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Cartographic Model of River Basins of European Russia

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Abstract—An analysis made of the worldwide existing geoinformation systems (HydroSHEDS, CCM, Ecrins, WBD, etc.) suggests that there are as yet no models of adequate quality for the basin boundaries of small rivers in the European part of Russia. For the territory of the European part of Russia with a total area of more than 4 mln. km^2 the GIS technology tools were used to construct the electron vector map of river basins and their interbasin spaces. The map thus obtained displays the basins of first-order rivers for a given level of generalization (sc 1:1 000 000). The GMTED2010 model was used as the digital elevation model. A total of 63 553 basin geosystems were identified on the map, averaging 68 km^2 in area. Accuracy verification of identifying the basin boundaries showed a good agreement of areal and geometric characteristics of the method used with expert approach. In test areas, the men difference of the indicators of the area of the basins identified automatically and by use of the expert approach made up 3.6%. For areas with weakly dissected lowland topography this error does not exceed 5% while it is about 2% in areas with relatively dissected elevated topography. The basin geosystems thus identified are operational-territorial units with respect to which the geospatial data base is generated to characterize the natural-resource potential of the European territory of Russia. An example is provided for the generation of the geospatial database containing hydrological information covering 1763 hydrological stations collecting streamflow data.

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FORMULATION OF THE PROBLEM

The territory of European Russia (ER), a large geographical region (about 4 mln. km^2), is dissected by a dense network of rivers. The bulk of the population and the major percentage of the industrial and agricultural potential of Russia are concentrated in the region. Its basin geosystem are experiencing a significant anthropogenic load, which triggers a great variety of negative processes (erosion-channel processes, changes in the streamflow regime, shortages of drink water resources, etc.). The status of geosystems of small river basins, and the causes and intensity of the ongoing changes across such a vast territory can only be assessed on the basis of a comprehensive spatiotemporal analysis of long-term monitoring data, cartographic products of State surveying and widespread use of Earth's remote sensing. On the other hand, such an analysis can only be accomplished on the basis of generating the problem-oriented geoinformation system, and implementing cutting-edge geoinformation technologies and mathematical/statistical methods. The basis for such a GIS must be provided by the electronic map (layer) for the river basins of the study territory, while the river basins themselves are the basic operational-territorial units for collection and summarization of diverse natural and anthropogenic information as well as for the conduct of a spatial analysis.

The goal of this study is to generate the electronic map for the river basins of the European territory of Russia (ETR). This map can serve as the basis for determining the dependencies of the formation and functioning of small river systems and their catchments on the landscape-geographical conditions of the territory as well as for mapping the regularities of streamflows, determining the degree of anthropogenic load on the basins and for making an integral quantitative assessment of their geoecologicall status.

AN OVERVIEW OF INTERNATIONAL AND RUSSIAN MODELS OF RIVER BASINS

Nowadays, there are a large number of publicly available cartographic products in the form of models for catchments (a network of river basins) of some territorial coverage. Such products can differ in their purpose, detail of the network (characterized either by the mean basin area or by the stream order), in the degree of accessibility of data, etc. Publicly available products primarily include HydroSHEDS, CCM, Ecrins, and WBD.

The array of geo-referenced data sets (vector & raster) maintained by HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) is characterized by global area coverage [1]. Crucial to this base are the sets of layers representing the model of the stream network (streamlines), and sets of HydroBASINS data layers containing the model of catchments calculated for the estuarine points of the river network. The two models were constructed on the basis of the SRTM terrain model (resolution 3"); after that, the resulting geometry was generalized to detail corresponding to the resolution of 15" and 30" per pixel. With such an approach, the authors had to invoke significant time and computing resources but it was possible to preserve the structure of topographic surface: planimetric position and shape of watershed divides and thalwegs and their nodal points. HydroBASINS inherits all restrictions characteristic for the initial terrain model, which is responsible for serious errors in tracing watersheds on planate as well as forested and urbanized territories. Furthermore, considerable inaccuracies can arise in the case of the boundaries of river basins with a clearly pronounced delta as well as of the rivers with large dams and bridges. Also, higher quality data are concentrated within the latitudinal belt of SRTM coverage (up to 60° N); beyond this belt the watersheds were modeled in terms of the coarser-scale terrain model (GTOPO30) [2]. The basins were delineated for the nodal points of the system of thalwegs in the case where for a given point the watershed area was at least 100 km^2. This value was selected with a high degree of arbitrariness, because such an approach to the minimum dimensions of the basins for different landscape-climatic conditions is in error. And for the territories extended to the north of the 60° parallel it is unlikely to be appropriate. Here, in the taiga zone, river dissection increases in density and, accordingly, the first-order basins decrease in size. Thus, according to our data, for the sample of 500 basins the areas of the river basins in the steppe zone of ER averages 111 km^2, with 84 km^2 corresponding to the subzone of the middle taiga.

