to the middle of the nineteenth century by 30–40% in the forest-steppe zone of this plain (Golosov and Panin, 2006). As a result, the total length of dry valleys has increased proportionally to the shrinking of permanent streams. Consequently, enlargement of the dry valley network in the forest-steppe zone of the Russian Plain should lead to a reduction in the SDR from cultivated slopes to river valley bottoms.

Soil erosion within arable lands during the period of snowmelt (March–April) and the rainfall season (May–October) is the main denudation process in the Russian Plain where climate and land use/cover have changed over the last three decades. The fixed increase mainly in winter air temperatures led to the increase in soil temperatures (Park et al., 2014) and, as a consequence, to a reduction in frozen soil depths (Barabanov and Panov, 2012; Golosov et al., 2017; Gusarov et al., 2018a, 2018b, 2018c). As a result, surface water runoff on slopes during snowmelt has reduced considerably since the mid-1990s in the forest-steppe landscape zone (Petelko et al., 2007; Barabanov et al., 2018). Simultaneously, the area of cultivated lands has decreased after the USSR collapse in 1991 (Lyuri et al., 2010).

We know that sediments in the upper reaches of drainage systems are carried out by temporary watercourses. The study and modelling of sediment transport by temporary watercourses are complicated by their high spatial-temporal heterogeneity, which makes the construction of a widely applicable, physically based model extremely difficult. The vast territories of the Russian Plain were contaminated by the ^{137}Cs isotope after the Chernobyl accident (Izrael et al., 1994; De Cort et al., 1998). The Chernobyl-derived ^{137}Cs can be used as a chronomarker for sediment dating and evaluation of sediment storage in different sediment sinks of fluvial systems since April–May 1986 (Markelov et al., 2012; Golosov et al., 2013, 2017, 2018a, 2018b; Gusarov et al., 2018a, 2018b, 2018c; etc.). As a result, we are able to assess the volume of mobilized hillslope sediment and their proportion redeposited along the pathways from interfluve slopes to river valley bottoms. In the case of the existence of a dam located in a river (or creek) valley, we can evaluate the amount of sediment delivered by temporary flows to the river valley for a fixed time interval (Belyaev et al., 2013).

The purpose of this research is to evaluate the connectivity and mechanism of sediment transfer between small catchments (with dry valleys) and river valley bottoms (including terraces, floodplains, and riverbeds) in river basins with a high proportion of cultivated lands, located in the central part of European Russia, within the forest-steppe landscape zone, over the last 25–30 years. Particular attention is given to evaluation of the role of dry valley bottoms as sediment sinks along the mobilized hillslope sediment pathways from cultivated lands to river valley bottoms and to approaches for extrapolation of the results of quantitative assessment of sediment redistribution within small (1–3 orders) (sub)catchments to the entire area of small river basins.

2. Material and methods

2.1. Study areas

The study areas (the Temeva Rechka Creek catchment and the Plava River basin) are located in the central part of the Russian Plain, within the northern part (subzone) of the forest-steppe landscape zone with a high proportion of cultivated lands, in territories with different levels of ^{137}Cs contamination (Fig. 1A). The areas are characterized by a temperate continental climate: the mean annual precipitation is about 550–600 mm, one-third of which falls during the cold season (November–March). The generalized climate characteristics of the areas are presented in Table 1. Regional relief is characterized by the alternation of uplands and lowlands. Soil cover is represented by light grey and grey forest soils or chernozems (National Atlas …, 2011). The soil parent rocks are eluvium of dominantly limestones, marls, and sandstones of Permian (the Temeva Rechka Creek catchment) (Dedkov, 2003) and Devonian-Carboniferous (the Plava River basin) (Ratnikov, 1960) periods, covered by the Late Quaternary loess loams (the Plava River basin) or deluvium/solifluction loams (the Temeva Rechka Creek catchment). The most elevated areas of these uplands were not affected by the glaciations in the Pleistocene. So, topography of these areas was basically modified by incision of temporal and constant water streams and also by redeposition of eroded sediments. Soil

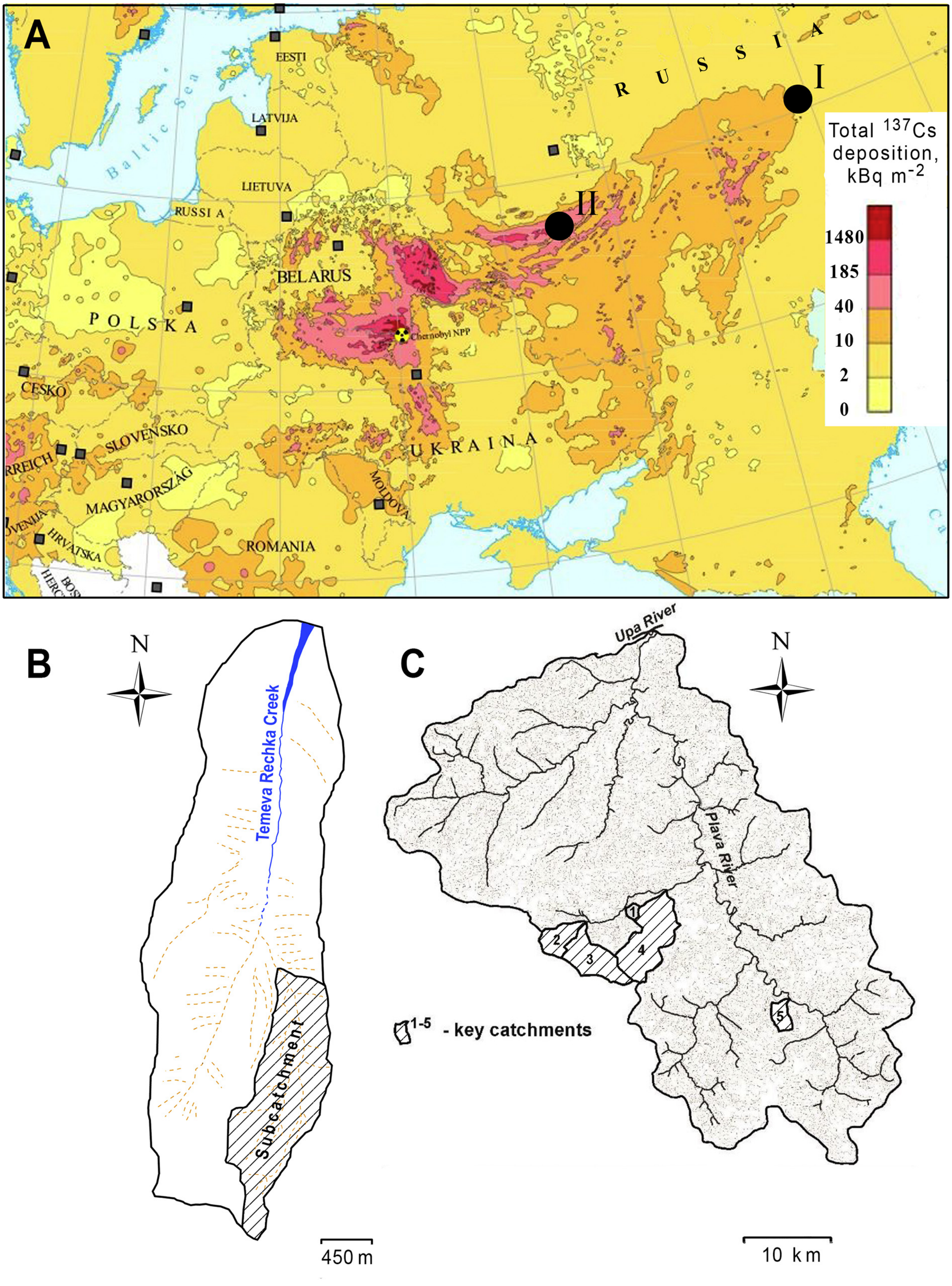

Fig. 1. Location of the studied catchments within the Chernobyl ^{137}Cs-affected area in the Russian Plain (A) (according to Atlas of Radioactive Contamination … (1998); I – the Temeva Rechka Creek catchment, II – the Plava River basin); (B) the Temeva Rechka Creek catchment with studied dry valley subcatchment; (C) the Plava River basin with studied key catchments: 1 – Lapki; 2 – the western part of the upper Lokna River basin (the western upper Lokna catchment); 3 – the eastern part of the upper Lokna basin (the eastern upper Lokna catchment); 4 – the Chasovenkov Verkh catchment; 5 – the Lyapunovka catchment.

Table 1
Some regional climate characteristics of the study areas (see Fig. 1).

Characteristics	The Temeva Rechka Creek catchment[a]	The Plava River basin[b]
Mean annual temperature, °C	4.8	5.6
Mean temperature for three calendar winter months, °C	−9.7	−4.7
Annual precipitation, mm	566	610
Total precipitation for May–September, mm	274	320

[a] According to the observations in a weather station of the city of Kazan (for 1986–2015).
[b] According to the observations in a weather station of the city of Tula (for 1981–2011).

erosion is observed mostly on cultivated fields during snowmelt (March–April) and the warm period of year (May–September) during intensive rainfalls. Gully erosion is not an important contributor of sediments in the region during the last 25–30 years. However, bottom gullies are observed within dry valley bottoms, and they are an important component of sediment redistribution within the dry valley catchments (Panin et al., 2001).

2.1.1. The Temeva Rechka Creek catchment

The Temeva Rechka Creek catchment is located in the central part of the Myosha River basin (a right tributary of the lower Kama River) within the West-Kama Upland, 39 km to the southeast from Kazan, the capital city of the Republic of Tatarstan (Russian Federation). Total area of the catchment is 4.87 km^2 upstream of the pond constructed in 1989. About 77% of its total area is cultivated lands. One of the second-order subcatchments, located in the upper reach of the Temeva Rechka Creek catchment (Fig. 1B), was selected for a detailed investigation of sediment redistribution. The mean absolute height of the dry valley subcatchment is 161 m, height amplitude is about 74 m. This subcatchment is representative of the entire creek catchment caused by its proportion of different land use/cover types and main morphometric characteristics (Tables 2 and 3). Total area of the subcatchment is 1.13 km^2, and the areas of uncultivated dry valley and dry valley bottom are 0.14 and 0.024 km^2 respectively. Small incisions with mean depth around 0.2–0.4 m and <1–2 m long are located along the bottom thalweg. The active bottom gully is located in the lower reach of the subcatchment. The gully has a depth up to 3.0–3.5 m, and it is partly fulfilled in its middle and lower reaches by sediments originated from the cultivated lands and reaccumulated deposits from the dry valley bottom. The latter has appeared mostly because of the gully headcut retreat. The bottom gully is directly connected with the main stream of the Temeva Rechka Creek catchment. The interfluve slopes of the subcatchment are dissected by a network of hollows that served as the main pathway of sediments eroded from cultivated slopes to the dry valley bottom. In addition, ephemeral gullies are formed in the hollow bottoms in cases of intensive surface water runoff formation on the cultivated slopes. These ephemeral gullies are more often observed during the period of spring snowmelt (March, April).

