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Sediment budget change in the fluvial system of the central part of the Russian plain due to human impact

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Abstract The sediment budget change within the fluvial system of the Zusha River (central Russian upland) was calculated for various climatic and land use conditions. These calculations were based on solution of the mass conservation equation using empirical coefficients calibrated with contemporary data on sedimentation processes in the system. The type and rate of aggradation in the fluvial system of the Zusha River are controlled mainly by the rate of erosion over the basin, and secondly, by precipitation volume.

INTRODUCTION

A fluvial system can be defined as a system of continuous water pathways and stores on the surface of the Earth, associated with the erosion, transport and deposition of sediment. One of the main characteristics of a fluvial system is its sediment budget. There are two main types of fluvial system. The first, the erosion type, is characterized by a general positive sign for the sediment budget; whereas the second, the sedimentation type, is associated with a general negative sign for the sediment budget. A fluvial system can change the type and sign of its sediment budget over time due to human impact and climatic change.

The main tool for estimating in detail changes in the erosion and sedimentation pattern through the fluvial system is solving the sediment budget equation for the real river net. The empirical coefficients in this equation have to be calibrated with contemporary and/or past erosion-sedimentation data. The calibrated equation can be used for reconstructing the sediment budget of a fluvial system under past climatic and land use conditions and for prediction of erosion and sedimentation under different scenarios of future climate and human impact.

TYPICAL FLUVIAL SYSTEMS ON THE RUSSIAN PLAIN

A fluvial system on the Russian plain usually consists of the following components: slope; rill; lozhbina (an elongated trough); gully and its fan; balka (aggraded gully or creek); creek; river (with channel and flood plain parts); and river delta. The sediment budget of the system will depend on the regional combination of intensity of erosion and sedimentation in the main elements of the system. In the central part of the Russian plain, erosion takes place on the upper parts of the slopes, and sedimentation may occur on the lower parts, with an overall predominance of erosion. The gullies are primarily areas of erosion, while the balkas and creeks mainly store sediment. Sedimentation prevails on the river flood plains. Very complex processes of sediment exchange between the bed and flow take place in small and medium-sized rivers, resulting in erosion in some rivers, and sedimentation in others. Erosion-sedimentation equilibrium is usually achieved in the large rivers. An intricate spatial pattern of erosion and sedimentation can be observed in delta areas. These processes can change their intensity and sign also over time due to human impact and climatic change.

THEORETICAL FRAMEWORK

Detailed estimation of the sediment budget of a fluvial system is based on solution of the depth-width averaged mass continuity equation for the river net:

$$\frac{\partial Q_s}{\partial X} = C_w q_w + M_0 W + D_b \frac{\partial B}{\partial t} - C V_f W \qquad (1)$$

where Q_s is the sediment discharge, ($Q_s = Q \times C$), Q is water discharge; X is the longitudinal coordinate; t is time; C is mean sediment concentration; C_w is sediment concentration of the lateral input; q_w is specific lateral discharge; M_0 is the upward sediment flux; W is the channel width; D_b is the channel bank height; B is the channel bank coordinate; and V_f is the sediment particle fall velocity in turbulent flow.

The term in the left hand part of equation (1) defines the sediment budget for the channel reach L. The right hand part of equation (1) defines the sediment flux: the first term is lateral flux (*LF*); the second is upward flux (*UF*); the third is bank erosion (*BE*); and the fourth is downward flux (*DF*). This equation can only be solved numerically, and for its analytical solution some assumptions must be made viz.:

(a) The lateral specific discharge q_w is constant for the length L, and water discharge in the channel increases linearly with the distance X from the initial value Q_0:

$$Q = Q_o + q_w X \qquad (2)$$

(b) The upward sediment flux is a function of the channel slope S and specific water discharge q:

$$M_0 = k_e q S P \qquad (3)$$

where P is the content of particles of suspended sediment size in bottom sediment. The coefficient of erodibility k_e has to be calibrated for the conditions of the fluvial system under investigation.

(c) The rate of bank erosion can be calculated using the empirical formula of Kamalova (1984), based on data for the central Russian plain:

$$\frac{\partial B}{\partial t} = k_b Q^m S^n \qquad (4)$$

(d) The channel width, depth, bank height, sediment particle size and the sediment concentration in the lateral input are constant for the channel reach with length L.

