

Geography and Geoecology of Russia in the Mosaic of River Basins

O. P. Yermolaev^{a, b, *}, S. S. Mukharamova^{a, **}, K. A. Maltsev^{a, ***}, M. A. Ivanov^{a, ****},
A. M. Gafurov^{a, *****}, A. A. Saveliev^{a, *****}, E. A. Shynbergenov^{c, *****},
P. O. Ermolaeva^{a, *****}, A. O. Bodrova^{a, *****}, and R. O. Yantsitov^{a, *****}

^a Kazan (Volga Region) Federal University, ul. Kremlevskaya, 18, Kazan, 420008 Russia

^b Belgorod State National Research University, ul. Pobedy, 85, Belgorod, 308015 Russia

^c Korkyt Ata Kyzylorda University, ul. Aiteke Bi, 29A, Kyzylorda, 120000 Kazakhstan

*e-mail: oermol@gmail.com

**e-mail: smukhara@gmail.com

***e-mail: mlcvkirill@mail.ru

****e-mail: maximko-87@mail.ru

*****e-mail: gafurov.kfu@gmail.com,

*****e-mail: Anatoly.Saveliev.aka.saa@gmail.com

*****e-mail: shynbergenov.erlan@mail.ru

*****e-mail: polina.ermolaeva@gmail.com

*****e-mail: anastasiaerm5@gmail.com

*****e-mail: romayantsitov@mail.ru

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Abstract—For the first time, an electronic vector map of small river basins and their interfluves with a regional level of spatial detail (1 : 1 000 000) has been created using GIS technology for the territory of main-land Russia with a total area of almost 17 million km². The GMTED2010 global model is used as a digital elevation model. The total number of basin geosystems is 388 627 and their area averages 47.8 km². The selected basin geosystems are used as operational–territorial units, in relation to which the geodatabase was created, characterizing the natural resource potential and geoecology of Russia. The open access River Basins of European Russia geoportal was created for a large part of the country, where all information thus obtained is posted. The article provides examples of solutions based on the previously formed GIS and the basin approach. A digital mosaic of small river basins makes it possible to “collect” territories of different scales (from local to transregional) and different taxonomies (from catchments of large rivers to federal districts of Russia) for geographical analysis. Such examples are given with the creation of specialized GIS for the great rivers of Siberia: the Ob and Lena, and a number of federal districts: the Volga and Siberian districts. Based on the map thus created of basins and GIS, a number of major geographical and geoecological problems are solved: the evaluation of current intensity of soil erosion, density of gully erosion, modeling of river runoff and anthropogenic impact on basin geosystems.

Keywords: basin geosystems, GIS, erosion, geoportal, modeling, river flow

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INTRODUCTION

The basin approach to conducting geographical and geoecological research is widespread both in Russia and abroad. It was also implemented in the water management zoning of the territory of the Russian Federation. The systematization of all hydrological information is carried out by basin districts, which, in turn, are successively divided into hydrographic (basin) units of smaller territorial coverage. Among open sources, the most complete picture of the basin approach to accounting for water resources is provided by the State Water Register, created by Decree of the Government of the Russian Federation No. 253 of April 28, 2007 On the Procedure for Maintaining the State Water

Register [1]. With the advent of computers and specialized software, GIS developments began to appear where river (watershed and elementary) basins act as territorial units of analysis. There is experience in creating hydrological GIS, including those that are publicly accessible on the Internet, both in the Russian Federation and in the former Soviet Union. An objective review of such GIS is given in the monograph of Perm geographers [2]. Most of these GIS are created at local or quasi-regional spatial levels. Interesting works in which electronic vector layers of the boundaries of drainage basins were created include studies in the Kuban River basin [3] or, for example, the developments of V.G. Kalinin and S.V. Pyankova [4]. At the