2.1.2. The Plava River basin

The Plava River (basin area is 1856 km^2; the length of the main water stream is 89 km) is a left tributary of the Upa River (a right tributary of the Oka River, the upper Volga River basin). The main watershed line (drainage divide) between the Plava River and Zusha River is in the highest interfluve of the Central Russian (Srednerusskaya) Upland with elevation about 290 m. The Plava River basin is characterized by gently sloping, elevated plain relief with a relatively strong erosional dissection (~60–80 m). Cultivated land areas were changed during the last 30 years within the range of 50–75% with the minimum in the end of 1990s and the beginning of 2000s. It was associated with the economic crisis after the USSR collapse in 1991. The Plava River basin is the most contaminated river basin on the long distance from the Chernobyl Nuclear Power Plant with maximum Chernobyl-derived ^{137}Cs contamination in the central part of the Russian Plain, within the Lokna River basin, a left tributary of the Plava River (Fig. 1A).

A detailed investigation of sediments and sediment-associated ^{137}Cs redistribution is undertaken at five key catchments of the Plava River basin (Fig. 1C, Table 4) and partly published elsewhere during the last 20 years (Fridman et al., 1997; Golosov et al., 1999; Kvasnikova et al., 1999; Walling et al., 2000; Panin et al., 2001; Golosov and Ivanova, 2002; Bezukhov et al., 2014; Ivanov et al., 2017). In addition, a detailed investigation was performed in the upper Lokna River basin, where sediment budget for the period since 1986 until the sampling time (2010–2012) was evaluated more carefully owing to the location of a small reservoir in the catchment outlet. The reservoir dam was constructed before 1986, so most of the sediments delivered to the reservoir from the catchment area are redeposited within the reservoir bottom.

2.2. Methods

The local features of topography and agro-landscape characteristics (cultivated fields configuration and their location in relation to drain network including uncultivated parts of hollows, dry valleys, and river valleys) control sediment transfer and redistribution from cultivated lands to river valley bottoms within the forest-steppe zone of the Russian Plain. This study is based on morphometric and Horton's analysis, comprehensive geomorphic mapping and evaluation of sediment budgets for the few typical small dry valley catchments. In addition, changes in land use/cover over the last 30 years within the studied catchments are taken into consideration as far as soils, eroded on arable lands, are believed to be the main sediment sources in agricultural landscapes of the temperate climate zone of the Russian Plain. The combination of methods, techniques, and erosion models were applied for evaluation of the soil loss/gain for the different morphological units, selected within the studied catchments, based on the morphometric analysis and geomorphological mapping.

2.2.1. Morphometric analysis

According to the results of field assessment of sediment redistribution within the arable lands in different parts of the central European Russia, we found that slope configurations were considerably influenced on the SDR from the cultivated slopes to the adjacent valley bottoms (Braude, 1991; Golosov et al., 1992; Golosov, 1996, 1998, 2006; Ivanov and Nazarenko, 1998; Panin et al., 2001; etc.). We selected five main types of slopes and hollow slope catchments, according to the classification of slope configurations (Panin et al., 2001; Litvin et al., 2003), for the uplands and lowlands of the Russian Plain (Fig. 2). At

Table 2
Land use/cover within the Temeva Rechka Creek catchment and its studied subcatchment (see Figs. 1 and 3).

Characteristics	The Temeva Rechka Creek catchment				Studied dry valley subcatchment of the Temeva Rechka Creek catchment			
Land use/cover	Ploughland	Woodland[a]	Grassland[b]	∑	Ploughland	Woodland[a]	Grassland[b]	∑
Area, ha	487	41	104	632	87	6	20	113
Proportion in the total area of the catchment, %	77	5	18	100	77	6.5	16.5	100

[a] Natural and artificial (planted) forests.
[b] Pristine meadows, and pastures.

Table 3
Gradients of the cultivated slopes within the Temeva Rechka Creek catchment and its studied subcatchment (see Figs. 1 and 3).

Characteristics	The Temeva Rechka Creek catchment					Studied dry valley subcatchment of the Temeva Rechka Creek catchment				
Gradients of the cultivated slopes, °	0–2	2–4	4–6	6–8	>8	0–2	2–4	4–6	6–8	>8
Area, ha	206.3	184.0	70.5	19.2	7.0	33.5	34.8	12.5	4.9	1.2
Proportion in the total area of the catchment, %	42.4	37.8	14.5	3.9	1.4	38.5	40.0	14.5	5.6	1.4

the same time, straight slopes can be found relatively seldom within the forest-steppe landscape zone of the Russian Plain. Topographic maps with scale 1:100,000 (for the Plava River basin) and 1:25,000 (for the Temeva Rechka Creek catchment and the studied dry valley catchments within the Plava River basin) were digitized. The GIS ArcMap 10.3 and MapInfo 11.5 were used for DEM construction. Topo to Raster tools were applied for DEM interpolation. Mapping of the different types of slopes and hollow slope catchments for the entire river basins was undertaken manually (Fig. 3).

2.2.2. Geomorphological mapping

Large-scale geomorphological mapping was carried out for the upper Lokna dry valley catchments and the Temeva Rechka dry valley subcatchment (Fig. 4). The principles of the mapping were previously outlined in publications related to the evaluation of sediment and sediment-associated ^{137}Cs redistribution within another key dry valley catchments located in the Plava River basin (Panin et al., 2001; Golosov and Ivanova, 2002; Bezukhov et al., 2014; etc.). The main goal of the geomorphological mapping was to split studied catchments on main morphological units with different intensity of erosion and deposition processes for the studied time window, as well as geomorphologically stable units without soil/sediment loss/gain. The area of each morphological unit was measured using GPS and a tape. In addition, some linear elements of local relief (which characterize sediment pathways or can potentially influence sediment redistribution) were also mapped, including field borders, thalwegs of uncultivated hollows that dissect the (dry) valley sides, bottom gully headcuts, and so on (Fig. 4).

2.2.3. Evaluation of erosion rates within cultivated slopes

Two erosion models were used for evaluation of erosion rates within cultivated slopes. One of them is an empirical model that used a combination of the modified version of the USLE-based approach for estimating rainfall-induced erosion (Larionov, 1993) and the Russian State Hydrological Institute (SHI, Saint Petersburg, Russia) model for estimating erosion during the snowmelt period (Bobrovitskaya, 2002). The other model is the LandSoil erosion model (Souchere et al., 2001) based on the STREAM soil erosion model (Cerdan et al., 2002) and the WaTEM/SEDEM tillage erosion model (Govers et al., 1994). The STREAM erosion model is a spatially distributed model; it was developed on the ArcGIS platform. This makes it possible to evaluate soil redistribution at the field/small catchment scale in medium terms. The LandSoil erosion model is successfully used for the plain landscape conditions (Ciampalini et al., 2012; Lacoste et al., 2014).

According to the results of verification undertaken for the central part of the Russian Plain, the USLE modified version overestimates the erosion rates caused by its inability to assess within-slope redeposition (Sidorchuk et al., 2006). However, input data can be collected easy enough. Some parameters required for the erosion rate calculations were taken from an existing database (Larionov, 1993). Meteorological parameters have been provided by the All-Russia RIHMI World Data Center (http://aisori.meteo.ru/ClimateE). Data about the spatial extent of different crop types for the Temeva Rechka Creek catchments for 1986–2015 were taken from the Russian Federal State Statistics Service (www.gks.ru). In the case of the upper Lokna River basin, information about crop rotation was provided by local farmers and an agricultural company. In addition, results of the interpretation of satellite images were used for identification of crops for individual fields. Crop rotation coefficients for modelling were calculated separately for both the warm period (May–September, rainfall season) and snowmelt period (March–April).

Table 4
The studied catchments of the Plava River basin (see Fig. 1): area and Hortonian order.

Catchments		Area, km^2	Hortonian order
Lapki		1.22	2
Lyapunovka		11.08	3
Upper Lokna	Western	15.05	3
	Eastern	24.08	3
Chasovenkov Verkh		39.67	4

The LandSoil erosion model was used only for the upper Lokna River basin because we had no opportunity to collect acceptable input data for the Temeva Rechka Creek catchment. The following inputs were collected for the LandSoil erosion model: (i) digitized version of topographic map (scale 1:10,000) produced in 1986 was used for the DEM; (ii) crop rotations and requested soil-surface characteristics (soil surface crusting, surface roughness, and vegetation cover). Information about crop rotations were collected from local farmers and an agricultural company. In addition, the results of interpretation of high-resolution satellite images and aerial photographs, taken during the summer of 1990, 2002, and 2009, were used for construction of land use/cover maps for different time windows within the upper Lokna River basin (Fig. 5). The monthly soil surface characteristics were attributed to different crops based on expert knowledge and field-survey data; (iii) soil tillage operation data (direction of tillage, the coefficient of tillage erosion, and the number of operations per year) were collected based on the information from local farmers; and (iv) rainfall event characteristics were collected from a weather station in the city of Plavsk located 8 km away from the study area.