With these assumptions the solution of (1) will take the form:

$$C = \left[C_0 - \frac{k_e Q_0 SP}{q_w(Y+1)} - \frac{C_w}{Y} - \frac{k_b Q_0^m S^n}{q_w(Y+m)} \right] \times \left[\frac{Q_0}{Q} \right]^Y + \frac{k_e QSP}{q_w(Y+1)} + \frac{C_w}{Y} + \frac{k_b Q^m S^n}{q_w(Y+m)} \tag{5}$$

Here C_0 is sediment concentration in the channel flow at the beginning of the reach, and $Y = (q_w + V_f \times W)/q_w$.

The sediment concentration can change its value through the fluvial system due to erosion-sedimentation, and due to inputs of sediment and dilution by flow. To exclude the latter process, the delivery ratio Dr must be calculated as the ratio between sediment transport, $T_j = C_j Q_j$ at the jth cross-section of the channel, and the rate of erosion in the contributing catchment, $E_j = \Sigma C_{wj} (Q_j - Q_{0j})$. In this definition erosion within the channels is not included in the E value, and Dr can be more than 1.

CASE STUDY OF THE ZUSHA RIVER BASIN

The basin of the River Zusha (a tributary of the upper Oka River, Fig. 1) is situated within the central Russian upland with an altitude in the range 140-280 m. The mean temperature in January is −9°C, and in July +19°C. The annual precipitation is 570-580 mm, and about 70% comes as rainfall. The catchment is covered by grey forest soils on a loess substratum. The contemporary rate of sheet and rill erosion for agricultural land was calculated by Belotserkovskiy *et al.* (1991) using two main soil loss models, which were verified for Russian plain conditions. These were the State Hydrological Institute Model, which was used for estimating erosion during the spring snowmelt, and the Universal Soil Loss Equation (USLE) for the period of rainfall. The calculated soil loss rate varies from 3.0 to 10.0 t ha^{-1} year^{-1} within the basin, but half of this volume is deposited as sediment on the lower parts of the fields. The volume of gully erosion (the volume of gullies more than 50 m long) for the period of intensive agriculture was calculated by Kosov *et al.* (1989) and the mean value is 640 t ha^{-1}.

Retrospective estimates of erosion rates were obtained for several points in time using the method described in Sidorchuk & Golosov (1993). Changes in the main factors were taken into account (Table 1). The spring and summer precipitation for the central part of the Russian plain during the last 500 years was reconstructed by Borisenkov *et al.* (1988). The history of land use and crop rotation was investigated by Krokhalev (1960). Information about changes in the area under cultivation was taken from the compilation by Tsvetkov (1957) or obtained directly from statistical yearbooks. Changes in the relative intensity of gully erosion were calculated from the ages of 500 gullies, estimated by soil profile depth measurements (Kosov *et al.*, 1989; Sidorchuk, 1995).

The precipitation amount varied within the range ±10%, and the level of protection of the vegetation cover (expressed in terms of the C factor of the USLE) varied within the range ±20% (with the exception of the natural vegetation cover). The main factor in the temporal change of the slope erosion rate averaged for a sub-catchment was the variation in arable land area. The same factor was the most important for the gully