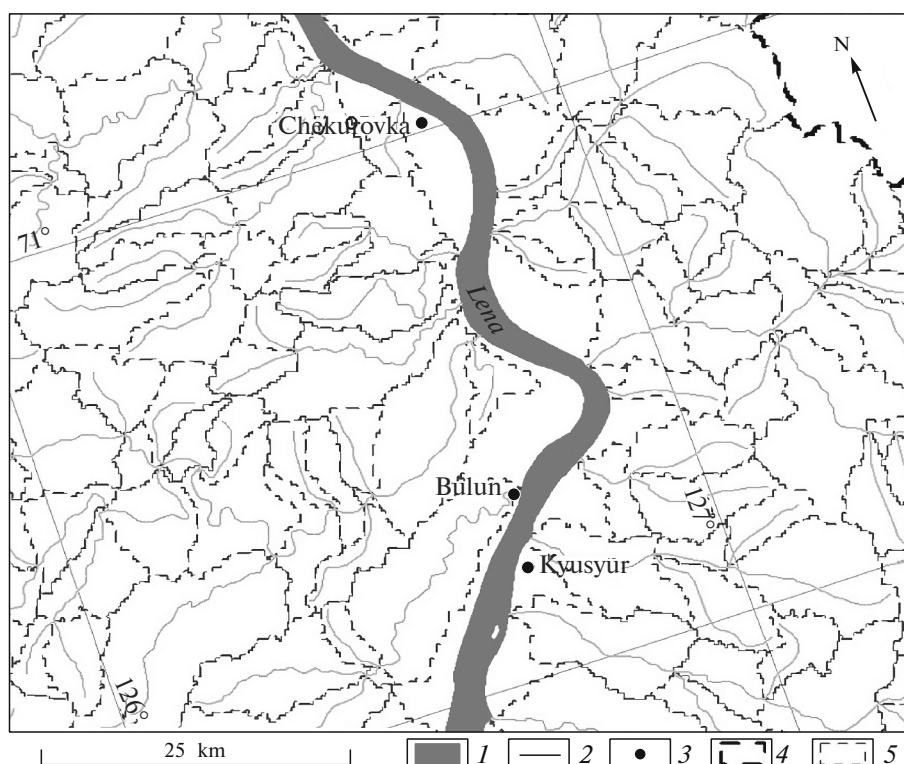


Fig. 1. Map of river basins (fragment) of the Lena River catchment area. (1) Lena River bed, (2) river network, and (3) settlements. Borders: (4) Lena River watershed and (5) pools.

global level of generalization, when creating GIS of river basins, a small scale is naturally used [5].

The relevance of using basins as operational–territorial units for geographic analysis is determined by the huge number of rivers in Russia—more than 2.3 million. Meanwhile, for the purposes of geographic and geoecological research using geoinformation technologies for processing large amounts of data, it is necessary to create electronic maps (layers) of the boundaries of river basins of various levels of spatial detail with the corresponding geodatabases. Currently, there are a number of open access cartographic products that represent models of basins of different territorial coverage. Such products may differ in purpose, network detail, degree of data openness, etc. Examples include the HydroSHEDS, CCM, Ecrins, and WBD geodatabases [6–9]. Unfortunately, there are currently no open domestic electronic maps of small river basins covering the entire territory of Russia. This circumstance determined the goal of this study: the creation of an electronic map of small river basins in Russia and a geodatabase on their natural resource potential using geographic information technologies to solve a wide range of geographical and geoecological problems.

MATERIALS AND METHODS

The boundaries of small river basins for the study area were constructed using an automated method based on an adjusted relief model and a raster model of

the hydrographic network. A corresponding electronic vector map has been created. The boundaries were selected automatically using an algorithm implemented in the Whitebox GAT software product [9]. A series of test calculations were previously carried out within areas with different relief conditions. The isolation of the basins was carried out planarly; i.e., not only were the basins of small rivers identified (on the accepted scale of 1 : 1 000 000, these were first-order watercourses), but so were their intertributary spaces (see Fig. 1).

