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Influence of different factors on the sediment yield of the Oka basin rivers (central Russia)

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Abstract In order to investigate links between basin/land-use characteristics and sediment fluxes of rivers within the Oka River basin, a database has been compiled from observations obtained at 25 gauging stations located in different parts of the basin. Relatively high correlations have been found between sediment yield from basin hillslopes and river sediment yield for: (i) rivers of the forest and northern part of forest-steppe zones ($r^2 = 0.50$); and (ii) rivers of forest-steppe zones ($r^2 = 0.52$). A linear positive relationship ($r^2 = 0.71$) has been found between sediment delivery ratio and weighted average gradient of river channel separately for the large river basins and small river basins of the forest zone. A negative relationship between sediment delivery ratio and forested area within basins is found separately for the small ($S < 2500$ km^2) rivers and large rivers of the Oka River basin. The influence of other factors as well as the problem of small river aggradation is also discussed.

Key words erosion; gauging station; river aggradation; Russia; sediment yield

INTRODUCTION

Under natural conditions, the contribution of the basin-derived sediment yield component decreases and the channel-derived component increases slowly from the upper parts of fluvial systems to the large river basins (Dedkov & Mozzerin, 2000). For example, results of field observations of different denudation processes within the Lown Tree small catchment (mountains of the southwestern USA, area 1.74 km^2) demonstrate that denudation rates vary from year to year within a range of 148–1575 t km^{-2} (Lerhe, 1982). The contribution of basin-derived components (landslides and hillslope erosion) was 7–44 times higher than that of channel erosion. The 30 year monitoring of different exogenic processes within 0.1–1 km^2 forested catchments (Oregon State, USA) allowed the ratio of basin-derived to channel-derived components of total river sediment yield to be determined as 1.4:1 (Swanson *et al*., 1982). It is likely that the relationship is close to 1 for undisturbed small catchments of plains, because they typically have relatively narrow valley bottoms allowing a significant part of the hillslope-derived sediment to reach channels. Increase of sediment yield with increasing drainage basin area is typical for river basins under natural conditions and is associated with increasing input of a channel-derived component (Dedkov & Mozzerin, 1984).

In contrast, soil and gully erosion on hillslopes are the main sediment sources for plain river basins located within intensively cultivated areas. The actual amount of basin-derived sediment reaching river channels within forest and forest-steppe zones is controlled by the area of cultivated land, its spatial linkages with river valleys and the structure of fluvial dissection of a drainage basin. The area of cultivated lands within steppe and the southern part of forest-steppe zones of European Russia exceeds 50%. In this study we have made an attempt to evaluate the influence of different factors on the contribution of basin-derived sediment to the total river sediment yield for drainage basins located in the transition zone between forest and forest-steppe zones. We believe that, in that area, the differences in conditions controlling the formation of the basin-derived component of river sediment yield are clearly manifest.

STUDY AREA AND METHODS

The Oka River basin was chosen as a study area. It is located on the border between the forest and forest-steppe zones (Fig. 1). The basin is characterized by forest area that has been relatively stable during the last 90 years (Idzon & Matveeva, 1973) and has a dense network of gauging stations monitoring river sediment yield. Data from gauging stations with periods of observation exceeding 10 years and without large reservoirs upstream were selected for analysis. The main hydrological characteristics and mean annual suspended sediment yields were determined for each of the studied drainage basins (Table 1). The bedload sediment yield was not taken into consideration because of a lack of regular measurements at most of the gauging stations.

Mean annual sediment yields from basin hillslopes were calculated for each study basin using data obtained from the *Map of Erosion-Prone Lands of European Russia*.

