Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996). IAHS Publ. no. 236, 1996.

Redistribution of sediment within small catchments of the temperate zone

VALENTIN GOLOSOV
Laboratory of Soil Erosion and Fluvial Processes, Department of Geography, Moscow State University, GSP-3, Vorob'evy Gory, Moscow 119899, Russia

Abstract The features of sediment redistribution within small basins of the temperate zone are investigated by studying each component of the sediment budget. The volume of sediment which accumulates between a cultivated slope and the river channel is the key component of the sediment budget. It has also been found that the individual features of a small basin are more important than the general landscape features in controlling the sediment budget. However the intensities of erosion and sedimentation processes are influenced by the landscape zone, since their intensities increase from the forest belt to the wet steppe belt.

INTRODUCTION

The temperate zone of the world occupies vast parts of North America, Europe, Asia and South America. This zone includes several landscape belts, namely, taiga, forest, forest-steppe, steppe, semi-desert and desert. Erosion and sedimentation processes are of limited activity in the taiga belt, because the area of arable land does not exceed 10-15% at a maximum. Almost the same situation exists in the semi-desert and desert belts. Here, erosion and sedimentation processes are only very active in the irrigated lands of middle Asia, which occupy less than 10% of the total territory occupied by these belts. The forest, forest-steppe and steppe belts are the major areas of agriculture with very productive soils such as chernozems. Processes of sediment redistribution are very intensive in these areas.

It is possible to select several types of variability, which are reflected in sediment redistribution. These include: (a) temporal; (b) spatial (Campbell, 1992); and (c) morphological. Temporal variability is closely linked with periods of intensive agriculture in different parts of the temperate zone. Much of western and central Europe was ploughed up in the medieval period and the maximum extent of arable land area was reached after the fourteenth century (Bork, 1989). Large tracts of virgin land were cultivated in North America in the middle of the last century (Knox, 1987). The period of intensive cultivation in eastern Europe and Siberia changes in moving from the area around Moscow (southern part of the forest zone), where the area of arable land reached 60-75% in the second half of the eighteenth century, to the territories of the steppe zone, some of which were only cultivated in the middle of this century. The Russian part of the steppe zone, and in particular the forest-steppe zone, are areas where it is more easy to assess changes in the sediment budget of small basins after the beginning of intensive cultivation, because information about the area of arable land, crop rotation, precipitation and other meteorological parameters are more readily available.

It is important to also consider the spatial variability when studying sediment redistribution in small basins with areas of 10-100 km^2. The sediment budgets of these basins are especially sensitive to climatic changes or anthropogenic influence (Boardman *et al.*, 1994). The major proportion of the sediment carried by intermediate and large rivers originates in these basins. If detailed studies of sediment redistribution are undertaken within small basins, delivery ratios for river basins of any size can be calculated more accurately.

Morphological variability also exerts an influence on the sediment budgets of river basins. The delivery ratios for mountainous river basins are usually very close to one in forested areas (Duijsings, 1986) as well as in cultivated areas (Sala, 1981; Froehlich & Walling, 1992). Very different situations are observed in plain and foothill zones, where delivery ratios can vary over a very wide range from 0 to 1 (Walling, 1983). This occurs because the components of the sediment budget of small basins can vary very rapidly.

The main aim of this paper is to present some details of sediment redistribution in small catchments of the forest, forest-steppe and steppe zones of the Russian plain, as typical basins of the temperate zone.

METHODS

The approach employed for calculating sediment budgets is based on the use of different methods for determining each component of the budget, in order to increase the precision of the calculations. Soil erosion rates on the arable land were determined by several methods. The first method was based on estimation of the volume of slope erosion, using the actual thickness of the eroded soil horizons (Dobrovol'skaya & Litvin, 1991). Another method for estimation of soil erosion volume is based on empirical erosion models. The intensity of erosion by rainfall was calculated using the USLE as modified by Larionov (1984). The model of the State Hydrological Institute, also modified by Larionov (1984), was used to calculate soil erosion during the period of snowmelt. This empirical model includes the following parameters: water storage in the snow, slope gradient, type of drainage and the grain size of the soil. Using these results, a map of soil erosion can be produced for any basin.