Based on the verification results, it was established that in the selected test areas the average difference between the indicators of the area of the basins identified automatically and expertly (i.e., manually) was 3.6%. For areas with a weakly dissected, low-lying relief, this error does not exceed 5%, and in areas with relatively dissected, elevated relief it is about 2%. Such an error can be considered quite acceptable, given the fact that the “manual” method of identifying boundaries is also not ideal in accuracy. The methodology for constructing the boundaries of river basins is described in detail in [10]. Thus, in several stages, for the first time, an electronic vector map of small river basins was created for the territory of Russia at the regional level of generalization. Polygonal objects of the basin layer are topologically consistent with the objects of the hydrographic network map at a scale of 1 : 1 000 000. The total number of allocated spatial objects (basins) is 388 000.

The next major task of the research was filling the geodatabase. Mainly open and stock sources were used. In particular, for European Russia (ER), a database of hydrological information has been formed on gauging stations, provided with statistics on average annual water flows and/or suspended sediment flows for a given observation period. Information was entered for 2015 gauging stations for the entire available observation period. Data from long-term measurements of average annual water flow rates provided 2005 posts and data from long-term measurements of average annual flow rates of suspended sediment provided 646 posts. A vector layer of point objects has also been created, representing the locations of hydrological posts that monitor water flow and/or sediment flow on the rivers of the European region. The objects of the gauging stations layer are topologically consistent with the objects of the hydrographic network map at a scale of 1 : 1 000 000. For the first time, a vector map of the boundaries of surface watersheds assigned to hydrological posts that conduct routine observations of river flow has been created for the territory of ER. The gauging station basins were identified based on a relief model prepared using GMTED2010 and a layer of point objects representing hydrological stations. The geographic information system River Basins of Russia was formed, integrating all collected geoinformation about the natural resource potential of the basins. Attributes of objects of the main GIS layers: the layer of river basins (388 000), as well as the layer of surface watersheds of river gauging stations (1892 basins) include the basin identifier, basin area (km²), the predominant soil type in the basin, the predominant type of soil-forming rock, predominant class of pre-Quaternary deposits, predominant type of landscape, predominant landscape subtype, forest cover (%), plowing (%), tininess (%), shrubs (%), swampiness (%), lakeness (%), average height (m), minimum height (m), maximum height (m), height range in the basin (m), average slope steepness (deg), average slope exposure (from “cold” –1 to “warm” 1), erosion potential of relief and sediments in the basin, length of streamlines (m), average annual air temperature (°C), average air temperature in January (°C), average air temperature in July (°C), average long-term maximum temperature per year (°C), average long-term minimum temperature per year (°C), average long-term temperature amplitude per year (°C), standard deviation of air temperature per year (°C), average long-term number of days with temperatures below +8°C, frequency of severe frosts (%), sum of active air temperatures (°C), average annual precipitation (mm), average precipitation in May–August (mm), average amount of precipitation during the cold period of the year (mm), average amount of precipitation for the warm period of the year (mm), coefficient of variation of annual precipitation (%), average value of hydrothermal coefficient, population density in the basin (people per km²), assessment of anthropogenic load on the basin (point),

model value of the water flow modulus in the basin (m³/s per km²), model value of the annual layer of water flow into the basin (mm), and model value of the suspended sediment runoff module in the basin (t/year per km²).

RESULTS

The map of Russian basin geosystems and a geodatabase on their natural resource potential can serve as a good basis for geographical and geoecological analysis of various territories of the country. From the mosaic of small river basins, one can “assemble” and construct territories of various scales and natural–administrative levels: from watersheds of medium and large rivers and from municipalities to federal districts. Here are some examples of research results and spatial analysis based on the created GIS and basin maps.