2.2.4. Sedimentological methods and dating

The Chernobyl-derived ^{137}Cs was used as a chronomarker to evaluate sedimentation rates in the different sediment sinks of the studied catchments for the period since 1986 (Golosov, 2002; Golosov et al., 2013, 2018a, 2018b; Gusarov et al., 2018a, 2018b, 2018c). The selection of sampling points for sediment sink sites was based on the results from geomorphological mapping of the catchments. The main attention was given to the evaluation of sedimentation rates in different sectors of the dry valley bottoms of the catchments, and (except the Temeva Rechka Creek catchment) in the lower parts of cultivated slopes, and in the uncultivated parts of hollow bottoms of the subcatchments. One sediment profile was excavated for each dry valley bottom reach (sector) (Fig. 4). The profile depths were changed in the range of 1–2 m depending on the total amount of sediments in the given locations. A detailed description with photos of the sediment profile was done. The profile face with the lowest disturbances by bioturbation was selected for incremental depth sampling. The depth incremental samples were taken out only from the prepared and described sediment/soil sections where sedimentation processes are believed to occur without any agricultural disturbance. This approach allows for avoiding any random mistakes linked to a mix caused by soil fauna and roots. Sediment samples without grass were collected from an area 15 × 15 cm at 2–3 cm depth increments for the upper 60–70 cm and at 5 cm depth increments below 60–70 cm from an area 10 × 10 cm. In addition, two cores were

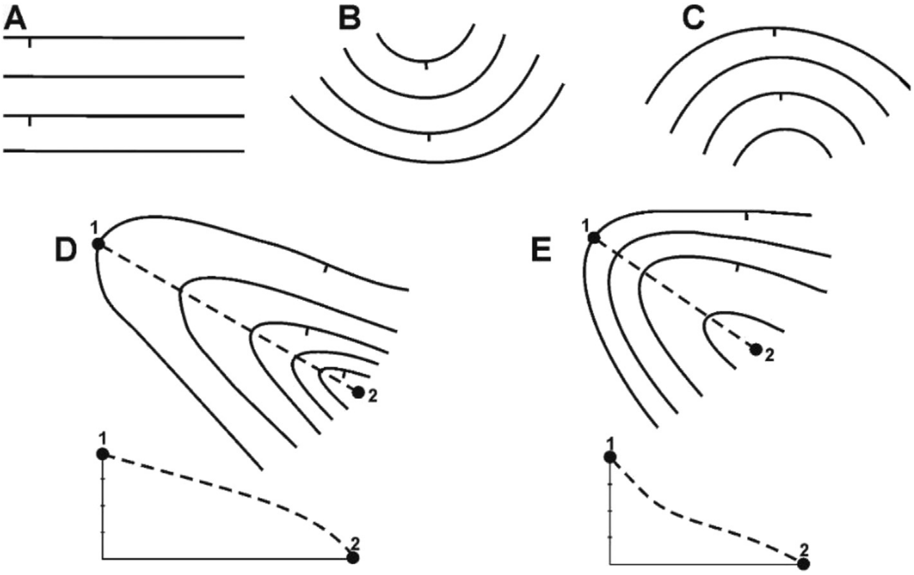

Fig. 2. Morphological classification (according to Panin et al., 2001) of slopes: (A) straight, (B) divergent, (C) convergent; and hollow slope catchments: (D) with a convex thalweg profile, (E) with a concave thalweg profile; 1, 2 – extreme points on the thalweg profiles.

carried out during the winter or spring periods from the stable ice surface from the bottom of the reservoir located in the outlet of the upper Lokna River basin. The half-cylindric hand corer with a 1 m long sample compartment was used for the sampling. During the sampling procedure the half-cylindric sample compartment was closed by the rotation of the top handle by 180° in order to prevent loss of the core and ensure maintenance of the more-or-less regular geometry. Upon lifting the core, the sample compartment was opened and left for a short period in order to let the potentially liquefied upper sediment layers freeze under open air conditions. Then the core was measured, described, and photographed. Finally, the frozen core was carefully cut into depth increments, in most cases at 3 cm intervals (Belyaev et al., 2012).

Subsequent laboratory processing of the ^{137}Cs samples involved oven-drying at 105 °C, disaggregation using a mortar and pestle, sieving to <2 mm, and homogenization of subsamples for γ-analysis. Plastic pots were used for the 100–110 g subsamples obtained from the depth incremental samples. The ^{137}Cs activity was measured at 661.66 keV using a high-resolution, low-background, hyper-pure germanium coaxial γ-ray detector with a maximum relative error of the isotope activity determination of ±5–7%. Totally, >1000 soil and sediment samples taken within the Temeva Rechka dry valley subcatchment and the upper Lokna River basin were analyzed. Sample preparation, treatment, and ^{137}Cs activity measurements were carried out at the Research Laboratory of Soil Erosion and Fluvial Processes, Faculty of Geography, Lomonosov Moscow State University, Russia.

Sedimentation rates for the period since 1986 were determined based on the interpretation of the ^{137}Cs depth distribution curves, allowing us to identify the Chernobyl-derived (1986) peaks for all sampling locations (Du and Walling, 2012; Golosov et al., 2013, 2018a, 2018b; Gusarov et al., 2018a).

2.2.5. Sediment budget assessment (for the upper Lokna River basin)

The sediment budget for the upper Lokna River basin for the period since 1986 is calculated as follows:

$$E_s = M_s + M_{us} + M_{dvb} + M_r \tag{1}$$

where E_s – total soil losses from cultivated fields, t; M_s – total sediment storage within the fields and on the boundary between the fields and uncultivated slopes, t; M_{us} – total sediment storage along the pathways from boundary of the cultivated fields and dry valley bottoms, t; M_{dvb} – total sediment storage in the dry valley bottoms, t; M_r – total sediment storage in the reservoir, t.

Soil losses from cultivated fields (E_s) are calculated as follows:

$$E_s = R_1S_1 \times 10 + R_2S_2 \times 11 + R_3S_3 \times 5 \tag{2}$$

where $R_{1,2,3}$ – calculated mean annual erosion rates in 1986–1996, 1996–2007, and 2007–2012 respectively, t ha^{-1} y^{-1}; $S_{1,2,3}$ – mean area of cultivated lands during 1986–1996, 1996–2007, and 2007–2012 respectively; 10, 11, and 5 – the number of observation years.

Sediment storage within cultivated fields and on the boundary between the fields and uncultivated slopes (M_s) is calculated as follows:

$$\begin{aligned} M_s = {} & E_{st} \times D_{st} \times 0.4 + E_d \times D_d \times 0.2 + E_c \times D_c \times 0.8 + E_{hcn} \times D_{hcn} \\ & + E_{cc} \times D_{cc} \times 0.6 \end{aligned} \tag{3}$$

where E_{st} – total soil losses from straight slopes, t; D_{st} – proportion of straight slopes area in the total area of cultivated fields; E_d – total soil losses from divergent slopes, t; D_d – proportion of divergent slopes area in the total area of cultivated fields; E_c – total soil losses from convergent slopes, t; D_c – proportion of convergent slopes area in the total area of cultivated fields; E_{hcn} – total soil losses from hollow slope catchments with convex thalwegs, t; D_{hcn} – proportion of hollow slope catchments with convex thalwegs in the total area of cultivated fields; E_{cc} – total soil losses from hollow slope catchments with concave thalwegs, t; D_{cc} – proportion of the area of hollow slope catchments with concave thalwegs in the total area of cultivated fields; 0.4, 0.2, 0.8, and 0.6 – the SDR coefficients for different types of slopes and hollow slope catchments (according to Panin et al., 2001; Golosov, 2006).

Sediment storage along pathways from the boundary of cultivated fields and dry valley bottoms (M_{us}) can be evaluated for slopes without flow concentration, based on the assessment of distance between the boundaries of these units. According to Novotny and Chesters (1981), a distance of 50 m of grass cover is more than enough for sediment trapping. However, it is much more difficult to evaluate the proportion of sediments that are redeposited on the dry valley sides if their length is <40–50 m, because deposition seriously depends on a number of random factors (microtopography of the field boundary, intensity and turbidity of surface water runoff, density of grass cover on uncultivated slope, etc.). Similar factors affect sediment deposition in the case of surface water runoff in the uncultivated lower reaches of hollows that often

