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Evaluation of Siltation of Rivers with Intensive Economic Development of Watersheds

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Abstract: In regions with a high degree of agricultural development with an active development of erosion processes and the critical level of degradation of the river network to which the Middle-Russian Upland belongs, the evaluation of sedimentation for various combinations of natural and economic conditions becomes an immediate problem. The evaluation of the silting-up of rivers, the catchment areas of which are undergoing an intensive economic development has been done at the regional and sub-continental level which allowed the adaptation of the GIS-analysis techniques for different scale levels. A possibility of assessing the risk of silting-up of rivers by calculating the sediment transport using hydraulic formulas and then comparing the sediment transporting capacity and sediment-production rate has been shown.

Key words: Fluvial system, watershed, fluvial morphology, sediment load, erosion, sediment transporting capacity

INTRODUCTION

The significance of erosion-accumulative processes in the transformation of agricultural landscapes has been recognized since long time ago but the approaches to the quantification of the redistribution of the sediment on its way from the parts of the cultivated slopes adjacent to the drainage divides to the mouth of the river network were developed only in recent decades thanks to the expansion of the methodological basis for the research works. Regions may vary by a particular characteristic range of indicators of water quality and therefore targets of water bodies to be set taking into account the ecological and economic situation in the catchment. This integrated approach to regulation of water bodies is used in Europe and the United States (King *et al*., 2005; Tran *et al*., 2010) and this principle was the basis of the Water Policy Directive of the European Union which aims to prevent the deterioration of aquatic ecosystems and groundwater and their protection and recovery (Moss, 2008).

The great amount of material that is washed away from the slopes and redistributed in the upper parts of the fluvial system is then carried out of the gulley, distributed on the lower parts of the slopes in the gulley debris cones in the bottoms of the hollows and enters the plains and the channels of streams and rivers of different sizes. The river network is a distribution system (Weissmann *et al*., 2015) which redistributes the sedimentary material and forms geomorphologic features of the currently-existing watersheds. The key moment in the space-time survey of the sediment redistribution in vast areas is the assessment of the dynamics of the changes of the middle layer of denudation in time and its correlation with the middle layer of accumulation in the valleys of the upper parts of the river network (Yermolaev *et al*., 2015). The redistribution of the sediment in the channel-erosion network is determined by the nature of the sediment balance in the "slope-hollow-gulley-stream-river-delta" erosion-accumulative complex The sediments transported by rivers (W) are composed of two components-the basin and river channel sediments. The sediments of the basin origin form a runoff of suspended sediment and in case of the flow oversaturation the deposition of the sediments and silting-up of the riverbed occur.

The main criterion for the stability of small rivers with respect to silting-up is their Sediment Transporting Capacity (STC). The recommendations available in the literature for calculating STC of the flow can be divided into three groups. The first includes a large number of works proposing empirical formulas (Zamarin, 1951). Most of these formulas are derived from the study of hydraulics and sedimentation regime in the laboratory flumes. Another group of formulas adopted the "flow drag force" as the main calculation parameter. The formulas of this

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group haven't gained wide usage in Russia, although they are often used abroad. The third group of formulas is based on the direct relation between the sediment discharge and the water discharge and the slopes of water surface. The formulas of this group are widely used abroad in particular by E. Meyer-Peter, R. Gilbert, H. Chang and others.

As a counter to the empirical approaches, another solution for calculating of sediment transport is obtaining dependencies as a result of complex theoretical and experimental studies that reveal, to a certain extent, the physical nature of the sediment transportation process. Among the researchers who developed the theoretical model of this kind we should mention (Zamarin, 1951) who uses a partial differential equation of diffusion for developing a sediment suspension model. Of special note are the studies of suspended sediment in a pulsating flow carried out by Frankl (1955) which have a great theoretical significance but which have not found any practical application yet.

In models of sediment load, describing the relationship between the watershed and the Specific Sediment Yield, t/km^2/year (SSY) from regional to global scale levels, using expressions (Milliman and Syvitski, 1992; Renwick *et al*., 2005; Syvitski *et al*., 2005):

$$SSY = \alpha A^{\beta}$$

Where:

A = Catchment area (km^2)

α and β = Empirical parameters

An alternative method for modeling the spatial variability of sediment yield is being developed (Basher *et al*., 2011). The volumes, composition and size depends on multiple natural factors: Precipitation, catchment surface slope, soils and permeability, etc. All this makes the riverbed process a complex multifactorial phenomenon. The analytical expressions of the sediment yield depending on natural characteristics is presented in numerous formulas (Dragoun, 1962). On the global scale, the issue of the evaluation of the fluvial sediment yield was raised by Fleming (1969). He plotted curves taking into account the relation of the water discharge, suspended sediment and the watershed area for the rivers of different countries with respect to physiographic zones and taking into consideration the vegetation canopy.