Assessment of the geoecological state of basin geosystems. This assessment was carried out at various scale levels: in general for the European territory of Russia, for two federal districts: Privolzhsky (68 787 basins, identified according to a more detailed grid of basins at a scale of 1 : 200 000) and Siberian (46 677 basins), as well as for the catchment area of the Ob River (30 738 pools).

The methodology for assessing the geoecological state of basin geosystems was created on the basis of a quantitative assessment of the anthropogenic load on the basins. The indicators that directly or indirectly reflect anthropogenic impact were population density in the basin, density of the road network (taking into account the type of roads), and agricultural development of the basin area. Population density was considered an indirect integral characteristic, indirectly reflecting the degree and direction of economic development of the territory. This indicator in the basins was estimated based on information on the population size in the settlements of ER (taking into account data from the 2010 All-Russian Population Census) and their spatial location in the basins. To calculate the density of the road network in the basins, a layer of roads with a scale of 1 : 500 000 was used, while information about roads of different categories (railways, roads, paved, unpaved, forest, field, etc.) was separately processed. The agricultural development of the basins was assessed based on the data accumulated in GIS on the plowability of the basins, obtained based on the interpretation of long-term MODIS Earth remote sensing data. The spatial behavior of these variables, their statistical distributions, and multicollinearity were analyzed, and they were brought to a single scale. For the territory of ER, we used our data on the intensity of soil erosion. Characteristics of the average intensity of soil erosion on the arable lands of the basin can serve as an additional indicator reflecting the direct degradation of the soil cover through the loss of the humus layer and reduction in fertility, as well as through the volumes of sediment transported

into small rivers and the pollutants that come with them. Various methods have been tried to summarize partial variables.

As a result, the final indicator of anthropogenic load was obtained as a linear combination of partial variables with weighting coefficients, the values of which were selected by an expert method taking into account the analysis performed. To summarize partial indicators, different methods were tested (classification, principal components, and weighted scores). As a result, the simplest linear assessment was used: the final indicator of anthropogenic load was obtained as the average value of the four indicators described above. The final indicator is given in five categories of load: very weak, weak, moderate, strong, and very strong anthropogenic. Using the described approach and prepared geodata, territories were zoned according to the degree of anthropogenic load on river basins (geoeological zoning), presented in the form of a vector layer and a thematic map created on its basis. For ER, such a map is posted on our geoportal [11].

A quantitative assessment of the river flow territory of Russia was carried out using the example of ER. The objective of the study was to construct models for the formation of river water flow and suspended sediment runoff using multiple regression for various landscape zones of ER, each of which is characterized by unique conditions for the formation of river flow. For this purpose, a geospatial database of river flow observations has been created. They were obtained from open and various sources: published materials of long-term regime observations at hydrological posts (State Water Cadastre of the Soviet Union) [12]; open sources (Laboratory of the Caspian Sea, Institute of Water Problems, Russian Academy of Sciences) [13]; the Automated Information System for the State Monitoring of Water Bodies (AIS SMWB), Federal Agency for Water Resources [14]; etc. Multidimensional samples were formed, the elements of which are gauging station basins (drainage areas assigned to gauging station locations), provided with data on water flow (first sample, volume 1767) and suspended sediment flow (second sample, volume 550). Samples include dependent variable Y , either the water flow module or the sediment flow module in basins. Their values were obtained as the long-term average of the average annual water flow or suspended sediment recorded at the post for the entire observation period, related to the basin area of this gauging station. Independent variables $\{X\}$ included in the samples are quantitative and qualitative characteristics that describe the conditions for runoff formation: catchment area, morphometric characteristics of the relief in the basin, climatic indicators (reflecting average values, range, seasonal fluctuations, and extreme values of temperature and precipitation), percentage of forest cover, plowed area, lagoon, swampiness of the basin, assessment of anthropogenic load on the basin, geographical coordinates of the centroid, predominant soil type, type of

parent rock, and class of pre-Quaternary sediments. The analysis of statistical dependencies was carried out separately for subsamples of gauging station basins located in flat and mountainous areas. The stability of the estimates was checked on subsamples with various restrictions (by catchment area, river order) with control of representativeness for the study area. For flat areas, correlation Y with independent variables was analyzed both for the entire territory and within landscape zones.

