Sediment Budget Change in the Fluvial System at the Central Part of the Russian Plain Due to Human Impact

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Abstract

Sediment budget change through the fluvial system of 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 with empirical coefficients, calibrated with contemporary data on sedimentation processes in the system. The sedimentological type and rate of aggradation in the fluvial system of Zusha River are controlled mainly by the rate of erosion over the basin, and secondly, by precipitation volume.

Introduction

The fluvial system can be defined as a system of continuous flowlines and reservoirs on the surface of the Earth, associated with the erosion, transport and deposition of the sediments. One of the main characteristics of the fluvial system is its sediment budget. There are two main types of the fluvial systems: erosion type, with general positive sign of sediment budget; and sedimentation type, with general negative sign of sediment budget. The fluvial system can change their type and sign of sediment budget in time due to human impact and climatic change.

The main tool to estimate in detail the erosion and sedimentation pattern change through the fluvial system is solving of the sediment budget equation for the real river net. The empirical coefficients in this equation have to be calibrated with the contemporary and/or past erosion-sedimentation data. The calibrated equation can be used for reconstruction of the sediment budget in the fluvial systems for climatic and land use conditions in the past, and for prognosis of erosion and sedimentation for different scenarios of future development of climate and human impact.

Typical fluvial system on the Russian Plain

A fluvial system on the Russian Plain usually consists of: slope; rill; lozhbina (an elongate trough); gully and its fan; balka (aggradated gully or creek); creek; river (with channel and floodplain parts); river delta. The sediment budget through the system depends on the regional combination of intensity of erosion and sedimentation in the main elements of the system. At the central part of the Russian Plain erosion takes place at the upper parts of the slopes, and sedimentation may occur at the lower parts, with the predominance of erosion in the whole. There are mostly erosion processes in the gullies, while the balkas and creeks mainly collect sediments. Sedimentation prevails on the river floodplains. Very complex process of sediment exchange between the bed and flow takes place in the small and medium rivers, with resulting erosion in some rivers, and resulting sedimentation in the others. Erosion-sedimentation equilibrium is usually achieved in the large rivers. An intricate space patterns of erosion and sedimentation can be observed in the delta areas. These processes can change their intensity and sign also in time due to human impact and climatic change.

Theoretical framework.

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

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

Here Q_s - sediment discharge, $Q_s = Q * C$, Q -water discharge; X- longitudinal coordinate; t-time; C- mean sediment concentration; C_w- sediment concentration of the lateral input; q_w- specific lateral discharge; M_0 - upward sediment flux; W - channel width; D_b - channel banks height; B - channel bank coordinate; V_f - sediment particles fall velocity in the turbulent flow.

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

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

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

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

$$M_0 = k_e * q * S \qquad (3).$$

The coefficient of erodibility k_e (which includes the content of the particles of suspended sediment size in bottom alluvium) has to be calibrated for investigated fluvial system conditions.

c) The rate of the bank erosion can be calculated with empirical formula of Kamalova (1984), based on the 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 particles size and the sediment concentration in the lateral input are constant for the channel reach with the length L.

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

$$C = \left(C_o - \frac{k_e Q_o S}{q_w (Y+1)} - \frac{C_w}{Y} - \frac{k_b Q_o^m S^n}{q_w (Y+m)} \right) * \left(\frac{Q_o}{Q} \right)^Y + \frac{k_e Q \ S}{q_w (Y+1)} + \frac{C_w}{Y} + \frac{k_b Q^m S^n}{q_w (Y+m)} \qquad (5)$$

Here C_o - sediment concentration in the channel flow at the beginning of the reach,

$$Y = \left(q_w + V_f * W \right) / q_w \ .$$

The sediment concentration can change its value through the fluvial system due to erosion-sedimentation, and due to pollution with sediments -- dilution with water. To exclude the latter process, the delivery ratio Dr have to be calculated as the ratio between sediment transport $T_j = C_j Q_j$ at the j cross-section of the channel to rate of erosion on the contributing catchment $E_j = \Sigma C_{wj} (Q_j - Q_{oj})$. In this definition the erosion inside the channels is not included into E value, and Dr can be more than 1.

The case study for Zusha River basin.