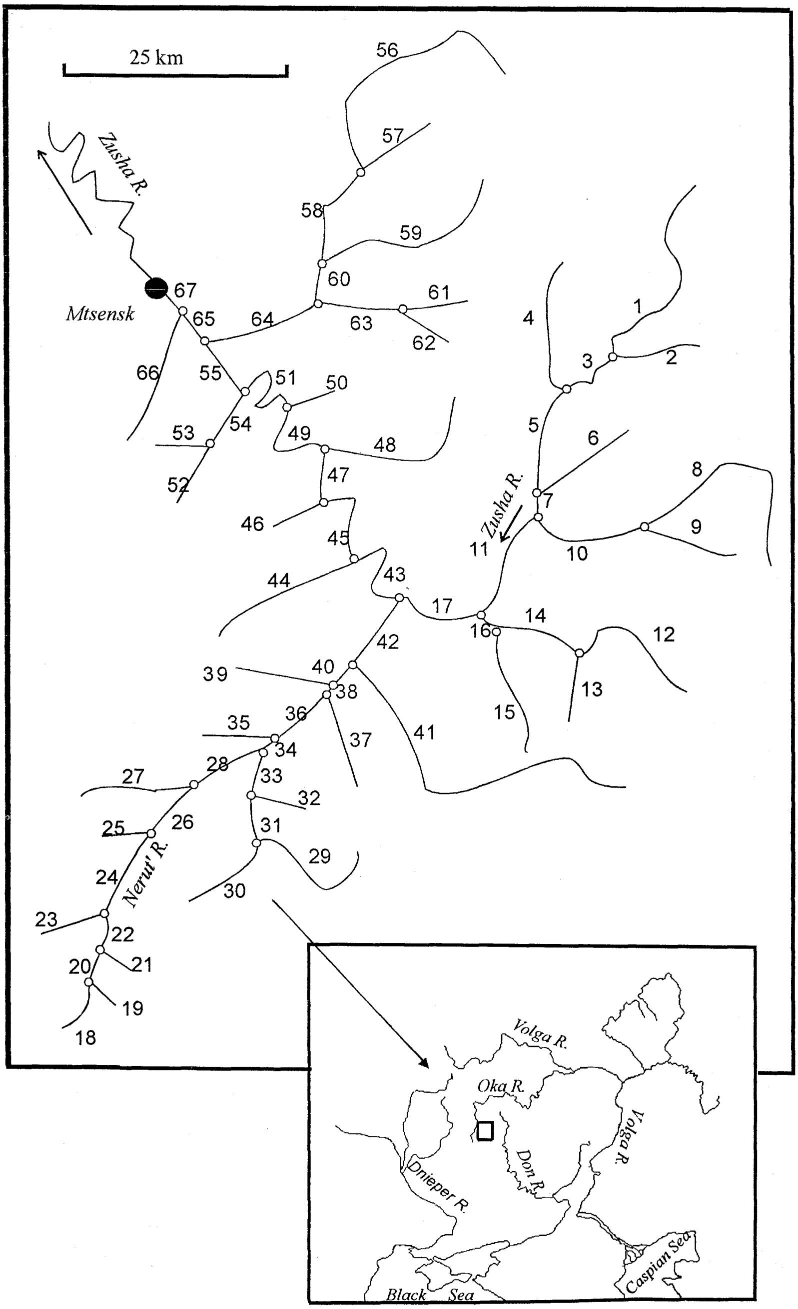

Fig. 1 Structure of the channel network of the Zusha River.

erosion rate, but a significant time lag between fallow tillage and formation of mature gullies is apparent (Table 1).

The structure of the main channel network (more than 10 km long) and the main morphometric and hydrological parameters, used in equation (5), were derived from

Table 1 Temporal change of the main erosion factors in the Zusha River catchment during the period of intensive agriculture.

Year	Precipitation depth (mm)	Percentage of arable land	Cover factor of USLE	Relative rate of slope erosion	Relative rate of gully erosion
1550	520	0.0	0.005	0.0	0.05
1620	580	14.0	0.28	0.18	0.8
1700	640	42.0	0.28	0.62	0.8
1800	580	51.0	0.28	0.75	1.6
1900	580	62.0	0.43	1.38	2.4
1925	580	47.0	0.43	1.04	1.0
1938	580	71.0	0.43	1.57	1.0
1950	580	44.0	0.36	0.81	1.0
1990	580	54.0	0.36	1.0	1.0

Hydrological Survey data (Table 2). All these parameters correspond to the mean annual discharge, as erosion of the basin takes place mainly during the summer rains. Suspended sediment is composed mainly of silt with mean $V_f = 0.002$ m s^{-1}. The content of these particles in the bottom sediment, P = 10-20%. The coefficients in the formula of Kamalova (1984) are $k_b = 2.5$ (if C is in g m^{-3}), $m = 0.46$, $n = 0.54$. Recent rates of erosion were obtained from Belotserkovskiy *et al.* (1991) and Kosov *et al.* (1989).