The volume of gully erosion is determined on the basis of direct field measurement of each gully within the small basin. The age of the gully is defined after comparison of large scale topographical maps produced at different times and after detailed study of the soil profiles on gully slopes.

The volume of slope accumulation can only be defined where it is greater than the precision of the sediment budget calculation. The depth of sedimentation is assessed for different areas of slope accumulation, including shelter belts; roads; water storage ponds; uncultivated foot slopes more than 100 m from erosional forms (gully, creek, balka etc.); and points of slope form change from convex to concave. As a rule, the bulk of the sediment delivered to such places is redeposited.

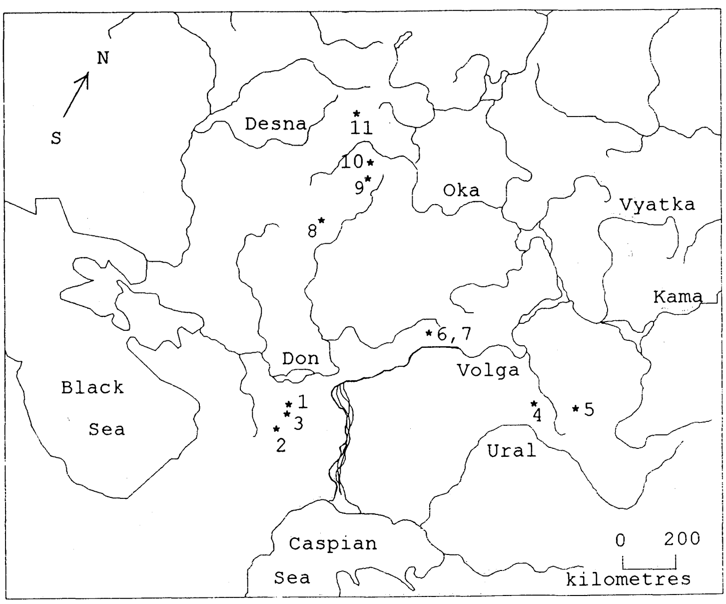
The volume of sediment contained in balkas, creeks and the upper reaches of small rivers is established by drilling holes or digging pits within the erosion form on cross-section profiles. The thickness of agricultural sediment is defined by analysis of its structure and colour and of sedimentary stratigraphic layers and buried soil horizons. The period of the beginning of intensive sedimentation was associated with rapid growth of the area of arable land. The spore-pollen method can be used for identifying agricultural sediments within small river and creek bottoms. The gradient and area of such sedimentation zones are calculated using special topographic plans derived from detailed tacheometric surveys.

The ^{137}Cs method can be used to date sediment accumulated in balka or creek bottoms. Samples of fine bottom sediment covering the whole depth of deposition are collected using an 80 mm diameter steel corer and in most cases the cores are sectioned at 10-15 cm intervals prior to analysis. All samples are dried, dis-aggregated and prepared for analysis by gamma spectrometry at the Institute of Experimental Meteorology (Obninsk city, Kaluga region) or at the Institute of Applied Geophysics (Moscow).

Results of experimental observations of snowmelt and rain-fed erosion undertaken at the "Satino" experimental station in the Protva river basin have also been used to provide some details of the redistribution of sediment on the edge of cultivated fields, including the tops of gullies and balkas.

RESULTS

Several small basins which are located in the different landscape belts of the Russian Plain were chosen for investigation (Fig. 1). The sediment budgets for these small basins



Legend: * - point of field observation.
1 - Suhoy Yar (Aigurka), 2 - Suhoy Yar (Kalaus)
3 - Shvedinka, 4 - Elhovka, 5 - Bezymyannaya,
6,7 - Kljuchi, Rdzavets, 8 - Gnilische,
9 - Stepin Rukav, 10 - Chasovenkov Verh,
11 - Protva.