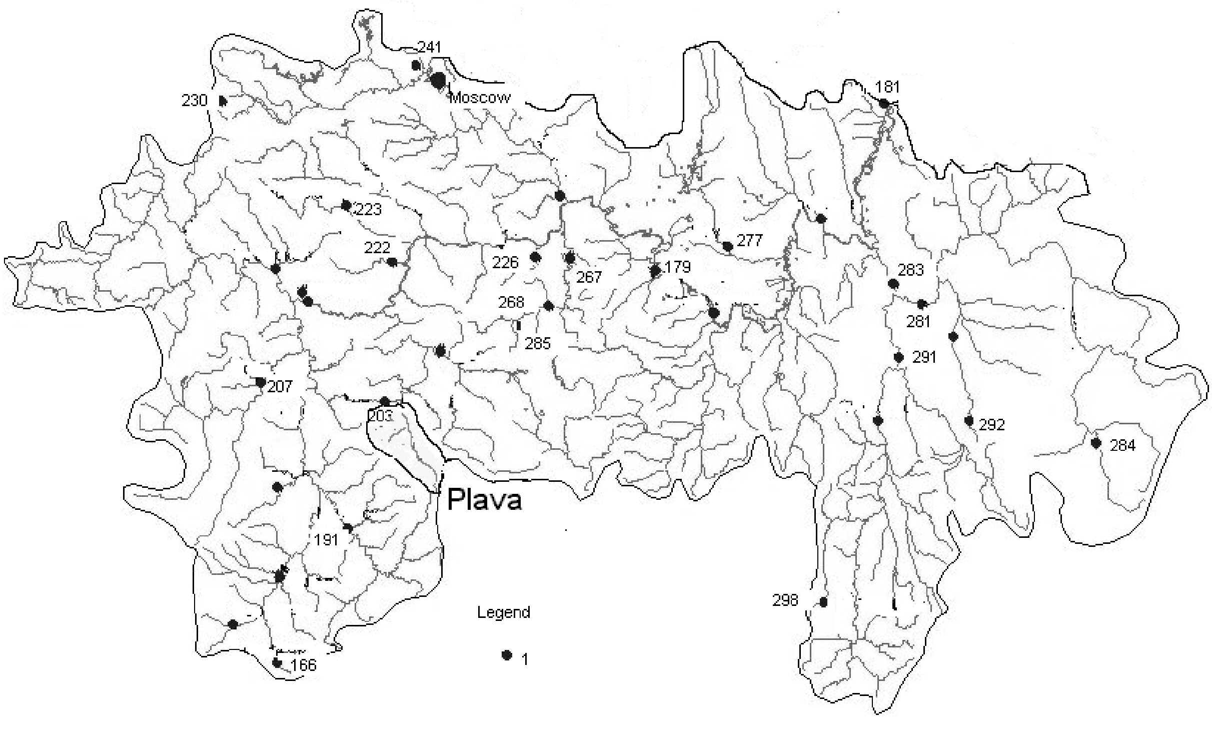

Fig. 1 Location of the Oka River basin, 1 - gauging stations.

Table 1 Some characteristics of the Oka basin rivers.

River	No. gauging station	Basin area (km^2)	Mean annual sediment yield for basin ($t\ km^{-2}\ year^{-1}$)		Relation-ship M_p/M_c (%)	Mean channel gradient (%)	Forest-ed area (%)	No. of gullies per km^2	Cultiva ted area (%)
			River, M_p	Slope, M_c					
Oka	166	513	55.0	464	11.9	1.2	7	59	75
Oka	179	54 900	19.0	435	4.4	0.12	23	46	55
Oka	181	188 000	7.5	317	2.4	–	35	42	59
Zhusha	191	6 000	53.0	454	11.7	0.32	7	68	67
Upa	203	8 210	20.0	461	4.4	0.21	8	60	55
Zhizdra	207	6 940	8.5	181	4.7	0.3	46	59	30
Tarusa	222	872	19.0	218	8.8	0.9	46	12	29
Protva	223	3 640	7.5	273	2.7	0.28	49	12	27
Osetr	226	3 020	17.0	340	5.0	0.43	14	47	64
Moksha	281	15 800	13.0	305	4.3	0.18	16	35	60
Moksha	283	28 600	9.9	261	3.8	0.18	25	66	50
Atmiss	284	2 310	63.0	320	19.7	0.6	9	75	70
Lomovka	285	1 110	40.0	266	15.0	1.50	17	37	40
Vad	291	527	25.0	248	10.1	1.80	24	37	45
Vad	292	1 930	8.9	174	5.1	0.7	37	37	35
Chelnovaya	298	323	18.0	130	13.8	1.80	1	15	60
Vysha	301	2 190	43.0	170	25.3	1.4	6	37	50
Buzha	277	1 100	0.5	10	5.3	0.26	65	12	4
Kerd'	270	537	22.7	322	7.0	1.00	5	54	70
Pronya	267	3 520	21.0	288	7.3	0.34	4	41	64
Pronya	268	2 300	8.0	278	2.9	0.35	3	31	62
Pronya	285	1 310	21.0	300	7.0	0.38	3	24	59
Medvedenka	250	40	61.0	737	8.3	0.6	45	12	51
Istra	241	1 950	7.1	262	2.7	0.46	60	12	21
Moskva	230	500	7.0	305	2.3	0.33	46	12	25