The basin of River Zusha (the tributary of the upper Oka River,fig.1) is situated at the Central Russian Upland with the altitudes in the range of 140-280 m. The mean temperature of January is -9°C, of July is +19°C . The annual precipitation is 570-580 mm, and about 70% comes as rainfall. The catchment is covered by grey forest soils on the loess substratum. The contemporary rate of sheet and rill erosion for agricultural lands was calculated by Belotserkovskiy et al. (1991) with two main Soil Loss models, which were verified for the Russian Plain conditions: State Hydrological Institute Model for estimation of erosion during the spring snow melting; and Universal Soil Loss equation for the period of the rainfall. The calculated soil loss rate varies from 3.0 to 10.0 t/ha per year within the basin. 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), the mean value is 640 t/ha.

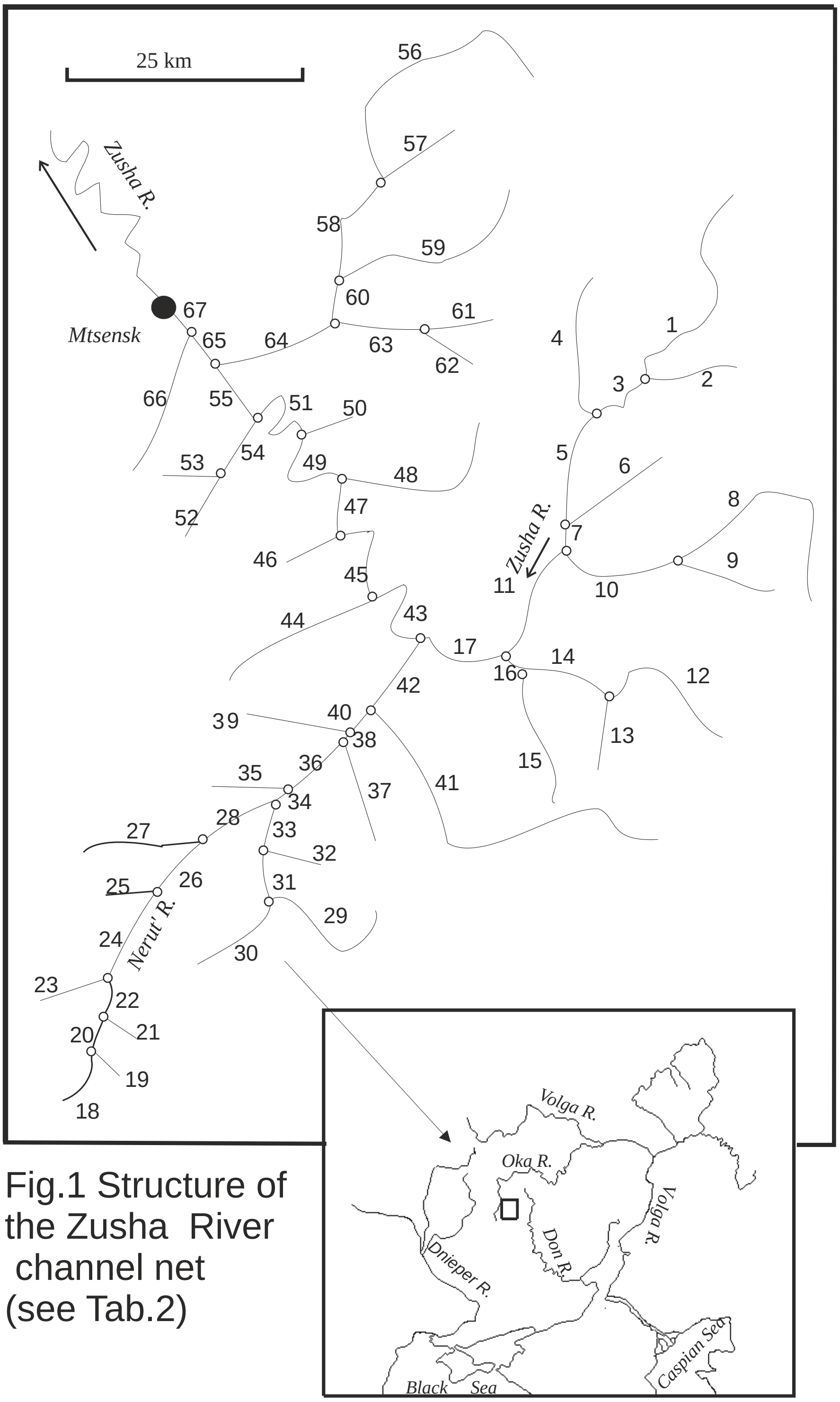

Fig.1 Structure of the Zusha River channel net (see Tab.2)