The integrated use of remote sensing data and the GIS analysis provide new opportunities for studying the hydrological and geomorphological processes on the territory of river watersheds (Zinchenkou *et al*., 2013; Buryak *et al*., 2015; Anatolievna *et al*., 2015) . More so that global climate changes can contribute to a more intensive and widespread manifestation of erosion for the coming decades around the world (Vanmaercke *et al*., 2016). And this demands a rapid and large-scale evaluation of the past and forecast changes in the hydrological and geomorphological systems of the catchments. The present study aims to develop methods of GIS-Modeling of the process of redistribution of sediment onto large areas when there is a lack of factual evidence. All studies were performed on the project Russian Science Foundation (RSF) "Geography and Geoecology of rivers and river basins" of the European Russia: spatial analysis, estimation and modeling.

MATERIALS AND METHODS

Study area: Forest-steppe zone of the East European Plain is a region with a high degree of agricultural development with an active development of erosion processes and the critical level of degradation of the river network. Therefore, two test areas has been chosen: Belgorod oblast (2.71 mln. ha, the proportion of agricultural land -78%, the proportion of arable land-61% of the territory) within the limits of the Middle-Russian Upland where the inventory of river network and evaluations of its current state were used for the design and implementation of basin organization of nature management and the Middle Volga Region-a large region (of 7 entities of the Russian Federation) with a vast variety of natural and economic conditions. The maximum contribution of the basin-related component into the fluvial sediment yield (>80%) was observed in the forest-steppe because that is where there is a combination of favorable conditions for the delivery of the sediment of basin genesis into riverbeds (Golosov *et al*., 2011). The territory of the Middle-Russian Upland differs both by its maximum development of water-erosion processes on the border of forest-steppe and steppe (Kotlyarova *et al*., 2015) and by a high degree of degradation of the river network resulting from the silting-up of the riverbeds. At the end of 18th century the length of the river network in the territory which is now occupied by the Belgorod Oblast was 7,907 km but by the 19th century it decreased by 38%; i.e. for the last 200 years the average rate of degradation of watercourses was 15 km per year. Small rivers (up to 100 km in length) degraded particularly intensively; their total length was reduced by 3,000 km or by 40%.

Degradation of river network: The assessment of the rates and regional differences in the reduction of the length of the river network on selected river watersheds was carried out for these two historical periods (end of

Table 1: The main parameters for the calculation of the transporting capacity of the belgorod oblast rivers (F in km^2, Q in m sec^{-1}, R in kg sec^1)

Indicators*	The studied river							
	Vorskla	Vezelka	Severskii donets	Tikhaya sosna	Oskol (source)	Oskolets	Oskol (downstream)	Valui
F	1870	394	740	2972	1540	494	8640	1290
Q_1	2.23	0.34	1.02	2.00	3.71	1.20	14.4	1.78
R_1	0.29	0.02	0.11	0.23	0.63	0.14	3.50	0.22
Q_2	10.8	2.18	4.23	10.6	7.47	3.50	46.7	5.51
R_2	2.99	0.36	0.87	2.68	1.79	0.71	20.1	1.17
Q_3	5.78	1.00	2.60	6.10	6.10	1.90	28.6	0.25
R_3	1.18	0.11	0.42	1.17	1.32	0.29	9.71	0.55
Q_4	4.75	0.33	1.43	5.38	4.20	1.23	25.1	0.25
R_4	0.88	0.02	0.17	0.98	0.76	0.15	8.00	0.53
Q_5	5.20	0.15	3.10	5.7	4.00	0.80	30.1	1.90
R_5	1.01	0.01	0.55	1.07	0.88	0.08	10.47	0.24

*Indices for Q and R: 1-dry year; 2-wet year; 3-normal flow rate; 4-2010; 5-2018 (forecast)

18th century and the end of 19th century) based on the topographic maps of 1784-1875 (Scale 1: 84,000) and modern maps of scale 1: 100,000.