Fig. 1 Map showing location of observation points.

included the following parameters: sheet erosion volume, rill volume, gully volume and volume of sedimentation on the slope, volume of sedimentation in the creek, balka and small river bottoms. In general, other processes operating in these areas, such as creep and landslides and are associated with volumes less than the precision of the total budget (Antonov & Golosov, 1994). The intensity of sheet erosion on the Russian plain varies from 2-3 t ha^{-1} $year^{-1}$ within the lowland area to 6-8 t ha^{-1} $year^{-1}$ in the upland areas. Geomorphological parameters (slope form, slope gradient and length) exert a more significant effect on sediment redistribution than other landscape characteristics. In the forest and forest-steppe zones, snowmelt and rainfall erosion have almost the same intensity. The major part of sheet erosion in the steppe zone occurs during spring and summer rainstorms.

Rill erosion occurs in all areas of the Russian plain, but the importance of rill erosion in sediment budgets increases dramatically in the wet part of the steppe zone within fields with high slope gradients. Maximum rates of slope erosion are observed in basins in the wet part of the steppe zone or in areas with the highest slope gradient (Table 1, items 2, 3, 6, 7). The increased intensity of rill erosion in these basins causes average annual sediment yields to increase twofold.

The accumulation of sediment on the uncultivated parts of the basin slopes depends on the amount of arable land within a small basin. A major part of the sediment mobilized in the forest zone accumulates on the slope (Walling *et al.*, 1986), because the area of tillage is not more than 35-40% here. Almost all slopes except for the very steep

Table 1 The redistribution of sediment within several small basins of the forest-steppe and steppe zones.

	Basin and area (km^2)	Location (river)	Average annual sediment yield (t km^{-2} $year^{-1}$)	Accumulation on uncultivated slopes (%)	Accumulation on creek bottom (%)	Delivery ratio (%)
1	Suhoy Yar-1 21.6	Aigurka	460	71	23	6
2	Suhoy Yar-2 11.1	Kalaus	1100	23	1	76
3	Shvedinka 26	Kalaus	1080	44	3	53
4	Elhovka* 27.4	Bolshaya Pogromka	400	50	36	14
5	Gnilische 17.2	Veduga	410	<1	96	4
6	Kljuchi 8	Peschan-ka	2000	<1	11	89
7	Rdzavets 18	Peschan-ka	850	<1	80	9
8	Chasovenkov Verh* 42.1	Plava	430	45	44	11

* Sediment budget for ^{137}Cs period.

slopes of creeks, balkas and river valleys are cultivated in the forest-steppe zone. The same situation is observed in the steppe zone, where the area of arable land within small basins is 55-65%. In addition the rate of sedimentation on grassy slopes depends on the rate of soil erosion on the cultivated part of the slope. According to results from experimental work undertaken during the snowmelt period, the volume of sedimentation increases in response to an increase in erosion rates on the arable land (Table 2).

Usually it is more difficult to calculate sedimentation rates in creek and balka bottoms. Using the ^{137}Cs method it is possible to establish the thickness of layers that were deposited during the last 35-40 years. Also, if the period of intensive cultivation is known, it is possible to estimate the rate of sedimentation during this period. Comparison of these data for different landscape belts of the temperate zone of Russia demonstrates that rates of sedimentation have increased in steppe and forest-steppe belts during the last 35-40 years, whereas they have dramatically decreased in the forest belt (Table 3). The increased sedimentation rates reflect changes in surface water runoff associated with use of heavy agricultural machinery and an increase in the proportion of inter-tilled crops in the crop rotation. As a result soil erosion rates have increased on

Table 2 The relationship between the volume of erosion and accumulation in the zone between the edge of the field and the head of the gully (based on experimental data from a slope basin).

Year	Type of cover	Volume eroded (t)	Volume accumulated (t) (% of eroded volume)
1982	tillage	51	39 (76)
1983	tillage	136	74 (54)
1984	winter corn	12	1 (8)
1985	tillage	53	30 (56)

Table 3 Annual rates of deposition in creek (balka) bottoms for the entire period of intensive agriculture and for the ^{137}Cs period.