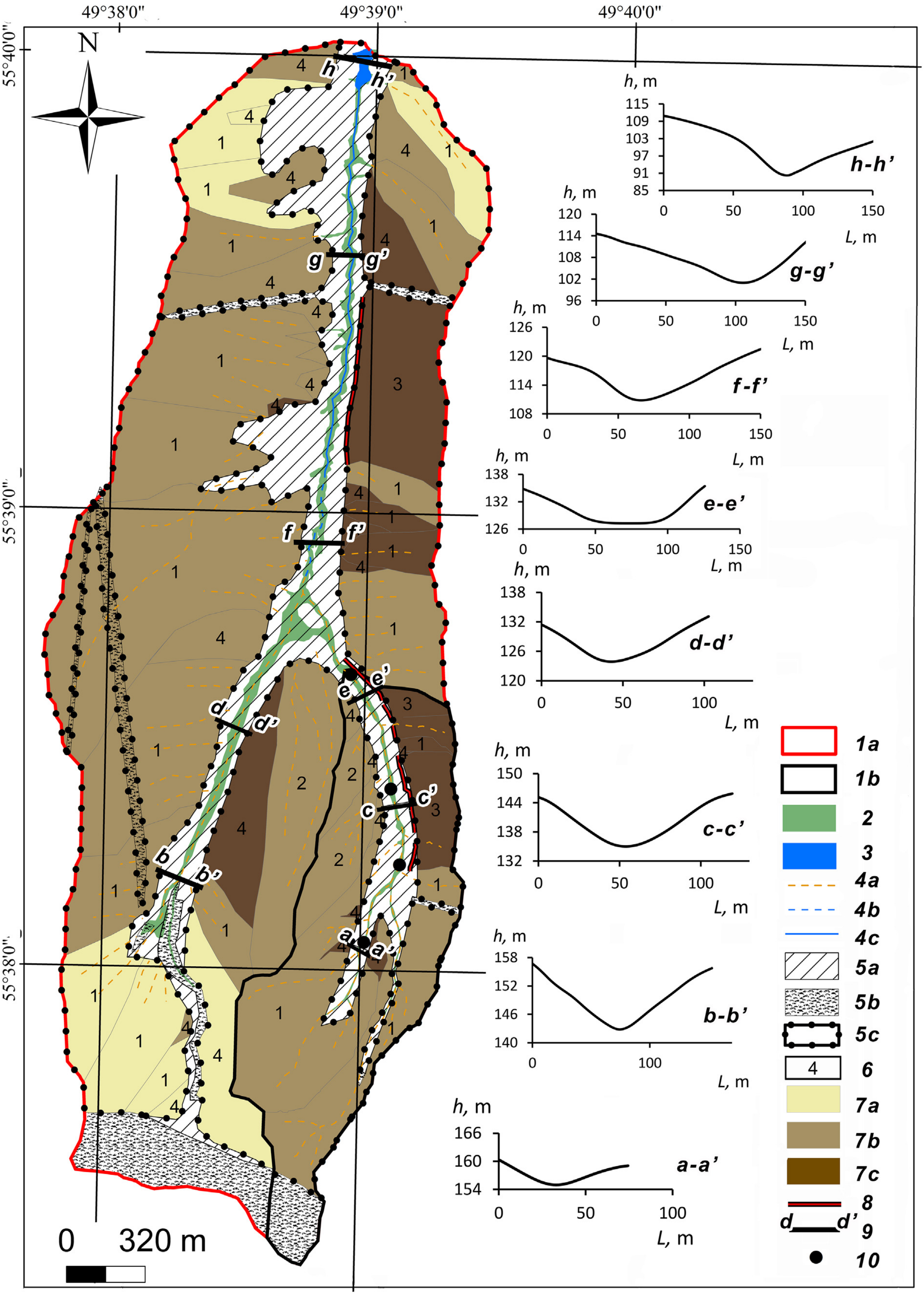

Fig. 3. Map of the Temeva Rechka Creek catchment with different types of slopes and hollow slope catchments. *1a* – boundary of the Temeva Rechka Creek catchment; *1b* – boundary of the studied subcatchment; *2* – valley (dry valley) bottoms; *3* – pond; *4a* – hollow thalwegs; *4b* – temporary watercourse; *4c* – permanent stream (creek); *5a* – meadow/pasture; *5b* – forests (natural and artificial); *5c* – boundary of cultivated fields; *6* – types of slopes and hollow slope catchments (1 – hollow slope catchment with a convex thalweg; 2 – hollow slope catchment with a concave thalweg; 3 – convergent slopes; 4 – divergent slopes); *7a,b,c* – cultivated slopes with different mean slope gradients (*a* – 0–2°, *b* – 2–4°, *c* – 4–6°); *8* – old boundary of cultivated field; *9* – dry valley cross section profiles location; *10* – sediment sections at the dry valley bottom of the studied subcatchment.

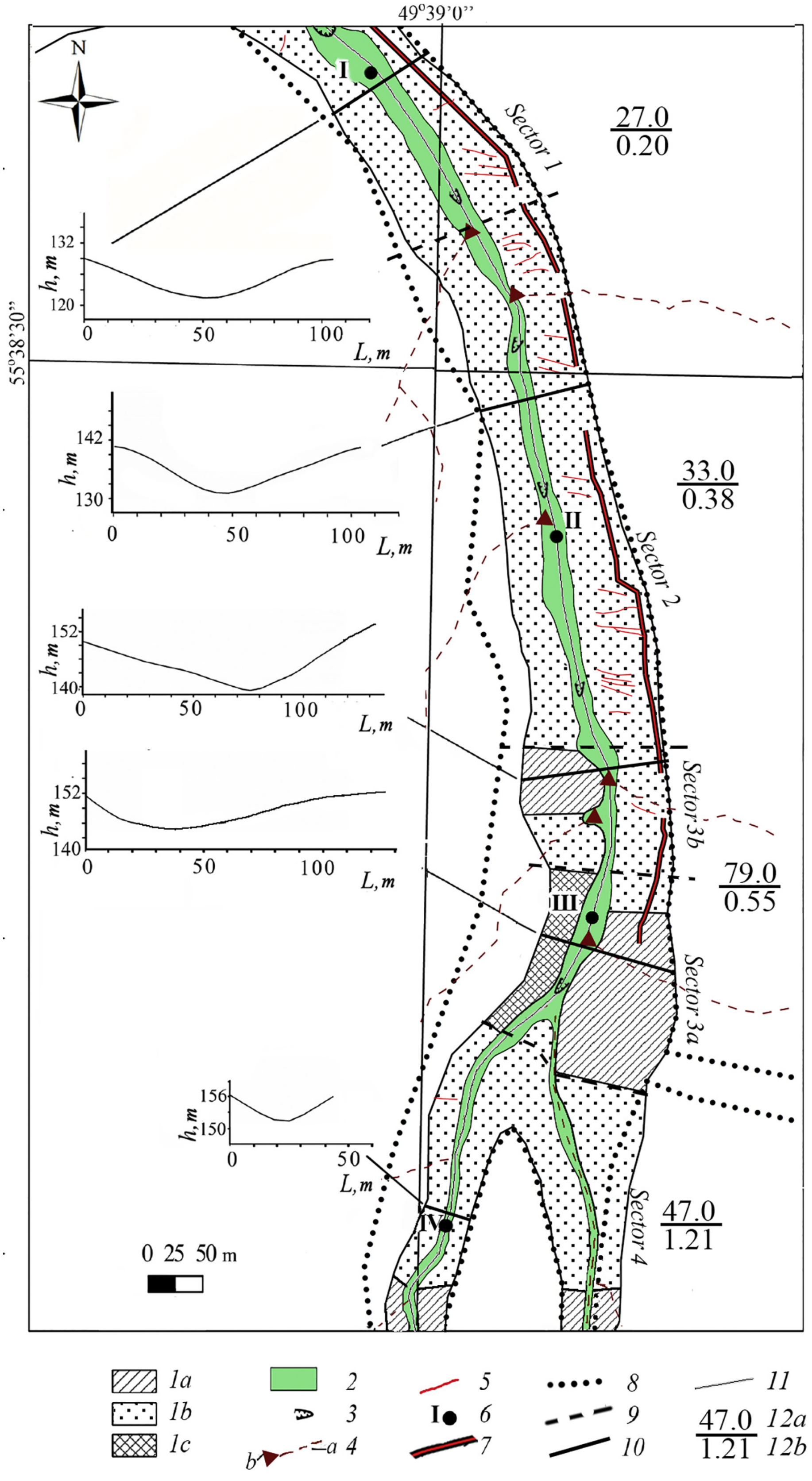

Fig. 4. Geomorphological map of the dry valley of the studied Temeva Rechka dry valley subcatchment. *1* – dry valley sides with different gradients: *a* – 4–8°, *b* – 8–15°; *c* – >15°; *2* – dry valley bottom; *3* – main headcuts in the bottom; *4* – hollow catchment elements: *a* – thalweg, *b* – sediment cone; *5* – relatively old rills; *6* – sediment sections location and their numbers; *7* – levee with a height of ~ 0.4–0.5 m (old boundary of cultivated field); *8* – actual cultivated field boundary; *9* – boundary of the studied dry valley bottom sectors; *10* – dry valley cross section profiles location; *11* – for the dry valley cross sections: *L* – horizontal distance; *h* – absolute heights; *12a* – mean annual sedimentation rate within a sector, t ha^{-1} y^{-1} during 1986–2015; *12b* – the mean annual soil losses (from cultivated area) for 1986–2015, based on the dry valley bottom sedimentation rate within a sector, t ha^{-1} y^{-1}.

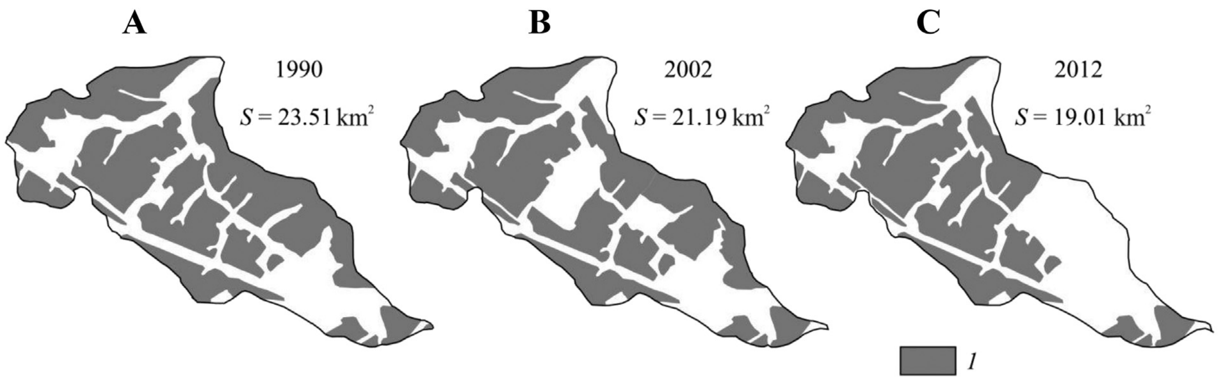

Fig. 5. The cultivated area (*1*,*S*) dynamics within the upper Lokna River basin (see Fig. 1C) during 1990–2012: (A) for 1990 (from Landsat ETM satellite images); (B) for 2002 (from Landsat ETM satellite images); (C) for 2012 (from Landsat ETM satellite images and direct field observations).

serve as main pathways of eroded soil material to dry valley bottom. A high spatial variability of sedimentation rates in these morphological units seriously complicates the quantitative assessment of the total sediment amount. However, available field observation, including evaluation of the deposition rates on dry valley sides, revealed that their proportion was within the range of 5–10% from the total sediment budget in the cases if the cultivated field boundaries are located at a distance of <5–7 m from dry valley sides (Panin et al., 2001; Golosov and Ivanova, 2002).

Sediment storage in dry valley bottoms (M_{dvb}) is calculated as follows:

$$M_{dvb} = (H_1S_1 + H_2S_2 + \ldots + H_nS_n)d \tag{4}$$

where H_1, H_2, H_n – depth of post-Chernobyl deposition within each geomorphic unit, m; S_1, S_2, S_n – areas of deposition units, m^2; d – dry bulk density of sediments, kg m^{-3}.

Sediment storage in the reservoir is calculated as follows:

$$M_r = H \times S \times d \tag{5}$$

where H – mean depth of post-Chernobyl deposition, m; S – the reservoir surface area, m^2; d – dry bulk density of sediments, kg m^{-3}.

The part of sediment budget components is defined based on quantitative evaluation of sediment storage for 1986–2012. Assessment of sediment storage in the reservoir defines the possible sediment delivery to the upper Lokna River. On the other hand, soil losses from cultivated lands are assessed using the erosion model calculations that were not verified based on the independent evaluation of the erosion rates for the studied catchments. So, there is only possibility to calculate the preliminary sediment budget that can be used for evaluation of the SDR for the eastern and western parts of the upper Lokna River basin.

2.2.6. Extrapolation of SDR assessment results to the entire Plava River basin

The SDR values were determined based on application of the combination of methods and techniques for the three studied third Hortonian order catchments (Table 3) that were selected as the most typical dry valley catchments for the Plava River basin. The catchments of the third Hortonian order were subdivided according to the total length of dry valley bottoms onto three groups: with short (1–15 km), medium (15–35 km), and long (35–55 km) lengths (Fig. 6) (Ivanov et al., 2017). At least one of the studied dry valley catchments belonged to each group of the dry valley catchments. This made it possible to use the SDR, evaluated for each of the studied catchments, for other catchments included in the three distinguished groups.