Loss of soils by erosion: The amount of matter carried away from the i-th catchment in the Belgorod Oblast was determined by calculations using the GIS-technologies. The estimation of the quantities of soil removed in drainage was done using the Universal soil loss equation (USLE) (Wischmeier and Smith, 1978) after substantiating all input parameters for the regional conditions.

Methods for calculating the river transporting capacity: In this study it was necessary, first of all to determine the features and differences of the sediment redistribution for the rivers flowing in a homogeneous and isotropic field of annual runoff. The authors used the formula of Zamarin (1951) which has been calibrated on the basis of the data about the transporting capacity of watercourses with the sediments (silt and fine sand): common for small rivers:

$$R = 0.022Q\left[\frac{U}{\omega}\right]^{1.5}\sqrt{HI} \quad (1)$$

Where:

- R = Sediment transporting capacity (kg sec^{-1})
- Q = Water rate (M^3/c)
- U = Flow velocity (M/c)
- ω = Settling velocity, M/c, the formula is true within the range of 0.002-0.008
- H = Flow depth (m)
- I = Slope

Nezhihovsky (1971) on the basis of processing a large hydrometric material, obtained the following hydrological and morphometric dependencies for rivers >10 km long:

$$B = 14.8Q^{0.51} \quad (2)$$

$$H = 0.8Q^{0.25} \quad (3)$$

$$I = A_3 / F^{0.35} \quad (4)$$

Where:

- B = Water channel width (m)
- F = Catchment area (km^2)
- A_3 = 0.0036 for hilly plains

Taking into consideration that:

$$U = Q/(BH) \quad (5)$$

By converting (Eq. 1) on the basis of (Eq. 2-5), we obtained the following formula for the calculation of the flow transporting capacity:

$$R = \frac{0.001188Q^{1.485}}{40.74\omega^{1.5}F^{0.175}} \quad (6)$$

The variability of the sediment yield of the studied rivers is 2 times higher than the variability of the water runoff. The analysis of the dynamics of the water discharges showed a significant synchronous fluctuations in the water flow of the rivers of Belgorod Oblast (Lisetskii *et al*., 2014). For the purpose of modeling the watercourse silting-up processes we calculated the transporting capacity of the rivers for the dry year (1975) for the wet year (1981) for the normal flow rate of the studied rivers for the period of evaluation of soil erosion (2010-an average year with respect to water flow). We made a forecast of the flow dynamics for the rivers of Belgorod Oblast up to 2020 with the help of neural networks (Lisetskii *et al*., 2014). The obtained data were used to predict the silting-up of rivers in 2018-a dry year, as the most interesting period for the silting-up risk assessment (due to its aridity).

The transporting capacity values were calculated for the main rivers of the Belgorod Oblast and also for small rivers: for the main water artery of the city of Belgorod-River Vezelka and for River Oskolets which has been considerably transformed by the mining industry

Table 2: Delivery ratios for arable land depending on the combination of morphometric parameters (Golosov, 2006)

	Delivery ratios for the plane curvature of the slopes (%)			
Morphometric indicator	Slope >3°	Slope <3°	Slope >3°	Slope<3°
Profile curvature				
+(concaved)	0.71	0.31	0.71	0.31
+(convex)	0.78	0.59	0.86	0.32

activities. For River Oskol, the calculations has been done for its upper and lower segments. The selection of the subjects of research has been dictated, among other factors by the availability of information on the water discharge at hydrological gauge stations. The calculation has been done for eight rivers of order V with the catchment area (F) of <800 km^2 and of order VI (1,200 km^2<F<9,000 km^2) (Table 1). The results of calculations at u = 0.002 are shown. For larger sedimentations the transporting capacity of rivers is lesser than the obtained and is of no interest for the calculation purposes.

Methods of evaluating the delivery of sediments from the watershed slopes into permanent watercourses. In order to develop quantification methods for the evaluation of the sediment delivery from the catchment slopes into permanent watercourses for the purposes of GIS, we collected a thematic (attributive) information, which is present using the raster data model. The whole area is represented as a set of cells of a regular rectangular grid with the 709×607 cell size. The centers of the corner cells correspond to the corners of the area square. The size of each cell is 100×100m. The attribute information correlates with the centers of the grid cells. For the area under study, 13 raster (grid) layers has been created each of which determines the spatial distribution of the values of the corresponding attribute variable.