	Basin	Mean gradient of bottom	Period of intensive agriculture (years)	Annual rate of deposition (mm): For entire period of cultivation	Annual rate of deposition (mm): For Cs-137 period	Landscape zone
1	Suhoy Yar-1	0.01	50-60	38	51	wet steppe
2	Suhoy Yar-2	0.02	80-100	22	33	wet steppe
3	Shvedinka	0.009	140-160	19	50	wet steppe
4	Elhovka	0.0054	100-150	10	23	dry steppe
5	Bezymyannaya	0.0117	140-160	10	18	dry steppe
6	Gnilische	0.005	250-300	4.6	18	forest-steppe
7	Stepin Rukav	0.0116	250-300	5.4	10.5	forest-steppe
8	Protva*	0.01-0.02	300-350	3	0.6	forest
9	Chasovenkov Verh	0.0065	250-300	8	26	forest-steppe

* Several small basins with total area 4-8 km^2.

the arable lands. The changes of sedimentation rates in the forest belt can be explained by the decrease of the area of arable land.

It is possible to find zones within a basin with different relationships between sediment output and sedimentation (Fig. 2(a)). In the source areas the major part of the sediment mobilized from the field accumulates. Downstream, the sediment output increases up to 20%. The valley (balka) bottom in this part is characterized by a flat cross-section (Fig. 3(a)) and maximum bed gradient. Further downstream, the valley bottom is characterized by a change in cross-section form (Fig. 3(b)) and an increased sedimentation rate. Usually different surface levels are observed here. The major part of the sediment mobilized from the slopes in the lower reaches is deposited before it reaches the incised channel which usually occurs here (Fig. 3(c)). The output from this part of a small basin is therefore very low (Fig. 2(a)).

The length of each zone, with its different relationship between sedimentation and output, usually changes from one creek (balka) to another. Of course, parts of the creek

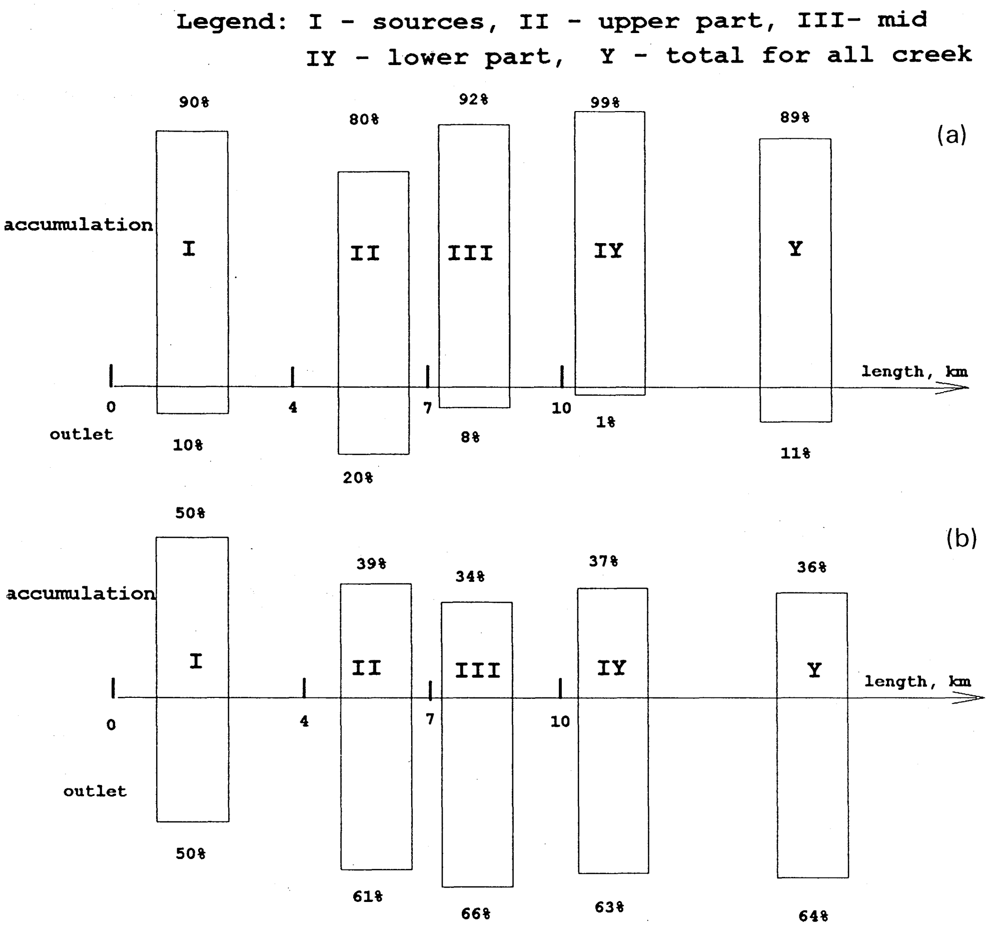


Fig. 2 The relationship between accumulation and output for different parts of Chasovenkov creek: (a) for the ^{137}Cs period; and (b) for the entire period of intensive agriculture.