RESULTS AND DISCUSSION

The erodibility coefficient value was calibrated using recent hydrological and morphometric data for the River Zusha basin and sediment concentration values for the end of the reach near the town of Mtsensk. Its value is 2000 (if $P = 0.1$ and C is in g m^{-3}), which is within the range of values of the coefficient (1600-3000), used in different transport capacity formulae (see Karaushev, 1977). The main erosion factors were then changed according to Table 1, and variations in sediment concentration and delivery ratio variations for the Zusha River catchment were calculated using equation (5) for the different levels of human impact. The results can be analysed in the form of relationships between delivery ratio and basin area along the main channel (Fig. 2). In the sixteenth century, under natural condition with a very low level of slope and gully erosion, *Dr* was higher than 1.0 for all the basin (conditions of channel erosion). Under conditions of low level human impact at the beginning of the seventeenth century, when 14% of the river basin was tilled, the value of *Dr* became less than 1.0 for the main part of the basin (Fig. 2). The rate of sedimentation in the channel was not very high under these conditions (about 35% of eroded sediment was transported out of the system); it decreased along the upper part of the channel until link N5 (see Fig. 1), and increased within the lower reach. Under conditions of high level human impact in 1938, when the

Table 2 The main morphometric, hydrological and erosion parameters of the Zusha River channel network.

