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Temporal–spatial variations in the sediment delivery ratio of small drainage basins: the Russian Plain example

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Abstract Most river sediment in areas of intensive agriculture is formed on basin slopes from surface and gully erosion. Sediment delivery ratio coefficients (DR) show high variability in basins of less than 100 km^2. Quantitative assessment of DR for small basins is central to evaluating sediment source changes for different sections of river channels. A detailed study in several small drainage basins of the Russian Plain established two stages of sediment transport and redistribution. The first is characterized by a quasi-equilibrium relationship between the volume of sediment delivered from eroded slopes and the volume of sediment redeposited in the valley bottom. Most sediment is redeposited within the basin. Sediment delivery ratio coefficients range from 0.01 to 0.3 depending on basin area and local landscape conditions. The second stage is intensive development of secondary gullies at valley bottoms because of changes in land use and management, irregularities in sediment deposition along the valley bottom or climatic fluctuations. Typical DR coefficients for this stage range from 0.5 to 0.95. Such small basins are the main source of sediment for the river system.

Key words sediment transport; sediment redistribution; cultivation; sediment budgets; variability; lowlands; Russian Plain

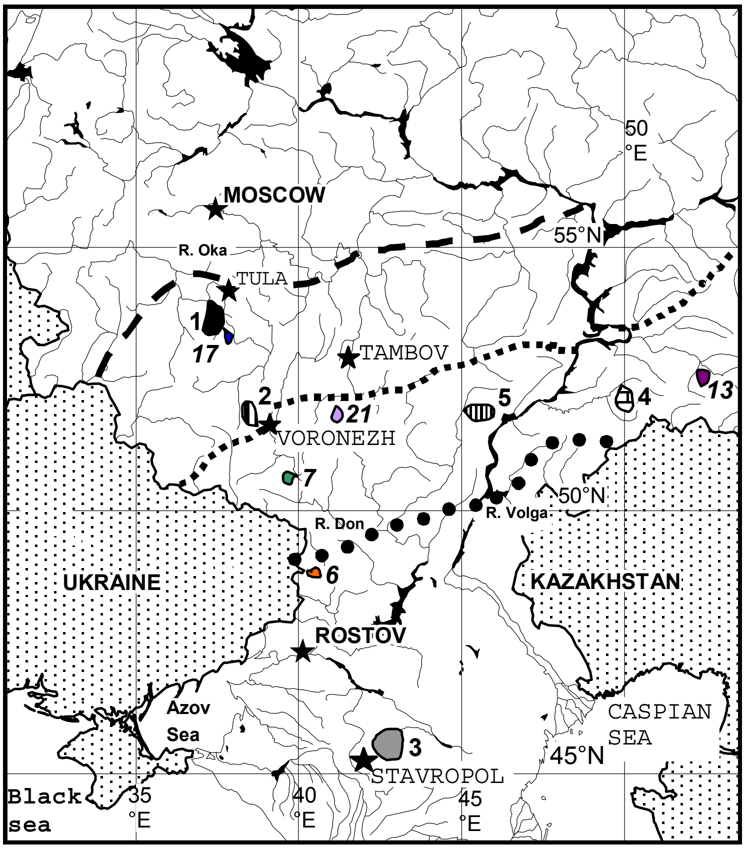
INTRODUCTION

Quantitative assessment of sediment redistribution within agricultural drainage basins is essential for lowland and plain areas, where the character of sediment redistribution is not as obvious as within mountain regions (Walling, 1983). Of greatest concern in such areas are on-site problems associated with soil loss and sediment deposition. The most visual examples are the consequences of intensive cultivation of the Great American and Russian Plains during the last two to three centuries. Tremendous volumes of soil were removed because of accelerated sheet, rill and gully erosion. This erosion occurred in conjunction with intensive sediment deposition at the base of cultivated slopes and within first-order valleys adjacent to cultivated fields, traditionally used as pastures (Trimble, 1974; Golosov *et al.*, 1997). These changes resulted in 5–7 fold increases in sediment discharge in disturbed river channels (Dedkov & Moszherin, 1984). The aim of this study is to evaluate the nature of sediment redistribution within small lower-order basins of the Russian Plain following intensive cultivation within their watershed.

Regular measurement of water and sediment discharges is the best tool for the detailed study of sediment transport. However such studies are not widespread due to their high cost and the necessity of monitoring over long time periods to receive statistically satisfactory data (Walling, 1991). New approaches developed during recent decades, based on using different markers for the assessment of erosion and deposition rates allow similar information to be obtained over shorter periods of time (Walling *et al.*, 1996). The application of these new techniques combined with traditional indirect methods allows the different stages of erosion and deposition processes within small agricultural basins to be understood.