As the source material we used raster models the flow directions, the hydrographic network (reservoirs, rivers and plain rivers), raster models of forests, roads, meadows, gullies and such morphometric parameters as slopes, profile and the plane curvature, catchment boundaries and the raster model with the values of the potential loss of soil (total annual removal by drainage).

The method has been implemented using proprietary application software written in Delphi. The algorithm is based on Golosov (2006) method of calculating the ratio of the sediment delivery from the watershed into water bodies and watercourses. This method has been adapted for implementation using a raster data model (Maltsev *et al*., 2015; Usmanov *et al*., 2015).

The routing of the hydrological flow according to DEM is considered (Kostrikov and Chervanyov, 2010) as the basic step in developing a model of the catchment geological and geomorphological system because it directly generates three layers of necessary data for such simulation: DEM with artificially filled depressions; the data layer which reflects the direction of surface runoff for each DEM cell; layer of the data for runoff accumulation values for each cell which is equal to the total number of cells, the drainage from which reaches the specified cell. The basic assumption of the method is that the material (soils) washed off from some operational-territorial unit (in our case, the area of one hectare) is moved by gravity into the next Operational-Territorial Unit (OTU). In such case, the soil material moved by the drainage from the slope surface is partly redeposited (accumulated) in the downstream parts of the slope without reaching the river.

The proportion of suspended sediment which is delivered to the neighboring OTU is called the sediment delivery ratio. This ratio is highly dependent on morphometric characteristics of the slopes and combinations thereof on the land use on the particular area and on the availability of active gullies serving as transit channels for the sediment runoff. The sediment delivery ratio varies greatly depending on the type of land-use. Gullies have the highest delivery rate-0.9%
For arable land delivery rates increase greatly. Depending on the morphometric characteristics of the watersheds, the following values were taken (Table 2).

It is assumed that the roads and forests completely retain the runoff of suspended sediment (RSS). Therefore, the sediment delivery ratio for these functional land-use types is 0. According to various estimates, the grasslands have the delivery ratio of 0.15 (i.e., 15% RSS reaches the next OTU), provided that they are in the hollows or 0 if they are in a scattering catchment area. Such differentiation is adopted because of the different energy of water flow in the scattering catchment area and in the runoff hollows.

As morphometric characteristics to calculate the RSS delivery ratio we adopted the plane curvature, the profile curvature and the angle of inclination. A positive or negative value of the plane curvature determines the presence of a runoff hollow or a scattering catchment in the OTU. A positive or negative value of the profile curvature determines the presence of a concave or convex profile of the slope.

RESULTS AND DISCUSSION

Evaluation of the changes in the length of river network over 200 years: The evaluations of the degradation of

Table 3: Changes in the length of the river network (L) in some watersheds of Belgorod Oblast

Watershed	L (km) XVIII c.	L (km) XXc.	Difference L (km)	Difference Percentage
Vezelka	138.78	76.57	62.21	44.83
Oskolets	125.95	54.62	71.33	56.63
Vorskla	895.89	696.77	199.13	22.23
Severskii Donets	1222.75	734.88	487.87	39.89
Tikhaya Sosna	680.06	321.85	358.20	52.67
Oskol	1838.37	965.43	872.94	47.48
Valui	380.09	199.40	180.69	47.54
Total	7906.65	4789.37	3117.28	39.43

Table 4: Sediment runoff module of the rivers of belgorod oblast (M. t/year from km^2)

Indicators*	Vorskla	Vezelka	Severskii donets	Tikhaya sosna	Oskol (source)	Oskolets	Oskol (downstream)	Valui
M_1	4.84	1.85	4.50	2.30	12.95	9.22	12.79	5.36
M_2	50.38	29.17	37.22	28.43	36.61	45.17	73.38	28.69
M_3	19.91	9.17	18.07	12.36	27.10	18.23	35.43	13.4
M_4	14.88	1.77	7.44	10.39	15.57	9.56	29.19	12.86
M_5	17.02	0.55	23.46	11.32	14.48	5.05	38.22	5.9

The studied river: Vorskla – Valui

*Indices for Q and R: 1-dry year; 2-wet year; 3-normal flow rate; 4-2010; 5-2018 (forecast)

the river network over 200 years (Table 3) showed that in individual watersheds the differences in the rapidity of shortening of the river lengths reaches 40%.

As shown previously (Lisetskii *et al*., 2014), the river network degradation intensity is manifested from the low-order watercourses to the high-order ones: the dying out of watercourses of the 1st-3rd order was registered as well as the silting of watercourses of the 4th and 5th order and insignificant changes in watercourses of the 6th and 7th order. It is important to understand what natural factors and economic differences in the catchment areas cause such differences.