N	L (km)	A_0 (km^2)	qw (m^3 s^{-1} km^{-2})	Es (t ha^{-1})	Eg (t ha^{-1})	A (km^2)	Q_0 (m^3 s^{-1})	W (m)	D (m)	S	C (g m^{-3})	Dr
1	19	163	0.46E-04	2.0	0.3	163	0.0	9.7	0.65	0.30E-02	529	0.22
2	16	175	0.58E-04	1.8	0.3	175	0.0	10.0	0.66	0.30E-02	525	0.25
3	31	267	0.46E-04	1.8	0.3	605	1.8	23.7	1.01	0.16E-02	437	0.32
4	26	174	0.36E-04	1.8	0.3	174	0.0	10.0	0.66	0.30E-02	525	0.25
5	10	86	0.46E-04	1.5	0.3	865	4.2	31.4	1.16	0.14E-02	412	0.37
6	7	51	0.39E-04	1.5	0.3	51	0.0	5.3	0.49	0.46E-02	600	0.34
7	14	120	0.46E-04	1.5	0.3	1036	4.9	34.3	1.21	0.13E-02	404	0.37
8	32	177	0.29E-04	1.8	0.3	177	0.0	10.1	0.66	0.30E-02	524	0.25
9	9	75	0.44E-04	1.8	0.3	75	0.0	6.5	0.53	0.40E-02	576	0.28
10	29	160	0.29E-04	1.5	0.3	412	1.3	19.8	0.92	0.19E-02	454	0.37
11	26	224	0.46E-04	3.0	1.6	1672	7.7	43.6	1.36	0.11E-02	384	0.32
12	16	104	0.35E-04	1.8	1.6	104	0.0	7.7	0.58	0.36E-02	556	0.27
13	14	88	0.34E-04	1.8	1.6	88	0.0	7.1	0.56	0.38E-02	566	0.27
14	19	124	0.35E-04	1.8	1.6	316	1.0	17.3	0.86	0.20E-02	468	0.36
15	22	100	0.24E-04	1.8	1.6	100	0.0	7.5	0.57	0.36E-02	558	0.27
16	5	33	0.35E-04	3.0	1.6	449	2.2	22.7	0.99	0.17E-02	442	0.39
17	18	155	0.46E-04	3.0	1.6	2276	11.3	51.9	1.48	0.96E-03	370	0.31
18	33	138	0.20E-04	1.8	0.3	138	0.0	8.4	0.60	0.32E-02	524	0.22
19	12	80	0.32E-04	1.8	0.3	80	0.0	6.3	0.53	0.39E-02	556	0.24
20	4	17	0.20E-04	1.8	0.3	235	1.0	15.3	0.81	0.21E-02	460	0.38
21	14	89	0.30E-04	1.8	0.3	89	0.0	6.7	0.54	0.38E-02	550	0.23
22	16	69	0.20E-04	1.8	0.3	393	1.5	19.4	0.91	0.18E-02	438	0.34
23	12	80	0.32E-04	1.8	0.3	80	0.0	6.3	0.53	0.39E-02	556	0.24
24	8	34	0.20E-04	1.8	0.3	507	2.2	22.7	0.99	0.16E-02	423	0.35
25	11	76	0.33E-04	1.8	0.3	76	0.0	6.2	0.52	0.40E-02	559	0.24
26	9	39	0.21E-04	2.0	0.3	622	2.8	25.3	1.04	0.15E-02	414	0.34
27	20	117	0.28E-04	2.0	0.3	117	0.0	7.7	0.58	0.34E-02	534	0.20
28	13	56	0.20E-04	2.0	0.3	795	3.5	28.6	1.10	0.14E-02	403	0.32
29	15	35	0.11E-04	2.0	1.6	35	0.0	4.2	0.43	0.52E-02	609	0.23
30	13	85	0.31E-04	1.8	1.6	85	0.0	6.5	0.54	0.38E-02	553	0.24
31	4	9	0.11E-04	1.8	1.6	129	0.6	11.3	0.70	0.26E-02	491	0.39
32	11	76	0.33E-04	1.8	1.6	76	0.0	6.2	0.52	0.40E-02	559	0.24
33	7	16	0.11E-04	1.5	1.6	221	1.0	14.9	0.80	0.22E-02	463	0.38
34	1	4	0.19E-04	2.0	1.6	1020	4.8	33.0	1.19	0.13E-02	391	0.32
35	12	80	0.32E-04	2.3	1.6	80	0.0	6.3	0.53	0.39E-02	557	0.19
36	6	26	0.21E-04	2.0	1.6	1126	5.2	34.6	1.21	0.12E-02	387	0.31
37	16	87	0.26E-04	1.3	1.6	87	0.0	6.6	0.54	0.38E-02	550	0.33
38	6	26	0.21E-04	2.0	1.6	1239	5.7	36.3	1.24	0.12E-02	383	0.31
39	11	76	0.33E-04	2.3	1.6	76	0.0	6.2	0.52	0.40E-02	560	0.19
40	4	17	0.20E-04	2.0	1.6	1332	6.2	37.8	1.27	0.11E-02	380	0.31
41	30	156	0.25E-04	1.8	1.6	156	0.0	8.9	0.62	0.31E-02	517	0.22
42	12	52	0.21E-04	2.0	1.6	1540	7.1	40.4	1.31	0.11E-02	375	0.30
43	14	120	0.39E-04	3.3	1.6	3936	17.5	64.2	1.64	0.79E-03	336	0.25
44	26	176	0.31E-04	2.3	1.6	176	0.0	9.3	0.64	0.30E-02	507	0.16
45	16	138	0.40E-04	3.3	1.6	4250	18.9	66.8	1.67	0.77E-03	333	0.24
46	11	76	0.32E-04	2.3	1.6	76	0.0	6.1	0.52	0.40E-02	556	0.18
47	3	26	0.40E-04	3.3	1.6	4352	19.9	68.1	1.69	0.76E-03	332	0.24
48	33	237	0.33E-04	2.5	1.6	237	0.0	10.8	0.69	0.27E-02	491	0.14
49	19	164	0.40E-04	3.3	1.6	4753	21.1	70.7	1.72	0.74E-03	329	0.23
50	11	76	0.32E-04	2.3	1.6	76	0.0	6.1	0.52	0.40E-02	556	0.18
51	4	32	0.37E-04	3.3	1.6	4861	22.2	72.0	1.74	0.73E-03	328	0.23
52	19	106	0.26E-04	2.3	1.6	106	0.0	7.2	0.56	0.35E-02	536	0.17
53	13	84	0.30E-04	2.3	1.6	84	0.0	6.4	0.53	0.38E-02	550	0.18
54	18	101	0.26E-04	2.3	1.6	291	0.9	15.6	0.82	0.21E-02	454	0.24
55	8	69	0.40E-04	3.5	1.6	5221	23.6	74.5	1.77	0.71E-03	326	0.22
56	42	229	0.25E-04	2.5	1.6	229	0.0	10.7	0.68	0.27E-02	493	0.14
57	17	115	0.31E-04	4.3	1.6	115	0.0	7.5	0.57	0.34E-02	534	0.09
58	23	125	0.25E-04	4.3	1.6	469	1.6	20.3	0.93	0.17E-02	430	0.16
59	55	280	0.23E-04	4.0	1.6	280	0.0	11.8	0.72	0.25E-02	483	0.09
60	8	44	0.25E-04	4.3	1.6	793	3.4	28.2	1.10	0.14E-02	401	0.15
61	17	90	0.24E-04	1.5	1.6	90	0.0	6.6	0.54	0.37E-02	545	0.26
62	15	96	0.29E-04	1.8	1.6	96	0.0	6.8	0.55	0.37E-02	541	0.22
63	12	64	0.24E-04	4.0	1.6	250	0.9	14.8	0.80	0.22E-02	460	0.26
64	27	147	0.25E-04	3.5	1.6	1190	4.8	34.1	1.20	0.12E-02	385	0.16
65	5	43	0.39E-04	3.0	1.6	6454	29.4	83.2	1.86	0.66E-03	318	0.20
66	18	100	0.26E-04	4.0	1.6	100	0.0	7.0	0.55	0.36E-02	542	0.10
67	10	86	0.39E-04	3.0	1.6	6640	30.1	84.3	1.88	0.65E-03	317	0.19