During statistical analysis, distributions, multicollinearity of variables, partial correlations, rank relationships, etc., were studied. Statistical models were built using generalized linear models (GLMs) and generalized additive models (GAMs). When building models, the best subset of predictors was selected taking into account the statistical significance of their contribution to the model, the AIC information criterion, and the analysis of the VIF factor. All statistical assessments, modeling, and calculations were performed using programs written in the R statistical environment (mgcv, nlme, and geoR packages) [15, 16]. Note that the quality of the constructed models for the river water flow module is very good. The model obtained for lowland areas explains more than 80% of the data variability (adjusted coefficient of determination) and, for mountainous areas (Ural and Caucasus), about 72%. This suggests that the models reflect the main patterns of water flow at a given scale of study. The advantages of the constructed statistical model include its good interpretability in terms of the water balance equation (positive contribution of the amount of precipitation and negative contribution of temperatures, reflecting the evaporation process; positive contribution of relief steepness, explained by its inverse effect on evaporation; positive contribution of forest cover; etc.). The accuracy of the forecast given by the model for the logarithm of the water runoff modulus with a confidence probability of 95% is approximately 0.6 (for comparison, the range of sample values is 4.3); i.e., the forecast error is within 14% of the data spread.

The suspended sediment runoff modulus model for lowland areas was built using nonlinear methods (GAMs), which made it possible to explain 65% of the data variability due to the nonparametric representation of partial dependencies. The predictors included in the model were the average steepness of the slopes, the percentage of plowed water in the catchment area, the module of water flow, the area of the catchment area, the degree of soil washability, and the erosion of soil-forming rocks that predominate in the catchment area. The model also includes a zonal–sectoral gradient, which can be specified either by the sum of active temperatures and standard deviation of air temperature or directly by geographic coordinates (longitude/latitude). This predictor reflects the influence on sediment runoff of latent factors that determine the natural (landscape) zoning of the territory. The contribution to the model of each of the predictors is well

interpreted (the positive contribution of slope steepness is higher, the more eroded the soil in the catchment area is; the positive contribution of the degree of plowing of the catchment area is also highest where soils are easily eroded, and decreases with increasing their erosion resistance, etc.). The nonlinear zonal–sectoral factor gives a background trend—a decrease (on average) in sediment runoff from south to north and its increase from west to east.

The model built for mountainous areas (sample of 153 in total) included the erosion potential of the relief, forest cover of basins, water runoff module, degree of soil washability, and erosion of soil-forming rocks as significant predictors. The modeling took into account the factor of association with the type of mountain systems (the young mountains of the Caucasus and the old mountains of the Urals). The model built by the GAM method explains 68% of the variability in the data.

Based on the models, prediction (model) values of river flow indicators were calculated for river basins planarly covering the study area [17]. Thus, an extrapolation of river flow values was carried out to hydrologically unstudied areas of this large region of the country. A cartographic representation of the results was constructed: a map of the water flow module, a map of the annual layer of water flow, and a map of the sediment flow module in river basins, most of which are available on our River Basins of European Russia geoportals [11].