STUDY AREA AND METHODS

The Russian Plain occupies the vast area from the Arctic seas on the north to the Azov, Black and Caspian seas and Crimea and Caucasus mountains in the south, the Ural mountains in the east, and the Baltic Sea, the Carpathians and Scandinavia in the west (Spiridonov, 1978). Territories with intensive cultivation (areas where arable land exceeds 50% of the total area) are more typical for the southeastern half of the Russian



Legend

Southern border of intensive cultivation zone:

— — — at the end of the seventeenth century

● ● ● ● at the end of the eighteenth century

■ ■ ■ ■ ■ at the end of the nineteenth century

Locations of studied basins (for number of basin see Table 1):

1 basins no. 18–20; **2** basins no. 14–16; **3** basins no. 1–5; **4** basins no. 9–12;
5 basins no. 22–23; ***6***, ***7***, ***13***, ***17***, ***21*** see Table 1

Fig. 1 Location of the studied small basins within the southern half of the Russian Plain.

Plain with a boundary along the south edge of the forest zone. Most of the Russian Plain has been intensively cultivated since the sixteenth century, reaching a peak at the end of the nineteenth century. Grain cultivation became widespread in the southern steppe zone in the twentieth century.

The relief of the southern Russian Plain is characterized by a combination of lowlands with typical amplitudes of 20–40 m and uplands with amplitudes of up to 80–100 m within some river basins. The upland topography is dominated by a relatively flat interfluve area surrounded by gentle and steep slopes, which have been dissected by ephemeral valleys of varying sizes. More smooth slopes are typical for lowlands. Holocene loess and sporadic moraine mantle the area. Precipitation decreases from 600 mm at the south of the forest zone to 300 mm at the southeast of the steppe zone. However some increase in precipitation is observed near the Caucasus Mountains.

Several key small basins with typical relief parameters and with arable land area exceeding 70% located in different parts of the Russian Plain were studied for a detailed assessment of sediment redistribution during the period 1986–1999 (Fig. 1). A large-scale geomorphological map was produced for each study basin. The morphological elements within the overall basin were classified into three groups in terms of their role in sediment transport:

- *essentially stable (reference) areas*, represented by flat cultivated interfluves (slope <1°), grassy valley slopes and valley terraces;
- *eroding areas*, represented by the cultivated mid-slopes and different types of gullies;
- *depositional areas*, represented by the field margins, the hollows which dissect the valley sides, and the valley bottoms. The latter were also subdivided into deposition and transport reaches.

A detailed topographic survey was undertaken using a geodetic GPS system (Trimble Geodetic Surveyor IIP 4000 SST/SSE series), used in kinematic mode, with one receiver serving as a stationary (reference) station, and the other as a rover device (Panin *et al.*, 2001). This was augmented by traditional theodolite survey. Detailed relief maps were produced and the area of each morphological element determined. The modified Universal Soil Loss Equation proposed by Larionov (1993) was used to estimate mean annual soil loss for rainfall erosion and the State Hydrological Institute model used for erosion during snowmelt. A soil morphological method (comparison of soil profiles) was also applied at each site. The length of the period of cultivation was derived from historical information and the mean annual erosion rates for the entire period of cultivation for individual points was determined as:

$$V = h\,T^{1}$$

where V is the mean annual soil loss (mm year^{-1}); T is period of cultivation (years); $h = H_f - H_i$ where H_f is the depth (mm) of the humus horizon on the interfluve and H_i is the depth (mm) at the observation point.

Gully growth was evaluated by comparing topographical maps produced over different time intervals. Several pits across a few cross-sections within each depositional element were dug and described. The depositional rate for each morphological element was determined using the method of buried soils in conjunction with the spore–pollen method.

Sediment budgets for most basins were established for the entire period of intensive cultivation. However, for some basins the sediment budgets for the period after 1954 (beginning of nuclear bomb testing) or after 1986 (Chernobyl Power Plant explosion) were established using the ^{137}Cs technique for dating sediment deposition (Walling & Bradley, 1988).

RESULTS AND DISCUSSION

Sediment delivery coefficient (DR) information, determined for basins with areas ranging from 0.18 to 224 km^2 changes considerably from basin to basin and over different time intervals (Table 1). The basins can be divided into two groups when DR

Table 1 Main morphological characteristics and sediment delivery ratio coefficients for the studied basins.