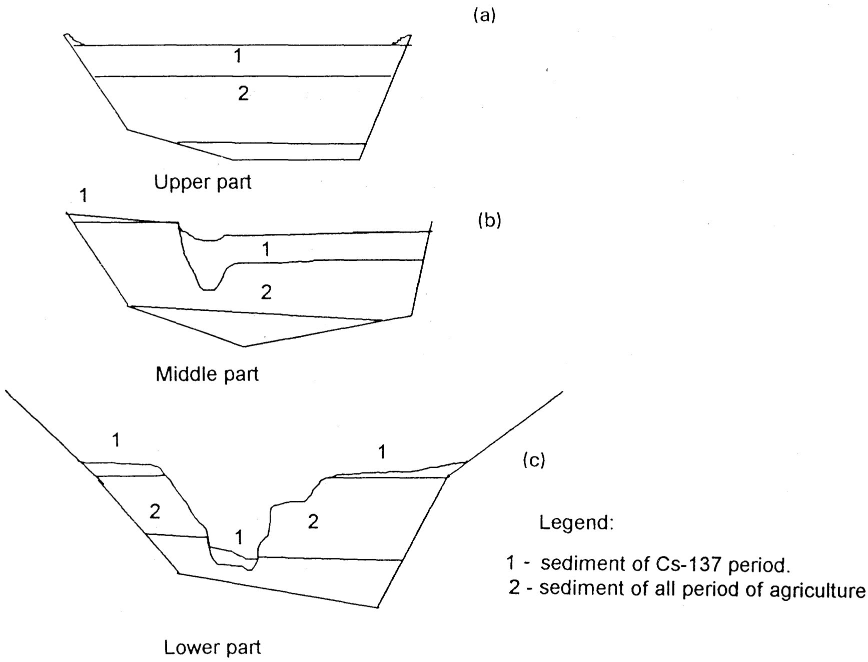


Fig. 3 Typical cross-section profiles of Chasovenkov creek for different reaches along its course.

will have only one zone, and the sedimentation volume can therefore change for different conditions as well as delivery ratio. The gradient of the creek or balka bottom also influences the rate of accumulation. According to our observations the rates of sedimentation decrease significantly when the bed gradient exceeds 0.02. The quantity of sediment deposited in the creek bottom may therefore range from 1% to 96% (Table 3).

Before the period of intensive cultivation, most of the dry creeks and balkas now found in the temperate zone were small rivers. They aggraded in response to the increasing soil erosion associated with the growth of the area of arable land. It is possible to confirm this by comparing recent and old maps with identical scales (Golosov & Ivanova, 1992). It may also be demonstrated by comparing sedimentation and output along the creek bottom for all periods of cultivation (Fig. 2(b)). This relationship is typical for small rivers on the Russian plain (Dedkov & Mozzherin, 1984).

The delivery ratios associated with small basins in the different landscape belts of the temperate zone can vary over a very wide range (Table 1). The delivery ratio will depend on the individual features of specific small basins. For example, the Kljuchi and the Rdzavets Creek basins are located opposite each other within one river basin (Fig. 1), but their delivery ratios are totally different (Table 1). The same situation is observed in the Kalaus River basin (Suhoy Yar-1, Suhoy Yar-2 and Shvedinka basins) (Table 1). The main reason for the differences in delivery ratio is the proportion of the sediment which is deposited on the slope and in the creek bottom within the small basin.