The map contains information about average rates of soil loss from the cultivated land calculated using a combination of the modified version of the USLE (for evaluating rain-storm erosion) and the State Hydrological Institute erosion model (for evaluating erosion during snowmelt) (Larionov, 1993). Mean annual sediment yield from hillslopes was calculated for each river basin using the following equation:

$$R_c = \Sigma r_{ci} S_i / S_b \qquad (1)$$

where R_c is sediment yield from hillslopes ($t\ km^{-2}\ year^{-1}$); r_{ci} is average value of a soil loss rate range taken from the map ($t\ km^{-2}\ year^{-1}$); S_i is area occupied by a given soil loss rate range on the map (km^2); and S_b is drainage basin area (km^2).

The areas of the drainage basins and cultivated land within these are taken from the Hydrological Reference Books, excluding possible errors resulting from carto-graphic distortions. Mean gully density (number of gullies per km^2) was calculated from the *Map of Gully Density* (Kosov *et al*., 1970) for each of the basins using a similar approach (Table 1).

RESULTS AND DISCUSSION

Under natural conditions, the sediment yield of rivers of the forest and the northern part of the forest-steppe zones averages 0.5–2 t km^{-2}, depending on basin area (Dedkov & Mozzerin, 1984). It is believed that the relationship between river sediment yield (M_p) and sediment yield from hillslopes (M_c) approximately characterizes a sediment delivery ratio for each basin. The mean sediment delivery ratio for the entire data set analysed was estimated as 7%, with a increasing trend from northwest to southeast. The above value is in the good agreement with the results of field observations and calculations of sediment redistribution within the Oka River basin obtained by Starostina (1972). If drainage basins with cultivated areas <25% are excluded from the calculation as weakly disturbed territories, the mean sediment yield for the rest of the drainage basins is 16 t km^{-2} with an increasing trend from the forest zone to the forest-steppe zone. The relationship between M_p and M_c for all the river basins analysed within the Oka River basin is relatively weak (r^2 = 0.36), because of differences in runoff formation conditions. However, it becomes stronger if the river basins analysed are sub-divided into two groups according to the landscape zones (Fig. 2). Rivers of the south-eastern part of the study area, which are completely located within the forest-steppe zone, are characterized by a higher input of hillslope-derived component into the total river sediment yield. It is mostly explained by a more intensive snowmelt runoff in that region, leading to the delivery of relatively large amounts of sediment from hillslopes to river channels. As a result, the hillslope-derived component constitutes more than 80% of the total river sediment yield. On the other hand, an essential part of the hillslope-derived sediment is re-deposited within uncultivated hillslope toes and dry valley bottoms of the forest and northern part of the forest-steppe zones. Hence, even within the intensively cultivated areas, the contribution of basin-derived sediment to the total river sediment yield is less than 60%.