The first version of the river and catchment database, CCM (Catchment Characterization and Modeling), was generated for the territory of Europe (including most of ETR), on the basis of the digital elevation model (DEM) with 250-meter resolution [3]. The last version, CCM v.2.1, includes the catchment model constructed in terms of DEM with 100-m resolution. Also, the declared spatial details correspond to topographic maps at scales from 1: 250 000 to 1: 500 000 [4]. The set of CCM was developed on the basis of five initial DEMs: SRTM 3", SRTM 30" (updated version GTOPO30) as well as the national terrain models of Norway, Sweden and Finland. An unquestionable merit of CCM (against HydroSHEDS) is the attempt to take into consideration the considerable differences of the geological and landscape-climatic conditions on the study territory as well as updating the minimum threshold area of the basins delineated. For this purpose, the layers were analyzed, which represented the spatial distribution of a large number of parameters: the mean long-term precipitation amount; the "energy of topography", or the range of altitudes in the neighborhood of the 7×7 cells relative to the target cell; the types of vegetation cover in a cell (if any); the infiltration capacity of soils, and the type of parent rock [5]. Coverage of the CCM catchment model encompasses the whole of Europe, including ETR, except for the Pechora river basin.

Ecris (European catchments and rivers network system) is another widely known hydrographic base of geodata (including also the basin boundaries). This set contains layers of rivers, lakes and "aggregated" and elementary catchments. The elementary catchments are delineated relative to each individual segment of the river network, i. e. the river basins themselves, and their interbasin spaces. The geometry of the Ecrins catchment boundaries is taken from the previously described model, CCM v.2.1. The "aggregated" catchments are the basins of the whole river systems. The area of the basin identified in Ecrins averages 62 km^2. A total of more than 1.3 million segments of the river network are contained in the dataset on the Ecrins rivers. The number of the identified catchments approaches this value. The area of coverage of the territory with this dataset corresponds with the area of CCM coverage. On the other hand, the attributive characteristics of the basin units in Ecrins and CCM are different. In the two datasets, for example, the attribute "order" is assigned to the basins, whereas in the CCM set this parameter is calculated according to the Strahler–Filosofov system [6–8], and Ecrins uses a classical system of the hierarchy of streams (and their basins) where the main river in a river system receives the first order, and its affluent streams receive the second order, etc.

In the 1990s, within NOAA's Coastal Assessment Framework, the database was developed for river basins (about 1000) from NOAA imagery. To date, however, these data are being supplanted by the more detailed data with a larger area of coverage. Thus, the area of coverage of the territory with the Watershed Boundary Dataset (WBD) is not smaller than the area of CCM or Ecrins. WBD, unlike the others described above, is constructed according to topographic maps at scales: 1:24 000 for the main part of the territory of the USA; 1:63 360 for the territory of Alaska, and 1:25 000 for the

Caribbean Islands (Puerto Rico, Vieques, Culebra, etc.). A large number of so-called Hydrologic Units, included in the dataset (streams and their catchments) are referred to six levels of hierarchy. The largest units (of the first level) are represented by 21 hydrological regions. The smallest units that planarly cover the territory of the USA are referred, respectively, to the sixth level of hierarchy. The number of such units identified is 160 thousand, with the area averaging about 103 km^2 [9]. In separate areas of the territory of the USA, the grids of streams and catchments are densified to seven or eight levels. Use of topographic large-scale maps for catchment delineation also involves the above problem, i. e. Delineating the watershed divides on flat topography. On the 1:24 000 topographic maps, however, the contour interval for subhorizontal areas of land surface is five feet (about 1.65 m) or more. The horizontals for topographic maps developed at these scale in recent years are generated automatically using data from the National Elevation Dataset. The root mean square values of the absolute and relative errors in elevations according to these data are about 2.4 and slightly more than 1.6 m, respectively [10]. This makes it possible to trace with much higher confidence the watershed divides in contrast to using the SRTM 1” product which has quite recently become available for the territory of Russia.