Retrospective calculations of erosion rates were conducted for several points in time with the method, described in Sidorchuk, Golosov (1993). The change of the main factors was taken into account

(Tab.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's rotation was investigated by Krokhalev (1960). The information about changes of the area under cultivation, was taken from the compilation by Tsvetkov (1957) or obtained directly from the statistical yearbooks. The change of the relative intensity of gully erosion was calculated by the ages of 500 gullies, estimated by the soil profile depth measurements (Kosov et al,1989, Sidorchuk,1995).

The precipitation amount varied within the range $\pm 10\%$, and the level of protection of vegetation cover (in terms of C factor of USLE) varied within the range $\pm 20\%$ (with the exception of natural vegetation cover). The main factor of temporal change of the slope erosion rate averaged for a subcatchment was an arable land area variation. The same factor was of the main importance for the gully erosion rate, but rather significant time lag between fallow tillage and formation of mature gullies is obvious (Tab.1).

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

Year	Precipitation depth mm	Percent 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

The structure of the net of main channels (more than 10 km long) and the main morphometrical and hydrological parameters, used in (5), were derived from Hydrological Survey data (tab.2). All these parameters are correspondent to the mean annual discharge, as the erosion at the basin takes place mainly during the summer rains. Suspended sediments are composed mainly of silt with mean $V_f = 0.002$ m/s. The content of these particles in the bottom alluvium is P=10-20%. The coefficients in formula of Kamalova

(1984), recalculated to SI values, are $k_b = 2.5$, $m = 0.46$, $n= 0.54$. Recent rates of erosion were obtained from Belotserkovskiy et al. (1991) and Kosov et al. (1989).

Table 2.
The main morphometrical, hydrological and erosion parameters
of the Zusha River channel net.

N	L km	A_o km^2	qw m^3/s km	Es t/ha	Eg t/ha	A km^2	Q_o m^3/s	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_o - area of subcatchment, contributed to the reach; qw - lateral discharge; Es - slope erosion rate; Eg - gully erosion rate; A - basin area, contributed to the end of the reach; Q_o - 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).

Results and Discussion

The erodibility coefficient value was calibrated by the recent hydrological and morphometrical data for River Zusha basin and sediment concentration value at the end of the reach near town Mtsensk. Its value is 2000 (if P=10%), which is within the range of values of the coefficient (1600-3000), used in different formulas of transport capacity (see Karaushev,1977). Then the main factors of erosion were changed according to the table 1, and the sediment concentration and delivery ratio variations at the Zusha River catchment were calculated with equation (5) for the different levels of human impact. The results can be analysed in form of relations between delivery ratio and basin area along the main channel (fig.3). At 16th century, in 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). In the conditions of low level of human impact at the beginning of 17th century, when 14 % of the river basin were 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 in these conditions (about 35% of eroded sediments were washed out of the system), it decreased along the upper

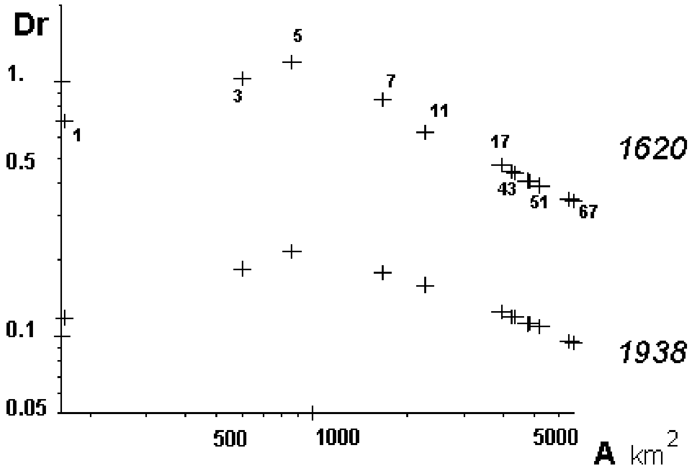

Fig.2 Delivery ratio change along the main channel of Zusha River for conditions of low (1620 year) and high (1938 year) human impact. (For numbers near points see fig.1 and tab.2)

part of the channel till the link N 5 (see fig.1), and increased at the lower reach. In the conditions of high level of human impact in 1938, when the river basin was tilled on 71 % of its territory, the value of Dr became less than 0.2 for the whole basin (fig.2). Only 8-9 % of eroded sediments were delivered to the end the system. Dr value also increased along the upper part of the channel till the link N 5 upstream of the mouth of Nerut' River, and increased along the lower reach.