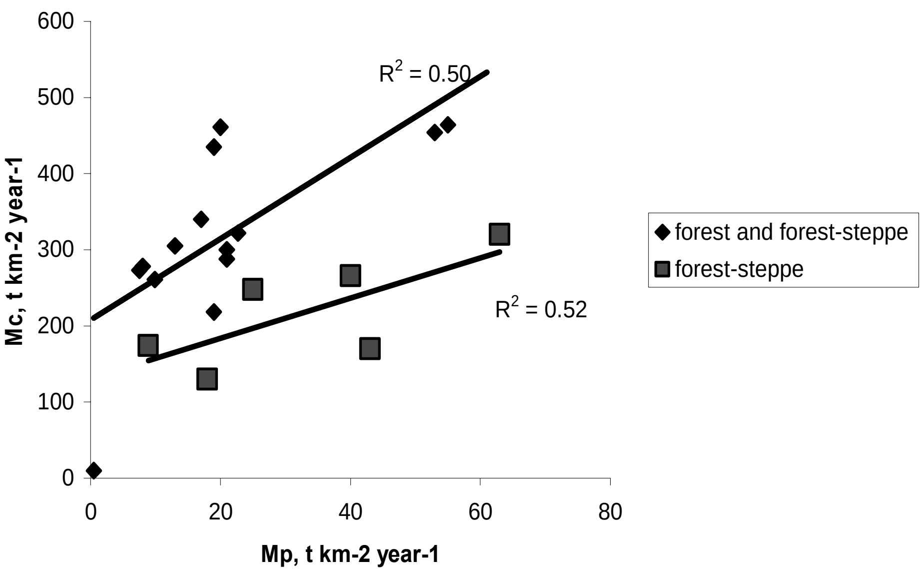

Fig. 2 Correlation between river sediment yield (Mp) and cultivated slope sediment yield (Mc) for the rivers of the Oka River basin of different landscape zones: 1, rivers of forest and north of forest-steppe zones; 2, rivers of forest-steppe zone.

There is no observed correlation between the number of gullies and river sediment yield for rivers of the Oka River basin (r^2 = 0.17). Most of the gullies are believed to have formed between the 17th and 19th centuries, when the cultivated land expanded substantially because of population growth. At present most of these are at the final stage of development with very low growth and sediment export rates (Butakov *et al.*, 2000). It can therefore be concluded that the gullies are not essential sources of sediment in the study area at present.

A general tendency of increasing river sediment yield with increasing cultivated area is observed, without a clear relationship (Fig. 3). The scatter of data points confirms that spatial connectivity of cultivated hillslopes with river channels exerts a greater influence on the amount of basin-derived sediment reaching the channels, rather than the total cultivated area. However, good relationships between forested area within a basin and sediment delivery ratio are established (Fig. 4). There is a closer relationship for the small rivers that may be explained by a more sensitive reaction of the sediment yield of small basins to the conditions of surface runoff formation.

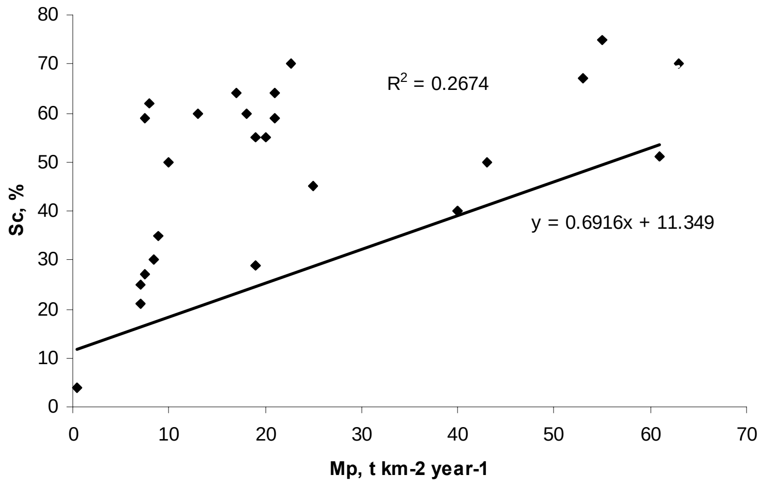

Fig. 3 Correlation between river sediment yield (Mp) and cultivated land area (Sc) for river basins of the Oka River basin.