No.	Basin, location	Gradient of valley bottom	Area (km^2)	Sediment delivery coefficient, DR	Order of valley near outlet	Presence of bottom gully*
Steppe zone						
1	Suhoy Yar-1, Stavropol region	0.01	21.6	0.06	1	–
2	Suhoy Yar-2, Stavropol region	0.02	11.1	0.76	1	+
3	Ternovaya, Stavropol region	0.014	8.5	0.85	1	+
4	Glubokii, Stavropol region	0.053	4.2	0.95	1	+
5	Shvedinka, Stavropol region	0.009	26	0.53	2	–
6	Tributary of Berestovaya, Rostov region	0.017	1.89	0.65	1	–
7	Markov Ruchei, Voronezh region	0.0003	142	0.02	3	–
8	Pogromka, Orenburg region	0.0004	224	0.015	4	±
9	Pavel'ev Yar, Orenburg region	0.0005	76.7	0.09	3	–
10	Elhovka, Orenburg region	0.0054	27.38	0.14	2	±
11	Dolgiy Yar, Orenburg region	0.0007	69.2	0.66	3	+
12	Grushin Les, Orenburg region	0.025	1.1	0.55	1	–
13	Kruotoi Yar, Orenburg region	0.0015	8.6	0.82	1	+
Forest-steppe zone						
14	Repniy, Voronezh region	0.02	3.5	0.83	1	+
15	Gnilische, Voronezh region	0.005	17.2	0.04	2	–
16	Vedyga, Voronezh region	0.009	86.9	0.01	3	–
17	Stepin Rukav, Tula region	0.021	4.6	0.83	2	+
17a	Stepin Rukav, Tula region†	0.0116	4.6	0.24	2	–
18	Chasovenkov Verh, Tula region	0.0085	42.1	0.64	3	+
18a	Chasovenkov Verh, Tula region†	0.0065	42.1	0.11	3	±
19	Tributary of Lapki, Tula region	0.088	0.28	0.24	1	±
20	Tributary of Chasovenkov Verh, Tula region	0.083	0.07	0.67	0	–
20a	Lapki, Tula region†	0.033	2.18	0.12	2	±
21	Popov Ovrag, Tambov region	0.0018	41.2	0.24	2	±
21a	Popov Ovrag, Tambov region†	0.002	41.2	0.1	2	–
22	Klyuchi, Saratov region	0.017	8	0.89	2	+
23	Rzhavets, Saratov region	0.01	18	0.09	2	–

* *Legend*: +, bottom gully along the main part of the main valley; ±, bottom gullies in some part of the main valley; –, flat bottom without bottom gully.

† Calculations of SD_C for period after 1954 using the ^{137}Cs technique.