N = number of the channel reach; L = length of the reach; A_0 = area of sub-catchment contributing to the reach; qw = lateral discharge; Es = slope erosion rate (minus sedimentation on the fields); Eg = gully erosion rate; A = basin area contributing to the end of the reach; Q_0 = discharge at the upper link of the reach; W = channel width; D = channel depth; S = channel slope; C = sediment concentration at the end of the reach (calculated); Dr = delivery ratio (calculated).

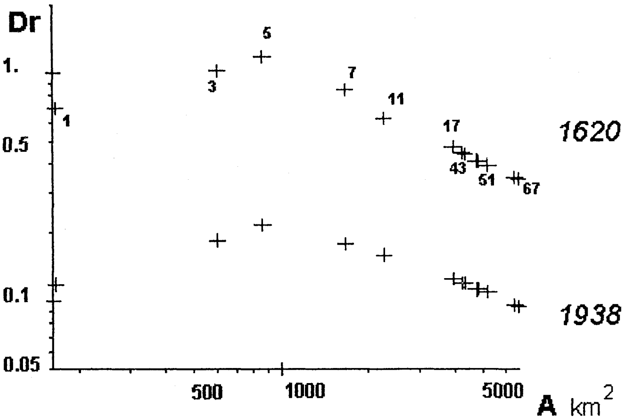

Fig. 2 Change in the delivery ratio along the main channel of the Zusha River for conditions of low (1620) and high (1938) human impact (for numbers near points see Fig. 1 and Table 2).

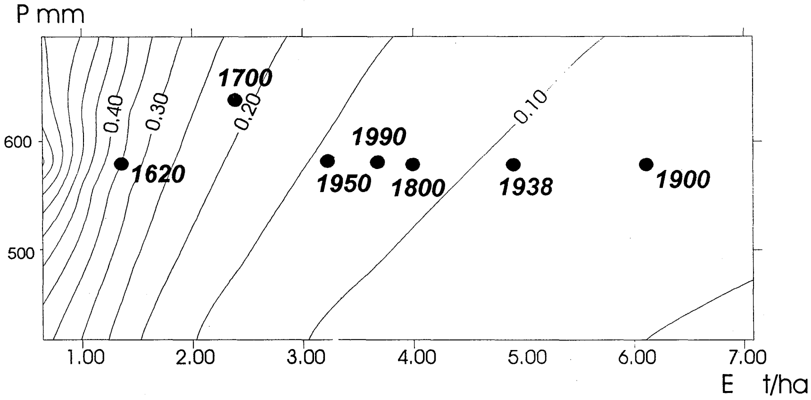

Fig. 3 Temporal change in the delivery ratio of the Zusha River system during the period of intensive agriculture. Isolines shows *Dr* variance with climate (precipitation depth *P*) and level of human impact (erosion rate *E*).

river basin was tilled over 71% of its territory, the value of *Dr* became less than 0.2 for the whole basin (Fig. 2). Only 8-9% of eroded sediment was delivered to the outlet of the system. The *Dr* value also increased along the upper part of the channel until the link N5 upstream of the mouth of Nerut' River, and increased along the lower reach.