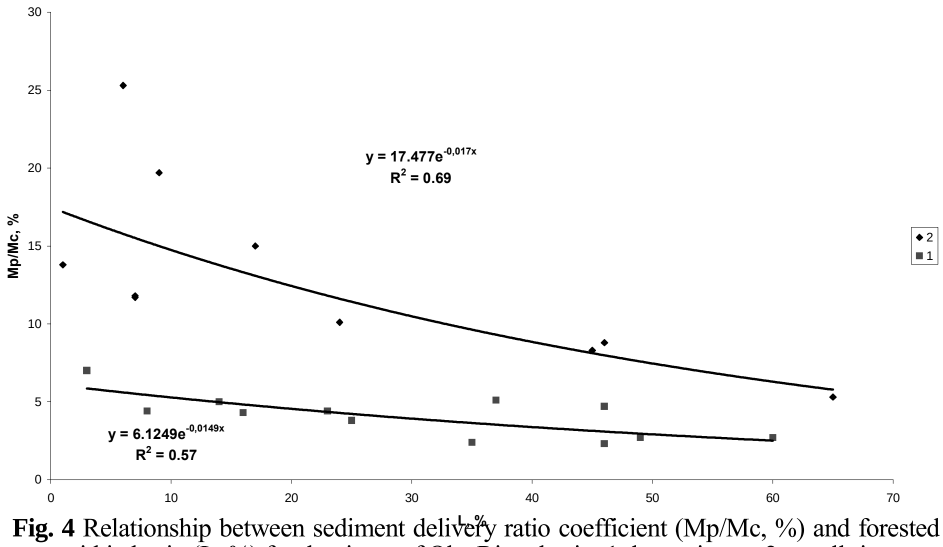

Fig. 4 Relationship between sediment delivery ratio coefficient (Mp/Mc, %) and forested area within basin (L, %) for the rivers of Oka River basin: 1, large rivers ; 2, small rivers.

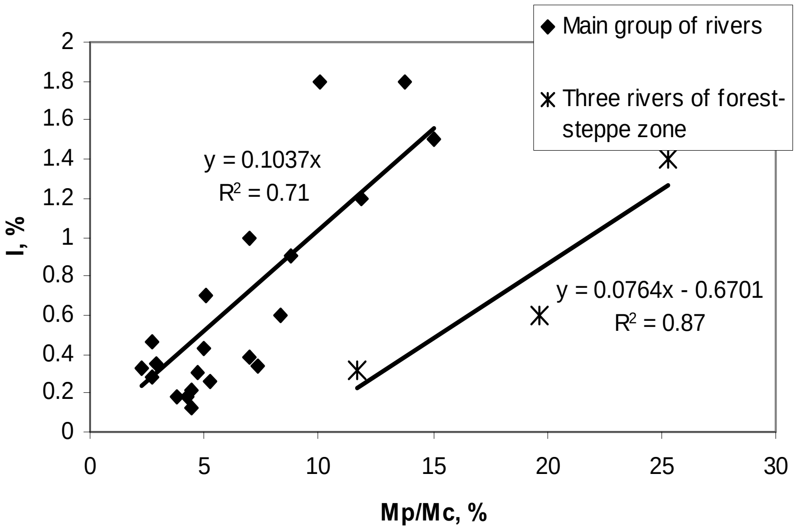

Fig. 5 Relationship between sediment delivery ratio coefficient (Mp/Mc, %) and river channel gradient (I) for rivers of the Oka River basin.

Sediment delivery ratio has a good correlation with river channel gradient (Fig. 5). It can possibly be explained by the increased connectivity between hillslopes and river channels with increase in local topographic range. Three rivers (Zhusha, Atmiss and Vysha) are characterized by distinctively individual relationships of these parameters (Table 1, Fig. 5). It is likely that the reason for this is the extremely high input of hillslope-derived sediment to these rivers compared with the other rivers, because of denser and relatively more active gully networks with direct connectivity to the river channels.

River sediment yield in the study area decreases with increasing basin area. This is confirmed by observations at several gauging stations located within the same river basins of the forest, forest-steppe and steppe zones of the Russian Plain (Fig. 6). It can be concluded that large amounts of sediment are re-deposited within river flood plains. In cases of a high input of hillslope-derived sediment to river valley bottoms, which are typical for small rivers of the Hortonian orders 1–3, intensive channel aggradation can occur. Together with the transformation of an annual hydrograph shape resulting from cultivation of a river drainage basin area, it leads to the disappearance of the upper part of a perennial watercourse and a reduction of the total length of the river network within the basin.