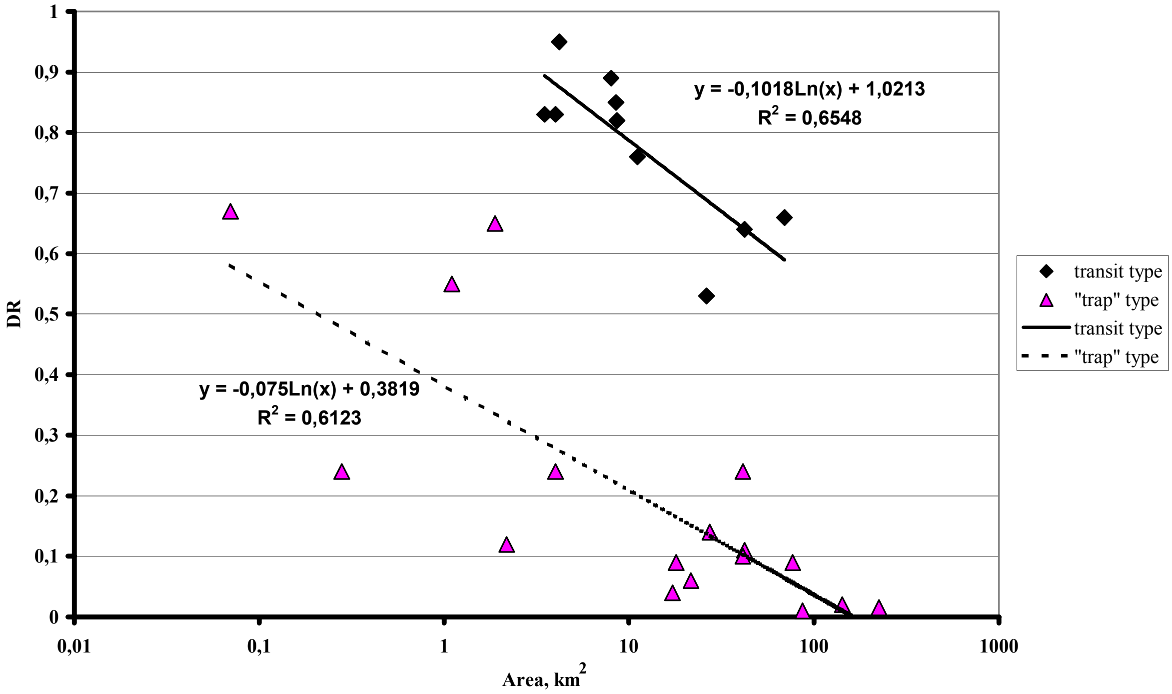


Fig. 2 Relationships between sediment delivery ratio and drainage basin area for different types of small basins in the Russian Plain.

values are plotted against basin area (Fig. 2). The differences between these two groups are the dominant processes in the valley bottom. Basins with DR close to 1 are characterized by intensive linear erosion because of gully development along the main part of the valley bottom. These lower-order basins are a “transit” type and mainly serve to deliver slope sediment to the next order valleys. They were widespread immediately after intensive increases in arable land area within each landscape zone of the Russian Plain because of considerable increases in surface water flow.

Basins with lower DR values are characterized by intensive deposition within the valley bottom. Some basins have both bottom gullies and reaches with intensive deposition. It has been shown that in this case the sediment eroded at the gully knickpoints was redeposited several tens of metres downstream (Panin *et al.*, 2001). Such low-order basins are “trap” type because most of the sediment eroded from the slopes and valley sides is redeposited within the basin with the maximum deposition rate in the main valley bottoms.

Investigations demonstrate that the distribution of different types of basins may be connected with the peculiarities of local regional development, for example, recent tectonic uplift. Also important is the individual stage of erosion and deposition process development within each individual basin. Intensive erosion in valley bottoms of most basins located within the Stavropol region is related to intensive uplift of the main interfluve of the Stavropolskaya upland relative to the Kalaus river valley (Belousov & Enman, 1999) and with a high recurrence of extreme rainfall events. The latter lead to intensive surface flow and active development of bottom gullies. Consequently, bottom gully tops almost reach the sources of small valleys, promoting sediment transport to the receiving valley. According to meteorological observations, rainfall events with maximum 30-min intensity of 0.3 mm min^{-1} and >100 mm of precipitation occur six times per century. Model calculations indicated that these may be responsible for 50% of eroded material. However, the timing of rainfall events in relation to the growth stage of different crops is more important than rainfall magnitude (Boardman, 1993). Regional development within the Russian Plain influences the sediment redistribution within low-order basins mostly in marginal areas where the Russian Plain borders mountains.

For the central parts of the Russian Plain sediment redistribution within small drainage basins depends on individual basin features and type of agricultural use. The local relief, area and the distribution of tillage within the basin, crop rotation and the recurrence of extreme flow events are the main natural and anthropogenic factors which influence the dominance of different basins types. Direct measurements of the consequences of extreme rainfall events show their considerable input in sediment redistribution within small basins. For example, about 20 cm of sediment was deposited along the first-order valley bottom located in the Orenburg region (southeast of the Russian Plain) after 60 mm rainfall with intensity 0.5 mm min^{-1}. Most of the cultivated layer (25 cm) was eroded from a field after 100 mm rainfall in the Orel region. The occurrence of these and more intensive rainfall events increases from one to three per decade from the south part of the forest zone to the steppe zone. Extreme rainstorms mostly influence sediment transport within small first-order valleys, where differences in depositional rates along the bottom lead to local increases of gradients and the development of bottom gullies. Transit type small basins are usually characterized by a recent deficit of sediment entering from cultivated slopes to the valley bottoms, for example, because of the application of soil conservation methods (Repniy and Klyuchi basins, Table 1). In some cases the sediment deficit is related to a reduction in the area of arable land (Kruotoi Yar and Dolgiy Yar, Table 1).

Relief parameters (gradient of valley bottom and banks, and basin slopes) of small basins are mostly responsible for the relationship between erosion and deposition processes within basins. A bottom gradient of 0.02 is the threshold value which divides basins with active erosion and deposition as the main processes within valley bottoms from more stable basins. Bottom gradients of >0.02 are typical for first- and second-order valleys of the Russian Plain.