In combination with the SDR assessment results for the different types of cultivated slopes and hollow slope catchments, we can evaluate the SDR for sediment transfer from the basin area to permanent river valley bottoms for the entire Plava River basin. For a correct assessment,

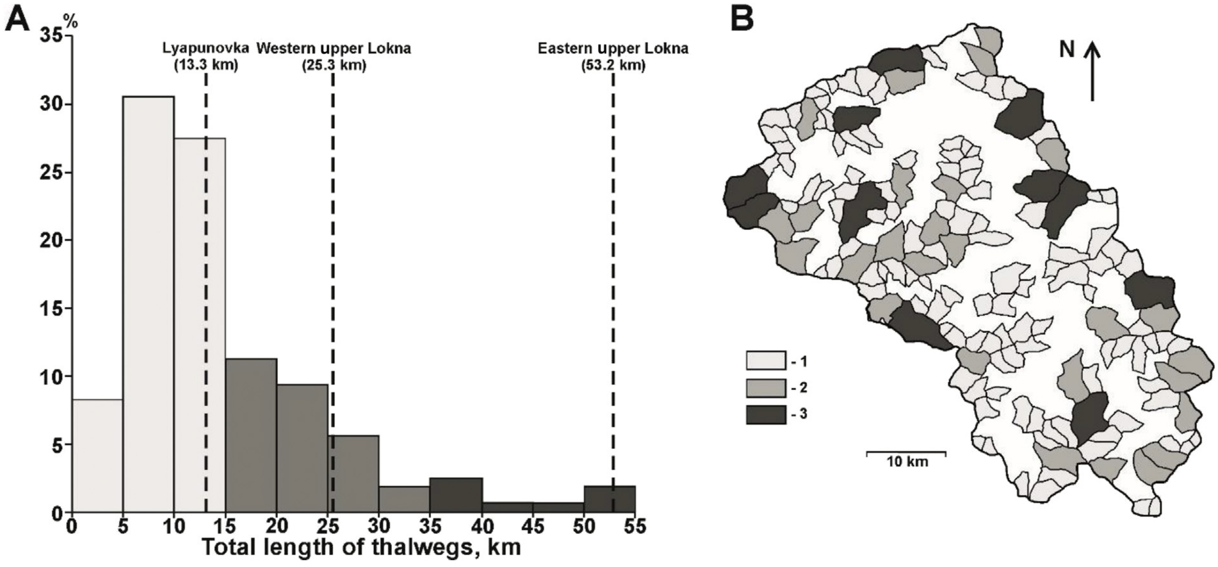

Fig. 6. The third Hortonian order catchments (A) and their redistribution (B) in the Plava River basin. The groups of dry valley bottom lengths: 1 – short length (1–15 km), 2 – medium length (15–35 km), 3 – long length (35–55 km).

it must be taken into account the part of sediment yield that was intercepted and then accumulated in ponds and reservoirs located in dry valleys or in sources of permanent streams of the Plava River basin.

3. Results

3.1. The Temeva Rechka Creek catchment

The proportion of slopes and hollow slope catchments within the total cultivated area is very similar for the detailed studied dry valley subcatchment and the entire area of the Temeva Rechka Creek catchment (Fig. 7). The high proportion (>60%) of hollow slope catchments with convex thalwegs indicates the high connectivity between cultivated slopes and dry valley bottoms. Land use/cover and gradients of the slopes within the studied subcatchment and the entire Temeva Rechka Creek catchment are also very similar (Tables 2, 3). The key dry valley subcatchment has an elongated configuration with about 57% of cultivated slope upstream from the confluence of the two dry valleys (Fig. 3). According to the soil erosion model calculations, maximum erosion rates are observed within relatively short and steep cultivated slopes located in the eastern part of the subcatchment (Fig. 8). However, connectivity of cultivated slopes with dry valley bottom is low in this part of the dry valley subcatchment caused by a swelling with a height of 0.4–0.5 m (old boundary of the cultivated field) (Fig. 4), which promoted the trapping of most of the sediments eroded from cultivated slopes. High sedimentation in the lower parts of cultivated slopes in this part of the subcatchment is confirmed by the increase in ^{137}Cs inventory there compared to the reference values. In addition, the relatively low steepness of the dry valley sides led to an increase in deposition down the slope, which could occur during extreme erosion events. On the other hand, it is more likely that the hillslope-to-dry-valley connectivity in the given part of the dry valley subcatchment used to be considerably higher before 1986 when the cultivated slope boundary was 20–30 m down the slope. Old rills with depths up to 0.5 m, which recently are completely protected by a grass cover, are clear indicators of strong surface water runoff that occurred within the subcatchment during the 1960s–1980s. Probably, vegetation cover of the dry valley sides was sparse during the 1960s–1980s owing to overgrazing: livestock in local villages was much higher before the 1990s. The decrease in sedimentation rates in the dry valley bottom by 5.2–6.7 times in its middle and lower sectors during 1986–2015 compared to 1963–1986 is the other confirmation of serious reduction in the cultivated hillslopes-to-dry-valley connectivity there (Sharifullin et al., 2018a, 2018b). Sediment storage in the valley bottom for a both time intervals has been determined based on interpretation of ^{137}Cs depth profiles and the dry valley bottom area. Within the upper reaches of the dry valley bottom, sedimentation rates were reduced only by 3.7–4.0 times between the same time intervals. So, we suggest that ~100% of sediment eroded from the cultivated slopes of the eastern part of the dry valley subcatchment has been redeposited on the dry valley sides.

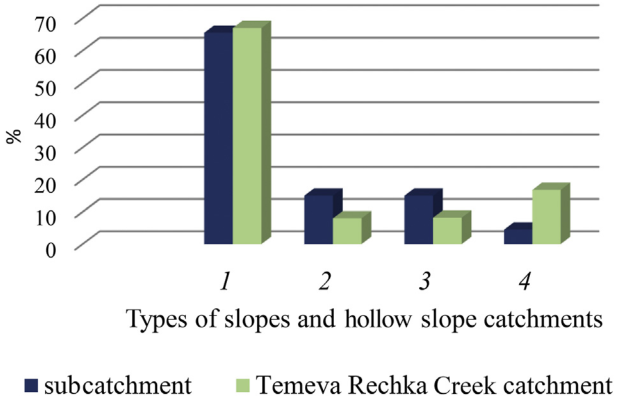

Fig. 7. The proportion of the different types of slopes and hollow slope catchments in the total cultivated area of the Temeva Rechka Creek catchment and its studied dry valley subcatchment (see Fig. 1B). *1* – hollow slope catchments with convex thalwegs; *2* – hollow slope catchments with concave thalwegs; *3* – convergent slopes; *4* – divergent slopes.

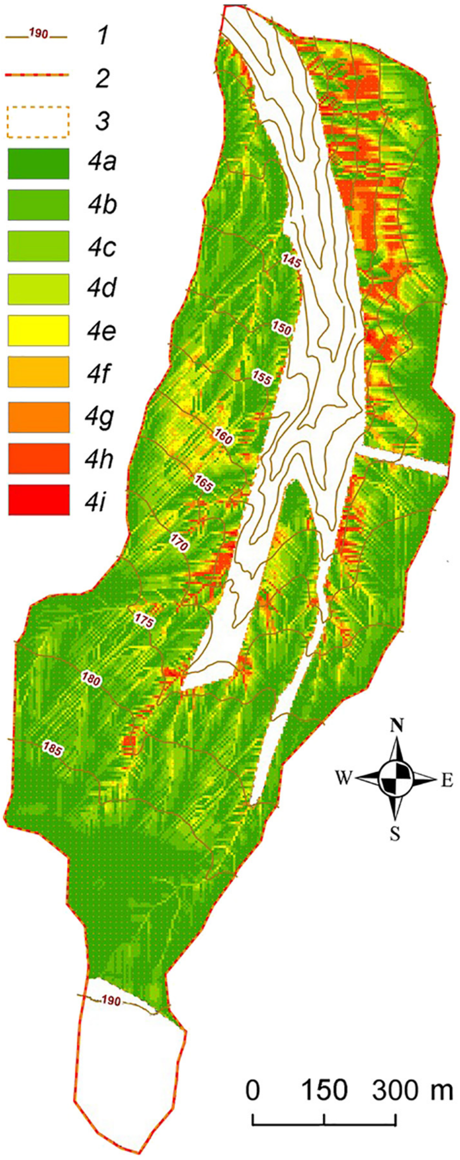

Fig. 8. The soil erosion rates map for the studied dry valley subcatchment of the Temeva Rechka Creek catchment, based on the erosion model calculations (according to the USLE + SHI modified versions) for 1986–2015. *1* – contour lines (isohypses); *2* – boundary of the subcatchment; *3* – uncultivated parts (forests, pastures, and pristine meadows) of the subcatchment (beyond the erosion model calculations); *4* – calculated soil erosion rates, t ha^{-1} y^{-1}: *4a* – 0–2, *4b* – 2–5, *4c* – 5–10, *4d* – 10–15, *4e* – 15–20, *4f* – 20–25, *4g* – 25–30, *4h* – 30–50, *4i* – >50.

Sediment transfer from hollow slope catchments to dry valley bottom is characterized by higher connectivity because of concentrative water flow in the hollow bottoms and their continuation up to the dry valley bottoms (Fig. 4). We were not able to quantify sediment deposition in the hollow cones located in the dry valley bottom because it is necessary to take incremental samples from the few sediment sections located in the different parts of each cone for the correct assessment. So, the sediments redeposited in this sediment sink have not been included by us into the total sediment budget calculation (Table 5). However, we also were not able to evaluate the possible input of sediments, produced owing to the retreat of small headcuts in the dry valley

Table 5
Sediment redistribution in the Temeva Rechka dry valley subcatchment for 1986–2015.