The total sediment output from the system decreases with an increase in arable land area and increases with precipitation increase (Fig. 3). The exponent b in the relationship $Dr = a A^b$ (where A = basin area), which represents the rate of change of sedimentation along the channel, is constant for these numerical experiments (Fig. 2) and has a value of about -0.45 for the lower reach. The positions of the points, related to different times in the agricultural history of the Zusha River basin and to different levels of human impact and climatic conditions (Fig. 3), show the main sedimentological characteristic of the system i.e. sediment output from the system.

CONCLUSIONS

The fluvial system of the Zusha River, which is typical of the central part of the Russian plain, is very sensitive to the level of human impact. This system was of an erosion type under natural conditions with a dense forest-steppe vegetation cover. When the natural vegetation was destroyed by tillage on more than 18-20% of basin area, the system transformed to a sedimentation type. The delivery ratio at the basin outlet rapidly decreased as the area of arable land increased from $Dr = 34\%$ in 1620 to $Dr = 7\text{-}9\%$ in 1900 and 1938. Dr values increased during the period of lower intensity agriculture and with an increase in precipitation. Human impact is the main factor controlling temporal change of Dr, with the climatic factor being second in importance.

The results of such numerical experiments depend on the accuracy of primary morphological and hydrological data, and on the precision in calibrating the coefficients. The terms in equation (5), which describes upward and downward sediment flux, can be written in different ways according to different sets of theoretical and experimental work. The morphological, hydrological and sedimentological characteristics of the system will change over time and these variations will also influence the calculations. To resolve these problems is the main goal of future investigations.

REFERENCES

Belotserkovskiy, M. Yu., Dobrovol'skaya, N. G., Kiryukhina, Z. P., Larionov, G. A., Litvin, L. F. & Patsukevich, Z. V. (1991) Erozionnyye protsessy na Evropeyskoy chasti SSSR, ikh kolichestvennaya otsenka i rayonirovaniye (Erosion processes in the European USSR, a quantitative and spatial assessment). *Vestnik Moskovskogo Universiteta Series 5, Geography* **2**, 37-46.

Borisenkov, E. P., Pasetski, V. M. & Lyakhov, M. E. (1988) Ekstremal'nyye klimaticheskiye yavleniya v Evropeyskoy chasti Rossii (Extreme climatic features of the European part of Russia). In: *Klimaticheskiye Izmeneniya za 1000 Let (Climate Change During the Last Millennium)* (ed. by E. P. Borisenkov), 205-209. Gidrometeoizdat, Leningrad.

Kamalova, E. V. (1984) Eroziya rechnykh beregov (Erosion of the river banks). PhD thesis, Moscow Univ. (in Russian).

Karaushev, A. V. (1977) *Teoriya i Metody Rascheta Rechnykh Nanosov (The Theory and Methods of Calculation of Alluvial Sediments).* Gidrometeoizdat.

Kosov, B. F., Zorina, E. F., Lyubimov, B. P., Moryakova, L. A., Nikol'skaya, I. I. & Prokhorova, S. D. (1989) *Ovrazhnaya Eroziya (Gully Erosion).* Izd. Moskovskogo Universiteta.

Krokhalev, F. S. (1960) *O Sistemakh Zemledeliya (On Agricultural Systems).* Sel'khoeiedat, Moscow.

Sidorchuk, A. Yu. (1995) Erozionno-akkumulyativniye protsessy na Russkoy pavnine i problemy zaileniya malykh rek (Erosion-sedimentation processes on the Russian plain and the problem of aggradation in the small rivers). In: *Vodokhozyaistvenniye Problemy Ruslovedeniya* (Water Resources Management and Problems of Fluvial Science), 74-83. Izd AVN, Moscow.

Sidorchuk, A. Yu. & Golosov, V. N. (1993) The history of erosion on the northern Ponto-Meotian during the period of intensive agriculture. In: *Proc. Workshop on Soil Erosion in Semi-arid Mediterranean Areas* (October 1993, Taormina, Italy), 161-173.

Tsvetkov, M. A. (1957) *Izmeneniya Lesistosti Evropeyskoy Rossii s Kontsa XVII Stoletiya po 1914 God (Change in Forest Cover in European Russia from the Late 17th Century to 1914).* Izd. AN SSSR, Moscow.