The calculation results for the sediment runoff module for the rivers of Belgorod Oblast: It is natural that the rivers with a high water discharge have the largest transporting capacities, i.e., the larger the river, the greater potential for sediment transportation it has. Differences in the sediment loads under different water discharge reaches 60% or more (Phillips *et al*., 1999). The erosion and transporting capacity of channel flows in the event of an increased runoff increases in a greater degree. For further interpretation of the results, the sediment discharge was transferred to the sediment runoff module (M t/year from km^2). The obtained results (Table 4) showed that the sediment runoff module of small rivers (M) in a wet year exceeds the dry year value by 6 times on the average, the value of M for the forecast period (2018) is greater by 1.6 times than in a year with an average water flow. The greatest sediment discharges on River Oskol decrease downstream due to their partial accumulation on the wide flood plain. The seasonal distribution of the sediment runoff as well as the flow of water is extremely uneven on all rivers. The most of the sedimentation (in many years up to 90-95% of the annual quantities) is generated and takes place in the spring months. The lowest sediment runoff is typical for September and October.

The natural flow is capable of a wide range of the change in its transporting capacity depending on the regime, quantity and composition of the incoming sediment by controlling the change of the longitudinal slope in the river reach and the morphological structure of the riverbed and floodplain, including such change due to the shape of the channel cross section (changes in the width/depth ratio of the channel which leads to a change in the type of the processes in the channel). The calculation of the transporting capacity of small rivers in their sections at the sediment runoff which flows into the river from the slopes of the watershed is the criterion of the vulnerability of small rivers in relation to silting in the conditions of anthropogenic load and an accelerated erosion in the catchment areas.

With the increase in the volume of the intermediate reservoirs the portion of the sediments reaching the outfall decreases, i.e., the sediment delivery ratio Dr (Delivery ratio) decreases. Knowing the delivery ratio and the amount of the matter carried away from the territory of the i-th catchment we can estimate the amount of sediment runoff in the outfall:

$$W_{di} = W_{yi} . D_{ri}, \quad (7)$$

Where:

W_{di} = The amount of the sediment runoff in the outfall, t/year from km^2

W_{yi} = The volume of the matter carried away from the area of the i-th catchment (t/year from km^2)

W_{Di} = sediment delivery ratio

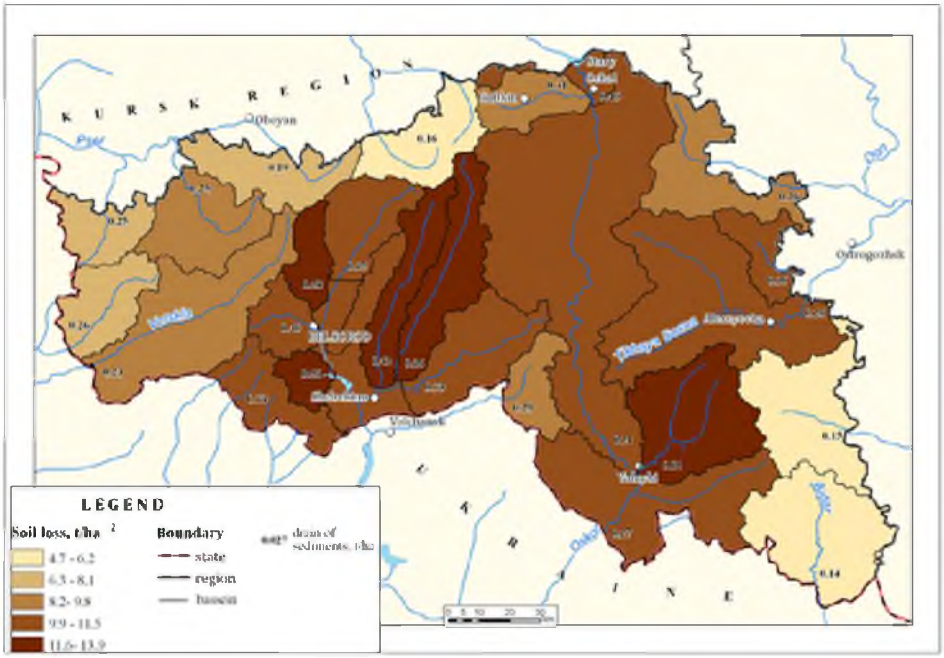

Fig. 1: Estimation of the amount of sediment in the outfall of the Belgorod Oblast rivers