The total sediment output from the system decreases with arable land area increase and increases with precipitation growth (fig.3). The exponent 'b' in relation $Dr = a A^b$ (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 about -0.45 for the lower reach. The positions of the points, related to different years of agricultural history on the Zusha River basin and to different levels of human impact and climatic conditions (fig. 3), show the main sedimentological characteristic of the system -- sediment output from the system.

Conclusions

The fluvial system of the Zusha River, typical for the central part of the Russian Plain, is very sensitive to the level of human impact. This system was of an erosion type in natural conditions with dense forest -- steppe vegetation cover. When the natural vegetation was destroyed by tillage on more than 18-

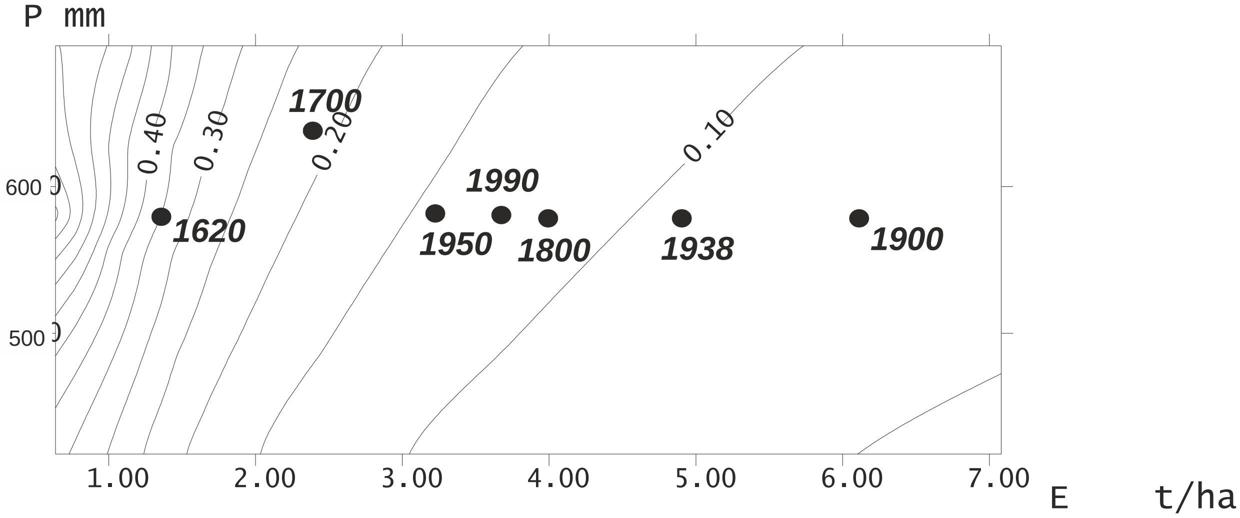

Fig.3 Temporal change of Delivery Ratio of the Zusha River system during the period of intensive agriculture. Isolines shows Dr variance with climate (precipitation depth P) and level of human impact (erosion rate E)

20% of basin area, the system transformed to a sedimentation type. Delivery ratio at the lower cross-section rapidly decreased with arable land area grows from Dr =34% in 1620 to Dr =7-9% in 1900 and 1938. Dr value increased at the period of lower intensity of agriculture and with increase of precipitation. The human impact is the main factor of Dr temporal change, the climatic factor being of the second order.

The result of numerical experiments depends on the accuracy of primary morphological and hydrological data, and on exactness of coefficient's calibration. 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 works. The morphological, hydrological and sedimentological characteristics of the system change in time and these variations also influence the calculations. To resolve these problems is the main goal of future investigations.

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