Characteristics	Types of cultivated slopes and hollow slope catchments[a]				Totally for the subcatchment
	1	2	3	4	
Area, ha	57	13	12	4	86
Erosion rates[b], t ha^{-1} y^{-1}	7.4	5.4	14.7	7.0	8.1
Gross soil losses, t y^{-1}	421.8	70.2	176.2	28	696.2
Sediment delivery ratio coefficient[c], %	100	60	80	20	–
Net soil losses, t y^{-1} (% in the total losses for this time interval)	421.8 (69%)	42.1 (6.9%)	141.0 (23.1%)	5.6 (1%)	610.5/488.0[d] (100%)
Total net losses from cultivated area, t y^{-1}	610.5 (100%)				
Mobilized hillslope sediments redeposited on the dry valley sides, t y^{-1}	0	0	141	5.6	146.6/117.5 (24%)
Mobilized hillslope sediments redeposited in the dry valley bottom, t y^{-1}	–	–	–	–	96.6 (20%)

[a] See Figs. 2 and 3.
[b] Calculated using the modified versions of the USLE and SHI erosion models.
[c] According to Panin et al. (2001).
[d] The numerator is calculated value; the denominator is corrected value based on the results of the model verification, in parenthesis is proportion in the total erosion/sedimentation.

bottom (Fig. 4), in the sedimentation rates in the dry valley bottoms. As we can see from Fig. 9A, the longitudinal profile of the main dry-valley-bottom thalweg has about 12 small headcuts with relative heights of ~0.2–0.4 m (Fig. 9A). It should be marked that all calculations of sediment redistribution were made upstream of the deep bottom gully, cutting the dry valley bottom in the lowest reach nearby the confluence with the main stream. The headcut of this gully is depicted in Fig. 9B.

It was suggested that the accounts of soil losses, based on the erosion model calculations, overestimate the actual soil losses because the USLE modified version does not calculate a deposition within cultivated fields (Larionov, 1993). Verification of the model calculations undertaken for slopes and hollow slope catchments in the western sector of the forest-steppe zone of the Russian Plain demonstrates that the model calculations systematically overestimate the actual soil losses by 1.20–1.25 times (Litvin et al., 2003). The corrected mean annual soil losses from the subcatchment cultivated slopes are 5.6 t ha^{-1} y^{-1}. These values are in correspondence with the mean values of soil losses for the uplands of the forest-steppe zone of the Russian Plain (Sidorchuk

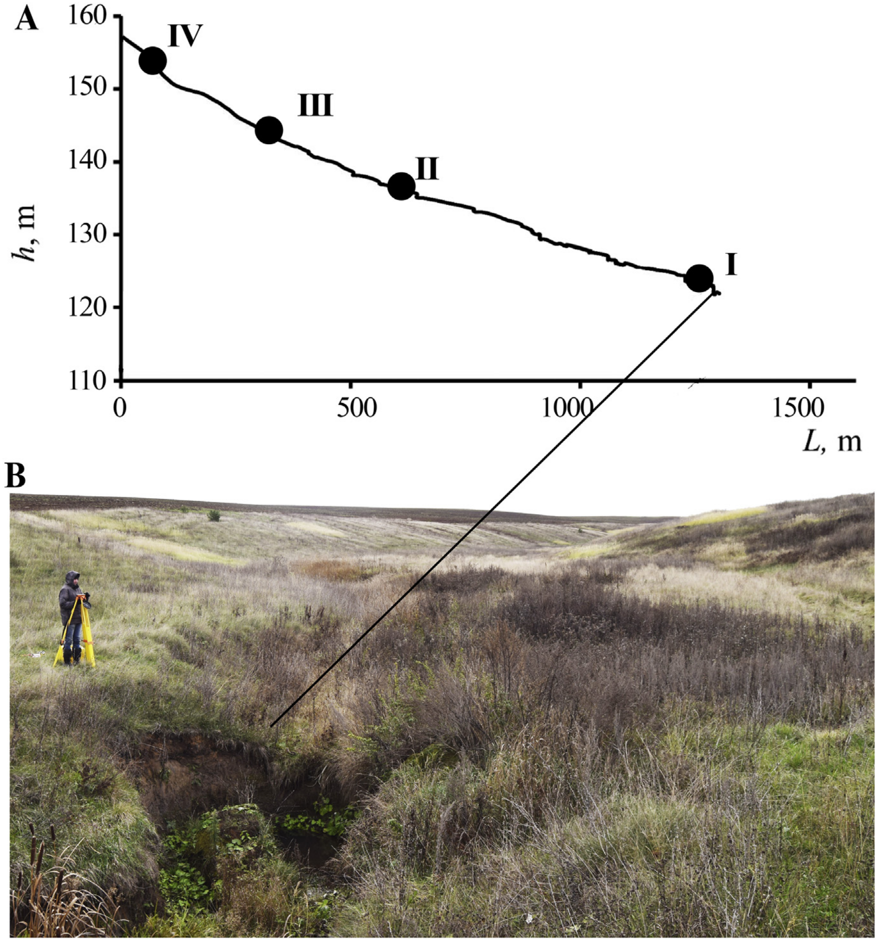

Fig. 9. Longitudinal profile of the dry valley bottom thalweg of the Temeva Rechka dry valley subcatchment (A), and view of the dry valley bottom from the point located a few meters downstream of the large gully headcut cutting through the bottom (B). Photo by A.G. Sharifullin (October 2016). I, … IV – sediment sections (see Fig. 4). *L* – horizontal distance; *h* – absolute heights.

et al., 2006). Sediments redeposited on the dry valley sides have reduced proportionally to corrected net soil losses from cultivated fields. The proportion of sedimentation volume in the dry valley bottom is about 20% from the total annual volume of eroded material (Table 5). As a result, the SDR coefficient for the Temeva Rechka dry valley subcatchment (the second Hortonian order) is about 0.56, which corresponds to the SDR values obtained for similar dry valley (sub) catchments located in other parts of the southern half of the Russian Plain (Golosov, 1998).

3.2. The Plava River basin

Results from the morphometric analysis of slopes and hollow slope catchments within the Plava River basin allowed for the evaluation of their proportion for cultivated parts of the studied dry valley catchments and for the entire river basin (Table 6). Hollow slope catchments with concave thalwegs occupy the maximum area within the most studied catchments, except the eastern part of the upper Lokna River basin where divergent slopes have equal area. Some differences in the proportion of different types of slopes and hollow slope catchments undoubtedly have an influence on the variability of cultivated-hillslopes-to-dry-valley connectivity in the different dry valley catchments. However, it should be noted that hollow slope catchments with convex thalwegs and divergent slopes dominate within all studied catchments and in the entire Plava River basin.

Quantitative assessment of sediment redistribution was undertaken for the upper Lokna River basin (Fig. 10). According to the LandSoil erosion model calculation, the mean annual gross erosion rates for 1986–2012 were 4.4 t ha^{-1} y^{-1}. The soil losses in range of 0–5 t ha^{-1} y^{-1} were observed for ~3/4 of the total area of the catchment cultivated lands. Maximum soil losses were observed on steep convex slopes in their lower parts located on a relatively short distance from cultivated field boundaries. Based on the proportion of slopes and hollow slope catchments it was evaluated that net annual soil losses were 2.6 and 3.1 t ha^{-1} y^{-1} respectively, for the eastern and western catchments of the upper Lokna River basin. High sedimentation rates on the lower field boundaries are confirmed by the clear identification of the accumulation in the sediment sections excavated. Partly, it is also confirmed by an increase in the total ^{137}Cs inventories in the sampling points, located in the lower parts of the cultivated slopes, compared to sampling points located near the watershed lines. But the high spatial variability of the initial Chernobyl-derived ^{137}Cs fallout is complicates the quantitative assessment of soil loss/gain based on ^{137}Cs inventories for cultivated parts of the catchments (Ivanov et al., 2016).

The area of cultivated lands has been changed considerably (by ~20%) during 1986(1990)–2012 in both catchments of the upper Lokna River basin (Fig. 5). So, the large part of sediments was intercepted along the pathways from cultivated fields to dry valley bottoms. It is difficult to make a detailed assessment of sediment storage within uncultivated parts of the slopes based on the evaluation of ^{137}Cs depth distribution curves for the different possible situations. However, we determined that sedimentation rates in the bottom of uncultivated reaches of hollows at a distance of about 25 m from the field boundary exceed 1 cm y^{-1}(Fig. 11A). An assumption was made that in the western and eastern catchments all sediments eroded from their upper areas had been redeposited within the slopes because all cultivated fields are located >50 m from the dry valley sides. Also, most parts of sediments eroded from the fields, which are separated from dry valleys by the forest-shelter belts and roads, were redeposited on uncultivated bottom parts of interfluve slopes. As a result, the mobilized hillslope sediments from 35 to 45% (for different time intervals) of the cultivated field area were not delivered to the dry valleys. The trapping effect of the dry valley sides is different within the upper Lokna River basin and mostly depends on the gradients and length of these sides. Deposition within valley sides may be assessed by the range of 10–25% of the net soil losses within the cultivated fields.

Table 6

Proportion (%) of different types of cultivated slopes and hollow slope catchments within the arable lands of the Plava River basin and its key studied catchments.

Basin and its catchments		Slopes			Hollow slope catchments	
		Straight	Divergent	Convergent	With a convex thalweg	With a concave thalweg
Plava River basin		4.7	23.9	11.5	43.7	16.2
Lyapunovka		1.3	31.2	8.8	45.5	13.2
Upper Lokna	Eastern	6.0	39.8	16.1	37.9	0.2
	Western	1.7	29.5	13.4	55.4	0.0
Chasovenkov Verkh		7.4	20.0	12.1	48.3	12.2

According to the Chernobyl-derived ^{137}Cs depth distribution curves interpretations, we found that mean annual sedimentation rates in dry valley bottoms are changed within the different cross sections in the range of 0.0–8.9 mm y^{-1}. The lowest sedimentation rates were established on the terraces of dry valley bottoms, where most likely the only sediments delivered from the valley sides were deposited. The highest sedimentation rates are established in the upper reaches of the bottoms of the first Hortonian order dry valleys and in the infilled bottom gullies located mainly in the valleys of the second and third orders (Fig. 11A).

Sediment storage in the dry valley bottoms was evaluated based on assessment of the mean sedimentation rates for individual cross sections located in the different reaches of the dry valleys, areas of the bottoms, and mean density of sediments separately for the eastern and western catchments of the upper Lokna River basin (Table 7). The high proportion of sediments redeposited within the western and eastern upper Lokna catchments compared to the Lyapunovka catchment, located at a distance from both of them (Fig. 1C), is associated with a few reasons. A first reason is caused by high storage of sediments within uncultivated lower reaches of the hollow bottoms (Fig. 11A) because the distance between the lower boundary of cultivated fields and the top of dry valley bottoms of the first order in their cases is typically 20–40 m. A second reason is caused by great lengths of uncultivated valley sides. A third reason is owing to the presence of forest shelter belts on valley sides in some parts of the first-order dry valley catchments, which promote interception of the most parts of the sediments transported by surface water runoff from cultivated fields during erosion events. As a result, the above-mentioned land use/cover features led to an increase in the proportion of sediments redeposited along the pathways from cultivated slopes to dry valley bottoms.