Golosov (2006) calculated the annual values of the slope and gully erosion for 13 large and medium rivers of the Don watershed (the catchment area of 550-45,000 km^2) with the mean annual values of suspended sediment runoff known from the measurements done by the Hydrometeorological Service. The results of field measurements on five small catchments in the steppe and forest-steppe zones of the European Russia were also used. Based on these data (Golosov, 2006) an empirical relation between the sediment delivery ratio (Dri) and the catchment area (F) was obtained:

$$D_{ri} = 0.65.F^{-0.27} \quad (8)$$

Basically, the sediment delivery ratio is determined by: the location of tilled soil in the catchment area relative to the boundaries of the erosion network by the morphology of the plowed up slopes (a well-developed network of gullies increases the transit capacity of slopes); the length and sediment retention capacity of drainage boundaries; the upland network density on the drainage basin and the position of outflows of erosion forms in relation to the channel of the receiving river; the structure of sown areas; the presence (absence) of the floodplain, its morphology and the condition of the landscape (natural, man-made).

The amounts of soil runoff from the area of the ith catchment which were calculated using the USLE and then on the basis of Eq. 7 and 8 were reduced to a total runoff at the outfall (Fig. 1). The criterion of the vulnerability of small rivers related to the siltation in conditions of the anthropogenic load and accelerated erosion in the catchments is their Relative Transporting Capacity (RTC), the ratio of the transporting capacity of the river in a given outfall to the sediment runoff into the river from the whole catchment area. Based on RTC, the direction and intensity of the longitudinal profile development can be determined. When RTC>1, the riverbed is deepened and cleared from sediments. Such river reaches are siltation-stable and the degree of stability increases with the increase of RTC. When RTC<1, sediments accumulate in the river, the level of the floodplain rises and the channel becomes silted up. Such reaches are unstable in relation to siltation.

Assessment of the siltation of rivers: The RTC calculations showed that the processes of silting-up prevail in the rivers of the Belgorod Oblast. At the rated runoff in the periods of medium water flow, the processes of cleaning from sediments are typical only for the most copious river of the Oblast-Oskol. The transporting capacity of this river prevails over the amount of sediment brought into it, excluding the most low-water years. In the most high-water period, the situation changes: the rivers are characterized by cleaning the channels from sediments and only the Vezelka and Valui rivers continue to silt up

Table 5: Assessment of the siltation of the rivers of delgorod oblast

	The studied river							
Indicators*	Vorskla	Vezelka	Severskii donets	Tikhaya sosna	Oskol (source)	Oskolets	Oskol (downstream)	Valui
Dr	0.03	0.04	0.03	0.02	0.03	0.04	0.02	0.03
Wd	22.25	40.59	34.77	24.92	27.94	31.06	17.50	31.46
M_1	4.84	1.85	4.50	2.39	12.95	9.22	12.79	5.36
RTC_1	0.22	0.05	0.13	0.10	0.46	0.30	0.73	0.17
M_2	50.38	29.17	37.22	28.43	36.61	45.17	73.38	28.69
RTC_2	2.26	0.72	1.07	1.14	1.31	1.45	4.19	0.91
M_3	19.91	9.17	18.07	12.36	27.10	18.23	35.43	13.40
RTC_3	0.89	0.23	0.52	0.50	0.97	0.59	2.03	0.43
M_4	14.88	1.77	7.44	10.39	15.57	9.56	29.17	12.86
RTC_4	0.67	0.04	0.21	0.42	0.56	0.31	1.67	0.41
M_5	17.02	0.55	23.46	11.32	14.48	5.05	38.22	5.90
RTC_5	0.76	0.01	0.67	0.45	0.52	0.16	2.18	0.19

*Indices for Q and R: 1-dry year; 2-wet year; 3-normal flow rate; 4-2010; 5-2018 (forecast)

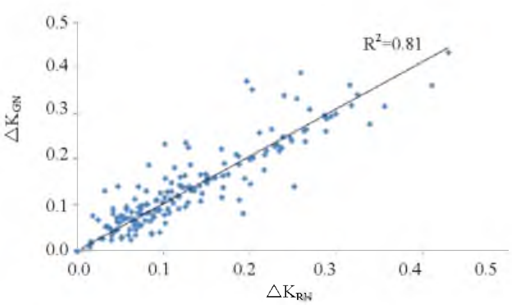

Fig. 2: The dependence of the change in the density of the river network (ΔKRN, km/km²) on the change in the density of the gully network (ΔKGN, km/km²) over 200 year

(in River Valui the situation is nearing the balance between the incoming sediment and the transporting capacity of the flow). The obtained forecast of water discharge in 2018 also permits to predict the predominance of siltation processes in all the studied rivers, except for the lower reaches of the River Oskol (Table 5).