The total length of the network of perennial watercourses was measured for some river basins within the Oka River basin using maps published in 1826–1839 and in the 1940–1950s. Values of stream net density (SND) changes demonstrate clear spatial differences (Table 2). In the forest zone the SND changes are within the range of ±10%, which is considered to lie within the precision of the cartographic method used. In contrast, the drainage basins located at the border between the forest and forest-steppe zones are characterized by a decrease in SND values of 20–40%. A more detailed assessment of SND changes for the period 1820–1980 was made for the Plava River basin, which drains a central part of the study area (Fig. 1). This basin is typical from the point of view of cultivated land dynamics for the transition zone between the

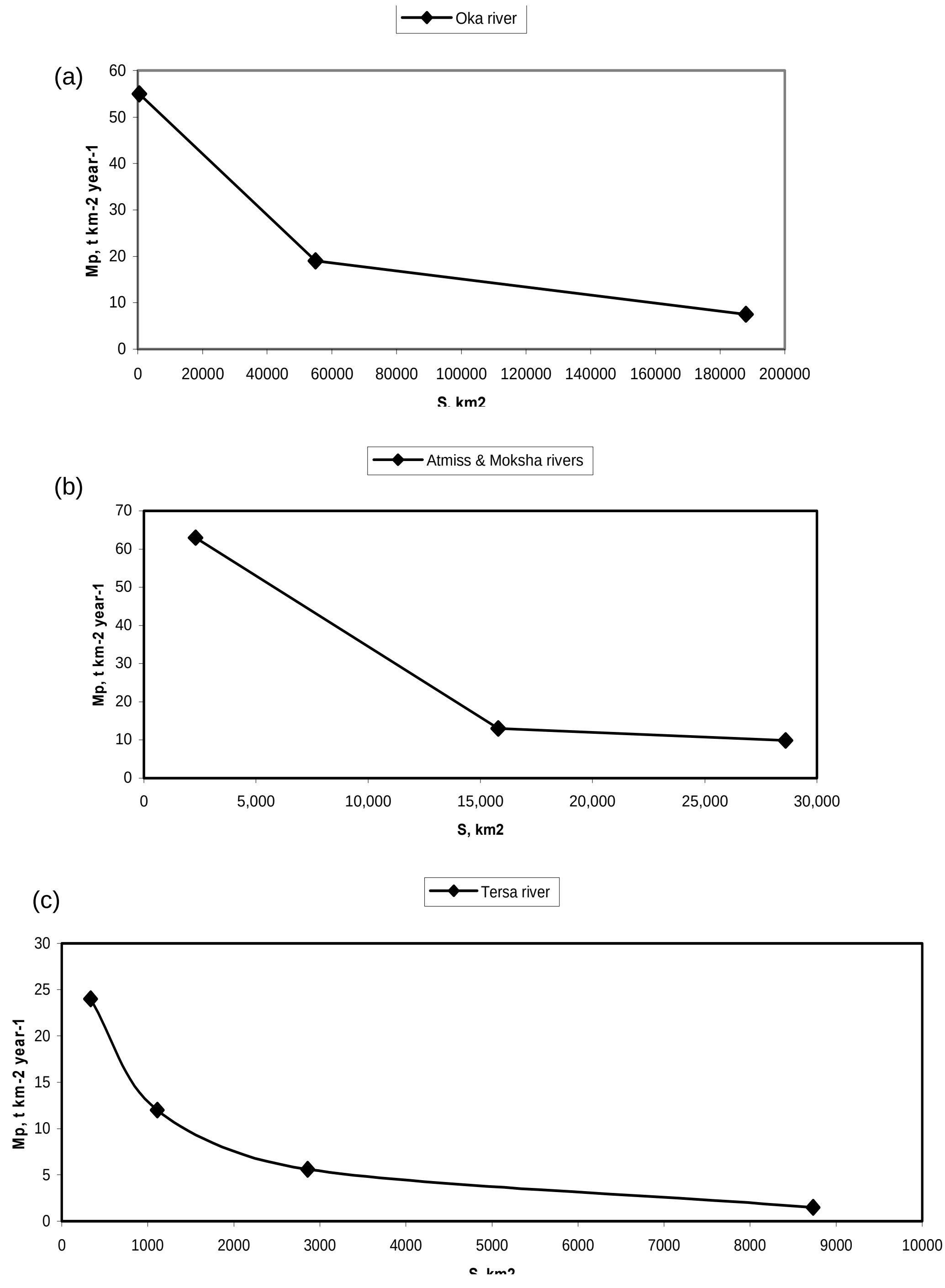

Fig. 6 Relationship between river sediment yield (Mp) and basin area for some rivers of the European part of Russia. (a) the Oka River (forest zone); (b) Moksha and Atmiss Rivers (forest-steppe zone); and (c) the Tersa (steppe zone).

forest and the forest-steppe zones. In the Plava River basin the most essential changes of the perennial drainage network occurred from the end of the 19th to the beginning of the 20th century, while during most of the 20th century it was stable, or some small increases of watercourse length were observed (Table 3). The latter may be explained

Table 2 Change of stream net density in a number of river basins over the Oka River basin in the 19th and 20th centuries (source: Golosov & Panin, 2006). SND is stream net density.