Assessment of soil erosion intensity. Soil erosion is a key factor leading to a physical reduction in the humus horizon and a decrease in its fertility; therefore, assessing the intensity of soil erosion against the backdrop of a changing climate and land use conditions is always relevant. We solved this problem on the basis of obtaining new and modern estimates of erosion factors (erosive potential of precipitation and topography, soil-protective role of vegetation, and water reserves in snow) for two macroregions of the country: EPR and the Lena River basin. Soil erosion values are determined in each raster cell with a step of 250 m, and then generalized to the best, from the point of view of interpretation of the erosion process, geosystem formations—small river basins. The assessment of the intensity of soil erosion losses during the period of storm surface runoff was carried out on the basis of a model given by the universal soil loss equation (USLE/RUSLE), where soil loss (t/ha per year) is defined as a composition of erosion factors: (R) precipitation factor (erosion potential of rainfall), (K) soil erodibility (washability) factor, (LS) relief factor, (C) vegetation factor (economic and agronomic), and (P) factor of the effectiveness of anti-erosion measures (not taken into account by us). To assess soil erosion losses from meltwater runoff, the methodology of the Research Laboratory of Soil Erosion and Channel Processes of Moscow State University was used [18]. During the research, a

methodology for estimating washout parameters was developed and new results were obtained [19, 20] on soil erosion. In particular, these are methods and results of assessing (monthly, annual, and average long-term) the spatial distribution of the R-factor (based on urgent data on precipitation at weather stations and constructed statistical models) and C-factor (based on the processing and analysis of data obtained from remote sensing of the Earth rasters of vegetation indices NDVI and EVI, phenological metrics VNP22Q2, and the biophysical parameter of vegetation Fcover). The results are presented in the Table 1.

For European Russia, the values of the estimate of the average long-term (for 2014–2019) annual intensity of soil erosion (soil loss rates) are characterized by the following values: the average value is 1.3 t/ha per year, with the median being 0.014 t/ha per year. The 95% quantile is equal to 3.7 t/ha per year, and the 99% quantile is 15.5 t/ha per year; standard deviation is 15.3 t/ha per year. In the geographical space within the flat part, the intensity of soil erosion increases sharply on arable lands. For them, the statistics of the annual intensity of soil erosion are as follows: average 2.4 t/ha per year, median 1.2 t/ha per year, 95% quantile equal to 8.6 t/ha per year, 99%—19.0 t/ha per year, and standard deviation 4.7 t/ha per year. Rain soil erosion is 2.1 t/ha per year and, from melt water runoff, 0.3 t/ha per year. Although the spatial distribution of soil erosion on arable land is very variable, a number of characteristic features of this phenomenon can be noted. Thus, when generalizing the data and generalizing it across the constituent entities of the Russian Federation within the flat part of the region, two characteristic regions with a high intensity of soil erosion can be identified. One of them is located in the west in the forest-steppe and steppe zones of almost longitudinal extent. Here, the intensity of runoff on arable lands increases from 2.5–3.0 t/ha per year (Bryansk and Rostov oblasts and Krasnodar krai) to 3–5 t/ha per year (Belgorod, Kursk, and Oryol oblasts). Another area stretches from west to east—northeast in a sublatitudinal strip within the forest steppe and southern part of the forest zone. Here, the general background of soil erosion on arable lands varies from almost 3 t/ha per year (Kaluga, Moscow, and Nizhny Novgorod oblasts and the republics of Chuvashia and Tatarstan) to 3.5–6 t/ha per year in the Tula, Kirov, and Perm oblasts and the Republics of Mari El and Udmurtia. Within Meshchera and the Oka–Don Plain and the eastern part of the Volga Upland in forest–steppe and steppe landscapes, the intensity of soil erosion on arable lands decreases from 1.9 to 0.9 t/ha per year (Tambov, Voronezh, Lipetsk, Ryazan, Penza, and Saratov oblasts).