Other watersheds are characterized by the predominance of the sediment accumulation processes. The most unfavorable situation is on the watershed of River Vezelka where the sediment runoff in the outfall exceeds by many times its transporting capacity. The vulnerability of large and more copious rivers is generally lower than that of medium rivers while the vulnerability of medium rivers is lower than that of small rivers. However, this is only true when comparing the large, medium and all small rivers. Among the small rivers, the values of the inertia and water flow in general become close. The nature of human impacts having the greatest effects on large and small rivers is also different. The erosion and transporting capacity of major rivers is very high and inertial too, therefore to make the river react it is necessary to bring in (or remove) too great amounts of sediments of the channel-forming or smaller sizes. In large rivers, changes occur only when they receive sediments of sizes larger than the channel-forming sizes and in large quantities too. This is what happens during the construction of dams, embankments, etc. The same can be said about the volumes of the incoming and removed water runoff.

The density of Gully Network (GN) in the catchment area is an important factor influencing the state of the river. We plotted the changes in the density of the river network (AKRN) as the function of changes in GN (AKGN) since the end of the 18th century to the present time (At = 200 years) for all watersheds of the rivers of Order IV in the Belgorod Oblast (Fig. 2):

$$\Delta K_{RN} = \frac{Kn - Kr}{t} \quad (9)$$

Where:

Kn = The density of the existing river network
Kr = The density of river network at the end of the 18th century
t = The studied period of reduction of the river network (200 year)

$$\Delta K_{GN} = \frac{Kn - Kr}{t} \quad (10)$$

Where:

Kn = The density of the existing gully network
Kr = The density of the gully network at the end of the 18th century
t = The studied period of growth of the gully network (200 years)

For value modularity, the river network density is calculated by subtracting its current values from the values of the last century and the density of the gully

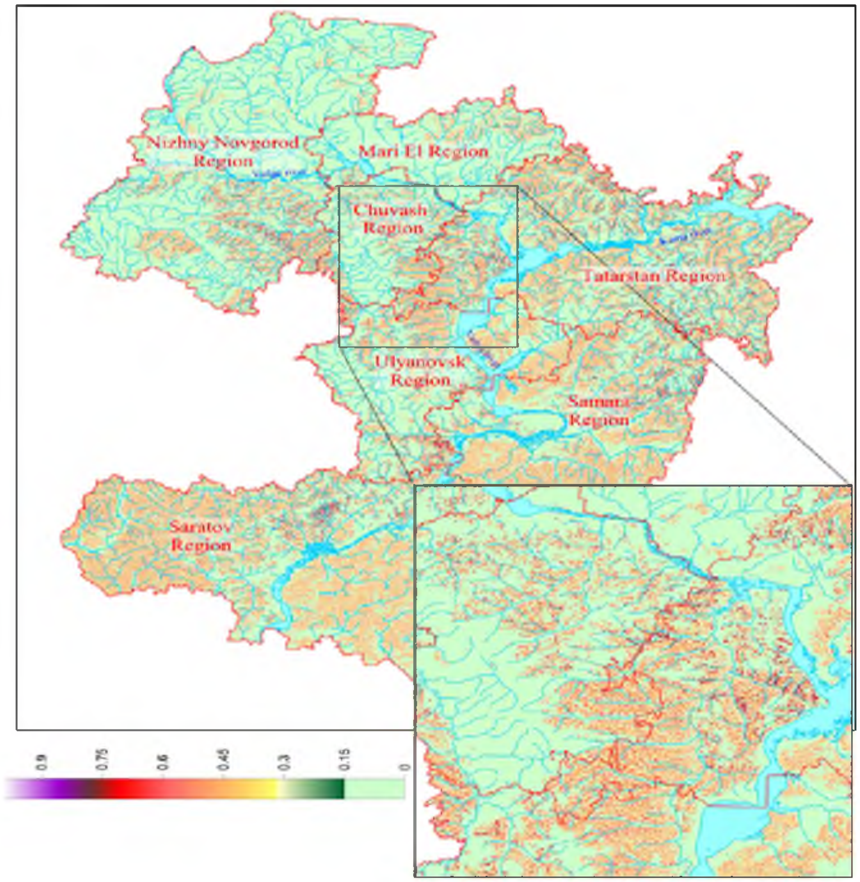

Fig. 3: The distribution of the calculated values of sediment delivery ratios onto the area of the Middle Volga Region

network-by subtracting the values of the last century from the present situation. The coefficient of determination showed a close relation between these indicators.