CONCLUSION

Sediment redistribution within small catchments of the temperate zone exerts a major influence on the sediment yield of intermediate and large rivers, because most of the sediment which enters the river channel originates here. It is difficult to define delivery ratios for small catchments in the steppe and forest-steppe belts, because they vary over a very wide range. The value of the delivery coefficient depends on the volume of sedimentation within the small basin. Recent rates of accumulation in creek (balka) bottoms of the steppe and forest-steppe belts have increased relative to the rates calculated for the entire period of cultivation (Table 3). It can therefore be suggested that the delivery ratios of small catchments in these belts have decreased due to an increase in the extent of the sedimentation zone. It is important to define the relationships between small basins with different types of sediment redistribution, if sediment redistribution within intermediate or larger basins is to be investigated.

Acknowledgements The author would like to express thanks to the John and Catherine MacArthur Foundation, the International Science Foundation and the Russian Government for providing financial support.

REFERENCES

Antonov, S. I. & Golosov, V. N. (1994) Osobennosti ispol'zovaniya balansovogo podhoda pri stacionarnyh issledovaniyah sovremennyh geomorphologicheskih processov v rechnom basseine (Budget method applied to stationary studies of present-day geomorphic processes in a drainage basin). *Geomorphologiya* **2**, 63-71.

Boardman, J., Ligneau, L., de Roo, A. & Vandaele K. (1994) Flooding of property by runoff from agricultural land in northwestern Europe. *Geomorphology* **10**, 183-196.

Bork, H.-R. (1989) Soil erosion during the past millennium in central Europe and its significance within geomorphodynamics of the Holocene. In: *Landforms and Landform Evolution in West Germany* (ed. by F. Ahnert). *Catena* suppl. **15**, 121-131.

Dobrovol'skaya, N. G. & Litvin, L. F. (1991) Pochvenno-morphologicheskii metod ocenki dynamiki obrazovaniya basseinovyh nanosov (Soil-morphological method of assessment of dynamics of basin sediment formation). In: *Proc. Sixth Conf. on the Problem of Erosion, Channel and Delta Processes* (Tashkent), 31-32.

Campbell, T. A. (1992) Spatial and temporal variations in erosion and sediment yield. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symp., August 1992), 455-466. IAHS Publ. no. 210.

Dedkov, A. P. & Mozzherin, V. I. (1984) *Eroziya i Stok Nanosov na Zemle* (Erosion and sediment yield on the Earth). Izdadelstvo Kazanskogo Universiteta, Kazan.

Duijsings, J. J. H. M. (1986) Seasonal variation in the sediment delivery ratio of a forested drainage basin in Luxembourg. In: *Drainage Basin Sediment Delivery* (ed. by R. F. Hadley) (Proc. Albuquerque Symp., July 1986), 153-164. IAHS Publ. no. 159.

Golosov, V. N. & Ivanova, N. N. (1993) Some causes of the disappearance of the river network due to intensive agricultural land development. *Wat. Resour.* **20**(6), 684-688.

Froehlich, W. & Walling, D. E. (1992) Use of fallout radionuclides in investigations of erosion and sediment delivery in the Polish Flysh Carpathians. In: *Erosion, Debris Flows and Environment in Mountainous Regions* (ed. by D. E. Walling, T. R. Davies & B. Hasholt) (Proc. Chengdu Symp., July 1992), 61-76. IAHS Publ. no. 209.

Knox, J. C. (1987) Historical valley floor sedimentation in the upper Mississippi valley. *Ann. Assoc. Am. Geogr.* **77**(2), 224-244.

Larionov, G. A. (1984) Metodica melko- i srednemashtabnogo kartographirovaniya erozionno-opasnyh zemel' (Methodology of small and medium scale mapping of erosion-prone lands). In: *Aktual'nye Voprocy Eroziovedeniya* (ed. by A. N. Kashtanov & M. N. Zaslavskii), 233-256. Kolos, Moscow.

Sala, M. (1981) Geomorphic processes in a small Mediterranean drainage basin (Catalan Ranges). *Trans. Jap. Geomorphol. Union* **2**, 239-252.

Walling, D. E. (1983) The sediment delivery problem. *J. Hydrol.* **65**, 209-237.

Walling, D. E., Bradley, S. B. & Wilkinson, C. J. (1986) A caesium-137 budget approach to the investigation of sediment delivery from a small agricultural drainage basin in Devon, UK. In: *Drainage Basin Sediment Delivery* (ed. by R. F. Hadley) (Proc. Albuquerque Symp., July 1986), 423-435. IAHS Publ. no. 159.