Sediment output from the upper Lokna River basin for 1986–2012 was preliminarily equal to sediment storage in the reservoir located in the outlet of the basin (Fig. 10A). Total sedimentation in the reservoir for 1986–2010 was 51,546 ± 3216 t, and it is about 20% of the total amount of mobilized hillslope sediment and ~33% of the net soil losses from cultivated fields (Table 8). These values are consistent with the previous assessment of sediment redistribution for the similar time interval for the Lyapunovka catchment (Table 7). The presence of the reservoir in the upper Lokna River basin outlet allows for the verification of the quantitative assessment of sediment redistribution for the western and eastern catchments. According to sediment budget calculations, total output from both catchments was within the ranges of 171–2160 t y^{-1}, while annual sediment storage in the reservoir was about 2058 ± 64 t (Belyaev et al., 2013). Probably some mobilized hillslope sediments were delivered directly from cultivated fields to the reservoir from part of the upper Lokna River basin that is located downstream of the confluences of the main dry valleys of the western and eastern catchments (Fig. 10A). Also, some sediments are redeposited in the dry valley bottom located between the reservoir and the confluence of the main valley bottoms of these catchments. On the other hand, the design and construction of the reservoir dam and, especially, the concrete well-type spillway (operated only when a particularly

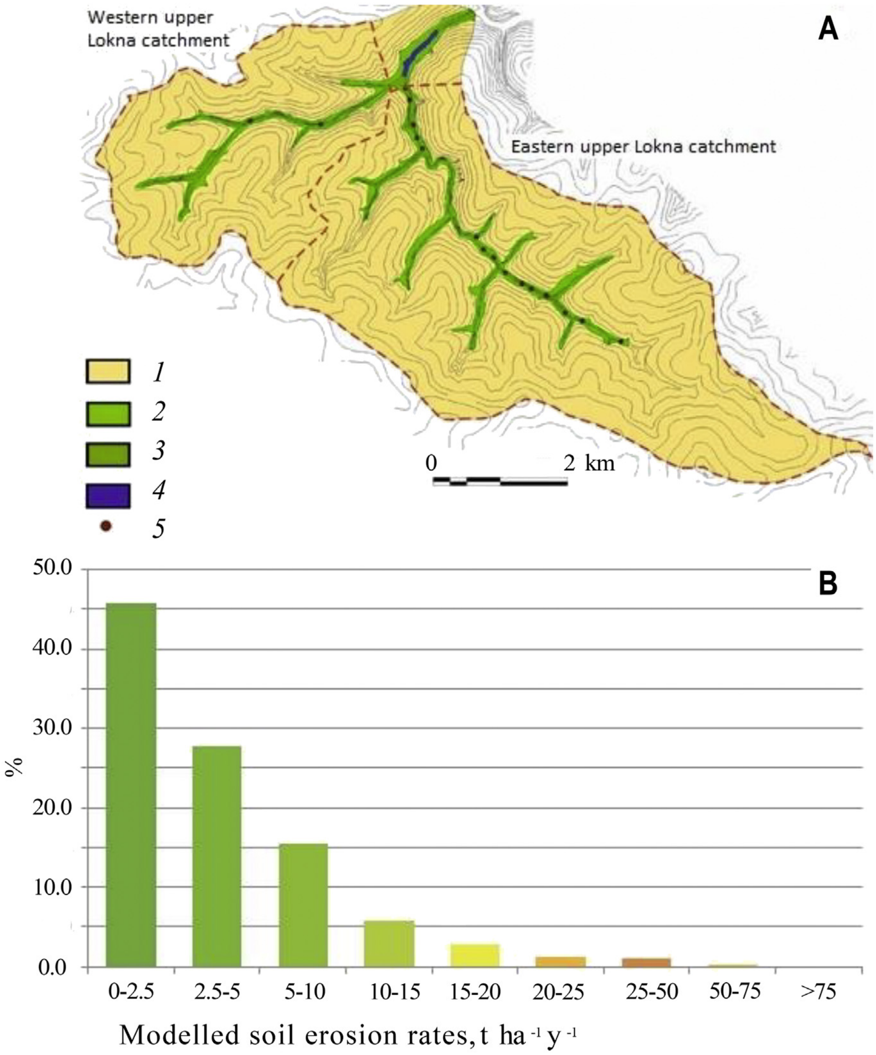

Fig. 10. The main morphological units within the studied catchments of the upper Lokna River basin (A), and proportional distribution of cultivated fields with different values of mean annual erosion rates calculated using the LandSoil erosion model, the upper Lokna River basin (B). *1* – interfluve slopes; *2* – dry valley sides; *3* – dry valley bottoms; *4* – the reservoir; *5* – small bottom gully headcuts with relative heights ~0.2–0.4 m.

high-water level is reached) allows for the suggestion that the reservoir trap efficiency should not be lower than 90%, as only the finest fractions of suspended sediments can reach and pass through the spillway after passage of peak water discharges (Belyaev et al., 2013). Finally, the SDR for the cultivated catchments of the third Hortonian order depends on morphological features (including total length and incision depth) and the land use/cover structure. However, for all catchments the SDR changes within the range of 0.30–0.35 with different proportions of sediment storage in the different sediment sinks along the pathway from cultivated fields to the catchment outlet. Earlier it was shown based on the sediment budget for the Chasovenkov Verkh catchment (fourth Hortonian order catchment), located in the Plava River basin (Fig. 1C), that for 1986–1997 only 7% of the mobilized hillslope sediments were delivered by temporary watercourses to the Lokna River valley bottom (Golosov and Ivanova, 2002). The main part of the sediments was redeposited in the dry valley bottoms.

3.3. SDR within the Plava River basin

Results from the morphological analysis of slopes and hollow slope catchments for the Plava River basin, and also the SDR assessment for different pathways from cultivated slopes to river valley bottoms, made it possible to build a map of sediment connectivity between cultivated slopes and river valley bottoms (Fig. 12). We took into consideration that mobilized hillslope sediments from 21.7% of the Plava River basin area could be intercepted by ponds and reservoirs. We also assumed that almost all mobilized hillslope sediments from their catchment areas were intercepted and were not delivered into the valley bottoms of contemporary permanent streams.

In the landscapes of the forest-steppe zone with a high proportion of the cultivated lands, most parts of the mobilized hillslope sediments are transported to river valley bottoms from the slopes and dry valley catchments of first and second Hortonian orders, located along the river valleys. According to our assessment, a maximum 27–28% of mobilized hillslope sediments were delivered from cultivated slopes to river bottoms. An essential part of them was accumulated in the sediment cones or along the lower parts of the river valley sides. So, under contemporary climate conditions, in order to reduce a surface water pollution, maximum attention should be given to activities providing protection against soil erosion within the cultivated lands of the first and second Hortonian order dry valley catchments, located at a distance of ≤50 m from the permanent streams.

4. Discussion

Currently, soil and rill erosion is the main process of interfluve relief transformation within the plains of the temperate climatic zone of Earth (Dedkov and Mozzherin, 1984; Syvitski et al., 2005; Dedkov et al.,

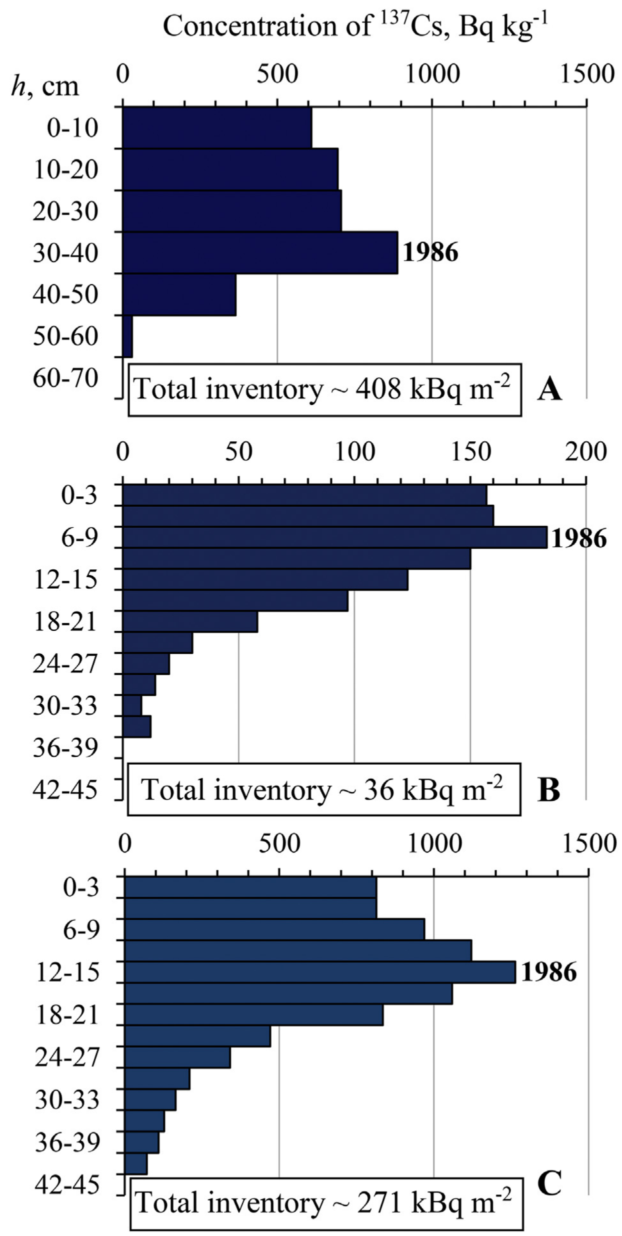

Fig. 11. The examples of typical ^{137}Cs depth (vertical) distributions in sediments deposited in different sediment sinks along the pathways from cultivated slopes to river valley bottoms: (A) the uncultivated hollow bottom located between cultivated field boundary and the upper reach of first-order dry valley, the western upper Lokna catchment; (B) in the middle reach of second-order dry valley bottom, the Lyapunovka catchment; (C) in the middle reach of third-order dry valley bottom, the western upper Lokna catchment.