Using a similar methodology, the values of soil erosion losses in the basins of small rivers in the catchment area of the Lena River were calculated (area 2 419 000 km², 49 570 pools). The results of these calculations show that the average value of annual soil loss taking into account the vegetation factor (the C-fac-

Table 1. Quantitative indicators of erosion parameters and assessment of the intensity of soil erosion on arable lands of European Russia (for 2014–2019)

Landscape zone	Factor						
	C	K	R	LS	Ar	As	A
North taiga	0.299	0.008	272.2	0.141	0.106	0.013	0.119
Middle taiga	0.158	0.035	276.1	0.539	0.804	0.815	1.619
South taiga	0.224	0.054	382.7	0.411	1.942	0.769	2.711
Mixed and broad-leaved	0.310	0.041	414.1	0.509	2.533	0.732	2.711
Forest—steppe	0.381	0.026	405.3	0.439	1.788	0.261	2.050
Steppe	0.454	0.029	501.0	0.357	2.031	0.128	2.159
Semidesert and desert	0.448	0.036	297.5	0.109	0.634	0.032	0.666

C is vegetation factor, dimensionless (from 0 to 1); K is soil washability, (t ha h)/(MJ ha mm); R is erosion potential of sediments, (MJ mm)/(ha h) per year; LS is relief factor, dimensionless; Ar is intensity of rain (storm) runoff, t/ha per year; As is intensity of melt runoff, t/ha per year; and A is intensity of annual melt-rain runoff, t/ha per year.

tor) in the study area is 0.04 t/ha per year. At the same time, melt runoff accounts for 0.01 t/ha per year, and storm runoff accounts for 0.03 t/ha per year. Due to the high proportion of forest cover and the lowland nature of the territory of the left bank of the Lena River basin, insignificant amounts of soil loss dominate. This category accounts for about 50%. Small and moderate soil loss is observed in half of the basin and very significant is observed in less than 0.05%.

Development of the River Basins of European Russia Geoportal. Another area of research is the development and placement online of the River Basins of European Russia geoportal [11]. Here we present not only the main results of our work, but also provide the opportunity to use both in specialized research and for educational purposes the geodatabase on river basins to the general public in our country and abroad. The geoportal displays the bulk of geodata accumulated in GIS using mapping web services. This is, first and foremost, the Basins layer—the basins of small rivers and their intertributary spaces. There are also Gidroposts layers—hydrological posts of Roshydromet, which present data on the average annual water flow of rivers; the Study Area, showing the boundary of the study area; and two layers in the Hydrography group, representing objects of the hydrographic network, presented on a map at a scale of 1 : 1000000. Current geoinformation on climatic parameters (16 indicators), the composition of pre-Quaternary formations, soils, landscape subtypes, forest cover, plowed land, grass cover, swampiness, population density, anthropogenic load on basin geosystems, morphometric indicators, and calculated fields of values of vegetation factors (C-factor) and precipitation erosion potential (R-factor) are presented in detail to assess the intensity of soil erosion. The assessment of the intensity of soil erosion during periods of rain and melt runoff, as well as the total annual soil losses from erosion (t/ha per year) in river basins, are

also presented cartographically. We also provided public (open) access to the developed resource and to the geodatabase on river basins.

CONCLUSIONS

During the study, an electronic map and a specialized GIS for small river basins with a geodatabase on their natural resource potential were created for almost the entire territory of Russia. The map of the country's basin geosystems is presented in the form of a vector planar layer of polygonal objects (river basins and their inter-tributary spaces). In the macroregions of Russia, the following are identified: in the European part, 53 865 small river basins with an average area of 71 km²; in the Asian part (Arctic and Pacific watersheds), 334 762 basins with an average area of 40 km². The resulting layer of Russian small river basins contains 388 627 objects (basins) with an average area of about 47.8 km². The assessment of the natural resource potential and economic development of river basins was carried out on the basis of an analysis of publicly available long-term monitoring data, the use of Earth remote sensing materials, and the accumulated fund of cartographic materials. In the specialized GIS, thematic, analytical, and complex geoinformation is presented with a fairly high degree of spatial detail, given the territory of such size. The examples of geographical and geoecological analysis indicate the wide possibilities of using the created information product for the geographical assessment of territories of various levels of generalization when solving problems of spatial development of Russian regions.

The River Basins of European Russia geoportal has been created for the macroregion of the country. It open access, making the map of river basin boundaries with a geoinformation database available to the general scientific community.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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