No	River basin	Area (km^2)	Location Latitude[a]	Longitude[a]	Landscape zone[b]	SND[c] (km/km^2) 1830s	1940s	SND change (%)
1	Moskva	8000	55.8	36.3	F	0.266	0.256	–3.8
2	Pakhra	2440	55.4	37.2	F	0.249	0.250	0.4
3	Severka	1490	55.3	38	F	0.185	0.184	–0.4
4	Nara	1890	55.2	36.7	F	0.232	0.226	–2.6
5	Lopasnya	1080	55.2	37.3	F	0.186	0.169	–7.6
6	Protva	4520	55.1	36.3	F	0.259	0.244	–5.8
7	Ugra	15600	54.9	35	F	0.238	0.220	–4.1
8	Osiotr	3250	54.6	38.4	F	0.253	0.219	–13.3
9	Zhizdra	9290	53.7	35.4	F	0.275	0.292	6.2
10	Nugr'	1550	53.3	35.9	F	0.282	0.260	–7.7
11	Oka	7280	52.9	35.9	F	0.273	0.271	–0.7
12	Upa	6310	54.0	37.6	F-FS	0.268	0.232	–13.7
13	Pronya	10300	53.9	39.5	F-FS	0.293	0.195	–33.4
14	Plava	1870	53.7	37.4	F-FS	0.210	0.136	–35.1
15	Zhusha	7000	53.0	37.1	F-FS	0.227	0.161	–29.3

[a] Latitude and longitude refer to geographical centre of each basin.
[b] F, forest zone; FS, forest-steppe zone; F-FS, means the basin is situated partly in neighbouring zones.
[c] SND measured along valley axis, i.e. reflects the length of valley stretches occupied by permanent streams with no respect to river sinousity

Table 3 Dynamic of stream and dry valley network density in the Plava River basin (source: Golosov & Panin, 2006).

River sub-basin	Area (km^2)	Density of dry valley network (km/km^2) 1830s	1940s	Stream network density in 1830s (km/km^2)	Density of stream network (% of 1830s) 1908	1940s	1980s
Kholokhol'nya	405	0.309	0.385	0.225	-	66	64
Malyn'	143	0.112	0.224	0.182	-	38	46
Lokna	182	0.225	0.280	0.198	-	72	53
Sorochka	117	0.077	0.239	0.265	-	39	39
Plavitsa	217	0.346	0.378	0.194	67	67	65
Plava upstream the Plavitsa R.	294	0.279	0.354	0.224	65	59	67
Total Plava Basin	1870	0.249	0.322	0.209	-	67	66

by some reduction of arable land area and an increase of groundwater runoff after widespread introduction of winter tillage since the middle of the 20th century (Golosov & Panin, 1995), as well as by fluctuations of precipitation. Good correlation was found between the rate of river network reduction and total valley length in different sub-basins during the period between the 1820s and the 1940s (Table 3). The latter is directly related to a decrease of the hillslope-derived sediment volume reaching the river channels after watercourse disappearance in the Hortonian 1-3 order valleys.

CONCLUSIONS

The contribution of hillslope-derived sediment to the total river suspended sediment yield increases from northwest to southeast within the Upper Oka River basin, linked to a decrease of forested area and increase of snowmelt runoff intensity in this direction. The average gradient of a river channel is another important factor controlling sediment transfer from hillslopes to river channels. Intensive deposition of sediment eroded from basin slopes occurs on a river flood plain. That leads to a negative relationship between total river suspended sediment yield and drainage basin area. The most intensive aggradation of the small river channels took place between the end of the 19th and the beginning of the 20th centuries within the forest-steppe part of the Oka River basin. It was associated with a high input of hillslope-derived sediment from the drainage basin area into the small (Hortonian 1-3 order) rivers valley bottoms.

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