As the bottoms of erosion forms without permanent watercourses retain a significant portion of sediment, ceteris paribus, the riverbeds on watersheds with a higher density of the gully network receive a relatively lesser amount of sediment from the slopes. However, the watersheds with a denser network of gullies have an increased load of moving the sediment. Therefore, the GN value can not be an unambiguous indicator of the river siltation potential. We have found that neither the relation between the current density of the gully network and the river network is observed nor the connection between the change over time in the density of the erosion network and the current state of the density of the river network. However, the change in the density of the river network depends directly on the changes in the density of the erosion network (R = 0.90). The data which we obtained, indicate that the highest rates of changes in the length of the gully network are characteristic of the watershed of the Chornaya Kalitva (33%), Potudan (24%) and Oskolets (23%). Valuy and Seversky Donets rivers have average growth rates of GN (21%). The watershed of River Vorskla (14%) has shown minimal changes.

Implementation of methods for calculating the sediment delivery from the watershed into the water bodies and watercourses using a raster data model: The method of calculating the delivery of sediments from the watershed is based on the integration of the GIS capabilities and the methods of assessing the sediment delivery ratio which takes into account the differences in the catchment area and the type of land-use (Ermolaev *et al*., 2014). Slope maps, profile and plane curvature maps, maps of the types of land use have been used for calculations. This allows an analysis of sediment redistribution for OTU, highlighting the river reaches which receive a greater or lesser quantity of sediments. An example of the implementation of the method that allows an automatic creation of maps of sediment delivery ratios with maximum detail on the subcontinental level is shown for the area of the Middle Volga Region (Fig. 3).

An analysis of the spatial distribution of the values of the sediment delivery ratios permits to say that their maximum and minimum values are assigned to the areas of elevated, strongly dissected horizontally or low-lying terrain. Their maximum is observed on the short side parts of convex slopes of the valleys of small rivers. The minimum values are assigned to the terrace complexes of medium and large rivers as well as to the near-watershed and watershed areas between the rivers. The territories located in the forest-steppe and steppe zone have a low forest coverage and usually have high indicators of terrain morphometry which as a whole, determine the high values of sediment delivery ratios.

CONCLUSION

The main cause of the degradation of small rivers is the soil erosion in their catchment areas. The main method of controlling the degradation of small rivers should be the widespread application of soil and water protection techniques of land-use. The sediment runoff from the slopes is an integral indicator of the slope erosion so the data about the sediments are necessary for the assessment of erosion processes and for the development of adapted systems of erosion control and water protection measures. The concept of the basin organization of nature management integrates the results achieved to date relating to the fundamental problems of general and applied geoecology, similarities and differences of terrain and natural and economic conditions in the catchments, assessment of spatial and temporal variability of regional and local water resources, optimization of certain types of natural resource management within the catchment (Anatolievna *et al*., 2015; Golosov, 2006; Korytny, 2001; Yermolaev *et al*., 2015; Pozachenyuk *et al*., 2015).

The mechanism of erosion and sediment transport is not the same in the upper and lower parts of the hydrographic network. While the lower parts of the network are more responsive to the changes in the tectonic environment, then the work of the upper parts is mainly determined by climatic conditions. Therefore, within one catchment oppositely directed processes may develop. The most vulnerable to siltation are rivers of Orders 4 to 7 because with the growth of the catchment's length and area and consequently, the water flow, the river's vulnerability to external impacts decreases. It is advisable to take into account these natural patterns during the territorial planning of an optimized (environmentally sustainable) structure of land resources which allows achieving the established indicators of soil, land and water resources quality.

Automated methods for assessing the delivery of sediment at the regional and sub continental level make it possible to reveal the areas most vulnerable to the processes of riverbed siltation to assess the ecological and economic stress. Maps of sediment delivery ratios provide a possibility of spatial co-ordination and prioritization of soil protection measures.

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