The surface water flow coefficient increases considerably immediately after cultivation of virgin soils (Table 2). As a result bank gullies and bottom gullies in the first-order valleys begin to develop. Some eroded sediment is redeposited in the bank gully cones, but the main volume of sediment is transported from the first-order valleys along bottom channels. The combined effect of the changed relationship

Table 2 Mean surface water coefficient, calculated using 18-years of observation on small slope catchments, southern part of the forest-steppe zone of the Russian Plain (Koronkevich, 1990).

Land use	Mean surface water coefficient during snowmelt
Winter crops	0.68
Stubble	0.5
Pasture	0.32
Lawn meadow	0.31
Land ploughed in autumn for spring sowing	0.27
Undisturbed (natural) meadow	0.07
Oak forest	0

Table 3 Change of river length in valleys of different order for the typical river basins (southern half of the Russian Plain).

Valley order	Total valley length, *L* (km)	River length in 1830: (km)	(% of *L*)	River length in 1940: (km)	(% of *L*)
The upper Don river basin, north of the forest-steppe zone, intensive cultivation since the seventeenth century					
1	4 447	521	11.7	66	1.5
2	1 772	632	35.7	214	12
3	902	681	75.5	284	31.6
4	487	466	97.5	391	81.5
5	176	176	100	176	100
6	202	202	100	202	100
The Khoper river basin, south of the forest-steppe and north of the steppe zones, intensive cultivation since the nineteenth century					
1	30 311	682	2.25	57	0.2
2	9 974	2 282	23.1	965	0.68
3	4 712	2 680	57	1 453	30.9
4	2 310	1 977	86	1 448	63
5	971	965	99.4	965	99.4
6	682	682	100	682	100
The Severskiy Donets river basin, steppe zone, intensive cultivation since the end of the nineteenth century					
1	61 025	68	0.11	12	0.02
2	20 623	1 239	6	74	0.36
3	9 318	3 149	33.8	314	3.4
4	4 111	3 364	82	1 239	30.2
5	2 500	2 453	98.1	2 032	81.3
6	939	939	100	911	97
7	609	609	100	609	100
8	751	751	100	751	100

between surface water and groundwater flows and the increase in sediment transport from the cultivated slopes are the main reasons for small river aggradation and transformation in dry creeks with relatively flat bottoms. Maximum changes in river characteristics were observed in second–fourth order valleys of the steppe and forest-steppe zones (Table 3).

As detailed studies of small drainage basins demonstrate (Ivanova *et al.*, 1998), first-order valleys of the Russian Plain were quickly (in one to a few decades) filled with sediment following intensive cultivation of basin slopes. This is usually followed by the transit-type stage, when most sediment is transported to the second-order valleys and partly further. The duration of the trap-type stage for second-order valleys of the Russian Plain ranges from 0.5 to 3 centuries depending mostly on local relief and rainstorm intensity. Very often the upper and lower reaches of small valleys function as different types. However, in these cases the trap effect exceeds the transit effect, so the DR should be closer to 0 than 1. At present most parts of small second–fourth-order basins within areas of intensive cultivation belong to the trap type. The trap effect of small drainage basins has therefore exceeded the sediment input from cultivated lands for the centre part of the southern half of the Russian Plain during the last five decades. This has occurred for arable land during relatively stable climatic conditions. As a result a regressive trend is typical for sediment discharges of rivers draining the centre of the southern half of the Russian Plain (Gusarov, 2001).

Morphological features of the valley bottom, and the DR–area relationship for small drainage basins (Fig. 2) can provide relatively precise calculations of sediment redistribution within the upper chains of river systems within the Russian Plain. However information about erosion rates and intensity of gully growth for the studied river basins is also required for evaluation of sediment delivery from small drainage basins to the river channel.

CONCLUSION

Sediment redistribution within small drainage basins of the southern half of the Russian Plain increased considerably during the last one to two centuries because of the intensive cultivation of their watersheds. Two types of small basins can be identified depending on the dominant processes in the main valley bottom. Transit-type basins are characterized by high sediment delivery ratios. Trap-type basins detain and store sediment entering from cultivated slopes and valley banks. At present the latter are widespread within the centre part of the Russian Plain and the former are more typical of marginal areas bordered with mountains. However, the basin type can change over time depending on valley morphology and the intensity of sediment input from the watershed area. The most intensive replacement is observed within first-order valleys, mostly because of extreme rainfalls. However, extreme events (rainstorms and intensive spring snowmelt) do not influence the development of second–fourth order valleys. Domination of trap-type basins in second–fourth-order basins of the intensively cultivated part of the Russian Plain is the main reason for the decreasing trend in river sediment discharge.

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