2008). It was proven that the considerable transformation of slopes and dry valley morphology during the Holocene was observed because of active sediment redistribution on arable lands (Wolf and Faust, 2013; Smetanová et al., 2017) and farther downstream through the hillslope-to-dry-valley-to-river-bottom cascades (Rommens et al., 2007; Houben, 2008; etc.). An application of the bomb- and Chernobyl-derived ^{137}Cs isotopes for sediment dating allowed for the evaluation of sediment storage in different sediment sinks of the cascades for a relatively short time interval of a few decades (Golosov et al., 2017; Gusarov et al., 2018a, 2018b, 2018c). The LandSoil erosion model calculations and ^{137}Cs dating allowed for the evaluation of sediment redistribution in a field scale (Lacoste et al., 2014; Golosov et al., 2018a). Evaluation of sediment redistribution within dry valley catchments located in different parts of the forest-steppe landscape zone of the Russian Plain demonstrates that slope morphology, field and catchment configurations, and density of the dry valley network are the principal parameters determining the SDR for the different elements of the fluvial sediment cascades. Depending on landscape features, the proportional contribution of the above-mentioned factors to sediment redistribution within different parts of small dry valley catchments could change considerably (Vanmaercke et al., 2011; Delmas et al., 2012; Chartin et al., 2013).

Results obtained during field studies in the Russian Plain confirmed the definition made by Delmas (2011) that the Index of Connectivity is a function of slope, land use, surface water runoff potential, and distance from a river channel. However, there are some significant differences in surface water runoff potential between the territories of the Russian Plain and the western European plains because surface water runoff during snowmelt is seriously controlled by the frozen soil depth (Barabanov et al., 2018; Golosov et al., 2018a, 2018b; Gusarov et al., 2018a, 2018b, 2018c). In those cases when the depth of frozen soils exceeds 40–45 cm, according to long-term monitoring, the coefficient of surface water runoff within the cultivated slopes is close to 1 (100%) in different parts of the forest-steppe and steppe zones of the Russian Plain (Barabanov et al., 2018). As a result, transport capacity of temporary water flow in dry valley bottoms increases (an increase in proportion of mobilized hillslope sediments transported to river bottoms). That explains the higher SDR for the dry valley catchments of the forest-steppe landscape zone of the Russian Plain compared to, for example, the plains in France (Delmas et al., 2012).

Despite the high proportion of sediments redeposited within cultivated fields (particularly in cases of divergent slopes), dry valley bottoms are the most important sediment sink within the hillslopes-to-river-bottom sediment cascades in the Russian Plain. A similar situation is observed in other plains of Europe (Rommens et al., 2007; Notebaert et al., 2009; Mitusov et al., 2014). Total length of the dry valley network has increased by 2.0–2.5 times within the forest-steppe zone of the Russian Plain during the last 150 years caused by intensive small river aggradation associated with considerable growth of soil-rill-gully erosion intensity after land reform in the Russian Empire in 1861 (Golosov and Panin, 2006). Reconstruction of sediment budget for a few time windows shows the increase in proportion to sediment storage in main valley bottoms from 13% in 1700–1954, when permanent streams flowed along more than half of the main valley bottoms, up to 51% in 1986–1997, when they did not already exist (Golosov and Ivanova, 2002). Consequently, the hillslopes-to-river-valley-bottom

Table 7
Sediment redistribution along the pathways from cultivated slopes to river valley bottoms within the studied dry valley catchments located in the Plava River basin for 1986–2010/2012.

Catchments	Net soil losses, t y^{-1}	Mobilized hillslope sediments redeposited on uncultivated parts of interfluve slopes and dry valley sides, t y^{-1}	Mobilized hillslope sediments redeposited in dry valley bottoms, t y^{-1}	Sediments output from catchments, t y^{-1}
Western upper Lokna	2360 (100%)	860–1070 (36–45%)	540 (23%)	750–960 (32–41%)
Eastern upper Lokna	3360 (100%)	640–880 (19–26%)	1520 (45%)	960–1200 (29–36%)
Lyapunovka[a]	2200 (100%)	218 (10%)	1326 (60%)	656 (30%)

[a] According to Belyaev et al. (2012).

Table 8
The preliminary sediment budget assessment for the upper Lokna River basin for 1986–2012.

	Total net soil losses[a]	Mobilized hillslope sediments redeposited on uncultivated parts of interfluve slopes and dry valley sides[b]	Mobilized hillslope sediments redeposited in dry valley bottoms	Sedimentation within the reservoir[c] (see Fig. 10)	Error
Tons	155,700	44,000	53,475	51,546	6679
%	100	28	35	33	4

[a] Calculations according to the LandSoil erosion model.

[b] High uncertainty. Assessment based on interpretation of very few ^{137}Cs depth profiles, morphological characteristics of interfluve slopes, and dry valley and land use/cover features.

[c] For 1986–2010 without correction to 1986–2012.

connectivity has recently decreased considerably in the forest-steppe zone of the Russian Plain over the last decades.

5. Conclusions

The study was focused on the quantitative assessment of sediment redistribution within dry valley catchments of different Hortonian orders with a total area of 1.5–39.0 km^2, located in the territories with a high proportion of cultivated lands within the western (the Plava River basin, Tula Oblast, Russian Federation) and eastern (the Temeva Rechka Creek catchment, the Myosha River basin, Republic of Tatarstan, Russian Federation) sectors of the forest-steppe landscape zone of the Russian Plain for the period since 1986. Sediment budgets constructed for both sites show that the proportion of mobilized hillslope sediments delivered to river valley bottoms depend on a distance between cultivated-slope low boundaries and river valley bottoms. Sediment storage in dry valley bottoms is a key component of the sediment budget. It is mostly controlled by dry valley density in the studied catchments. The mean annual sedimentation rates in the dry valley bottoms change within the range of 0.0–8.9 mm y^{-1} depending on net soil losses on the catchment slopes, the SDR, and catchment slope configurations. The proportion of the mobilized hillslope sediments

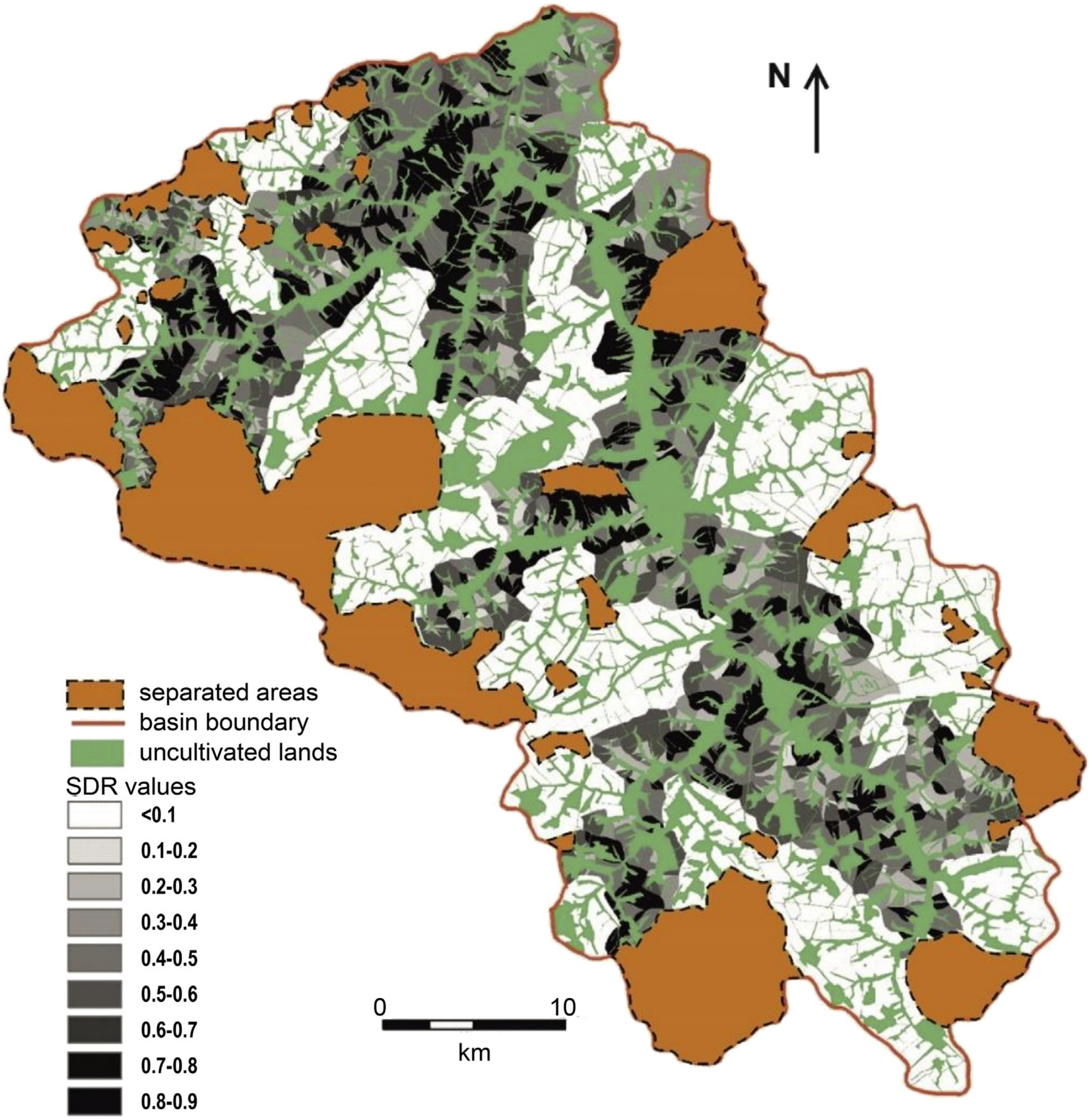

Fig. 12. Cultivated-hillslopes-to-river-valley-bottoms connectivity map for the Plava River basin for 1986–2012.

delivered to the river valley bottoms reaches the minimum values (<10% from the total soil losses) for catchments of fourth Hortonian orders owing to a high amount of sediments trapped in the dry valley bottoms of first through fourth Hortonian orders. The proportion of mobilized hillslope sediments redeposited within cultivated fields depends mostly on the slopes and hollow slope catchments configuration reaching maximum values within divergent slopes for the uplands of the Russian Plain. The mean hillslope-to-river-bottom SDR coefficients are 0.56, 0.33, and 0.07 for the dry valley catchments of second through fourth Hortonian orders respectively within the Plava River basin. Extrapolation of the results of sediment redistribution evaluation, obtained for the studied catchments, to the entire Plava River basin, allows us to determine that the mean hillslope-to-river-valley-bottom SDR is 0.27 for this basin.

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