Publicly available detailed electronic maps of small river basins covering the entire territory of Russia are lacking to date. Such maps or geobanks of data for the basins are only available for separate regions or constituent entities of the Russian Federation [11–17].

The aforementioned global models for basin geosystems, including for the ETR catchment basins, were developed in terms of the DEMs incorporating permanent (rivers) and ephemeral streams. There are no electronic maps for the basins of small rivers for the study territory.

THE OBJECT AND METHODS

The object for study includes small river basins of ER (Fig. 1). For the boundary of the territory we constructed a 100-kilometer buffer zone in order to avoid boundary effects when carrying out a spatial analysis and modeling. The subject of investigation implies generating the electronic map for small river basins by using GIS technology tools. In this study, we use the regional level of spatial activity corresponding to the cartographic scale of 1:1 000 000.

The river basins for extensive territories can be delineated by using automatic techniques implemented in many GIS packages (ArcGIS, QGIS, GRASS, SAGA, and Whitebox GAT). All these tools require that specified spatial detailing and maps of rivers at a corresponding scale are available as DEM input data. The process of developing the cartographic model of basins as the electronic vector layer of the basin boundaries can be subdivided into the following stages: 1) selection of input data; 2) preparation of the terrain model; 3) delineation of basins in the automatic mode using the terrain model thus developed, and 4) automatic and manual updating of basin boundaries.

Nowadays, the topography of the study territory is represented by several publicly available global models: GTOPO30 (spatial resolution 30 arc seconds/~ 1000 m; global coverage [18]); GMTED2010 (spatial resolution 7.5 arc seconds/~ 250 m, 15 arc seconds/~ 500 m, and 30 arc seconds/~ 1000; spatial coverage 84º N – 56º S [18]); SRTM (spatial resolution 1 arc second/~ 30 m, 3 arc seconds/~ 90 m; spatial coverage 60º N – 56º S [19,20]), and Aster GDEM (spatial resolution 1 arc second/~ 30 m; spatial coverage 83º N – 83º S [21]).

All these models use for geopositioning the latest revision of World Geodetic System (WGS 84) archived on the website of the NGA. There are also some other terrain models of global coverage; they are commercially available and are not considered in this study.

The best spatial detail for the study territory would be provided by the terrain model combined on the basis of two models: SRTM (30 m) south of 60º N, and Aster GDEM2 (30 m) north of 60º N. However, it is though that the demerit of Aster GDEM2 is a relatively large (compared with the other models) vertical error. On the other hand, considering the size of ER and the level of generalization used in this study where the spatial resolution is 250–500 m, such spatial detailing (30 m) becomes superfluous and is not compatible with the principle of co-scaling. Therefore, the best model for achieving the goal of our investigations is MTED2010 (Global Multi-resolution Terrain Elevation Data 2010) [18]. It was generated on the basis of 11 sources of data on terrestrial topography, including SRTM for the territories south of 60º N, as well as digital elevation data obtained by using 100-m resolution photogrammetry for the territories north of 60º N. End products are available with three spatial resolutions: 250, 500, and 1000 m. Also, for each resolution there are several versions of the GMTED2010 models which differ by algorithms of input data processing. We used the model with a resolution of 250 m which was obtained by using the breakline emphasis processing algorithm. This version of processing retains on the resulting model the position of thalwegs of an ephemeral and permanent hydrographic network which are constructed from data of initial resolution [22], and this is particularly useful when dealing with problems of hydrological modeling on large territories [23].

For validating the selection of the terrain model we carried out test delineations of the basins for two areas: in the taiga zone, and in the steppe landscape zone about

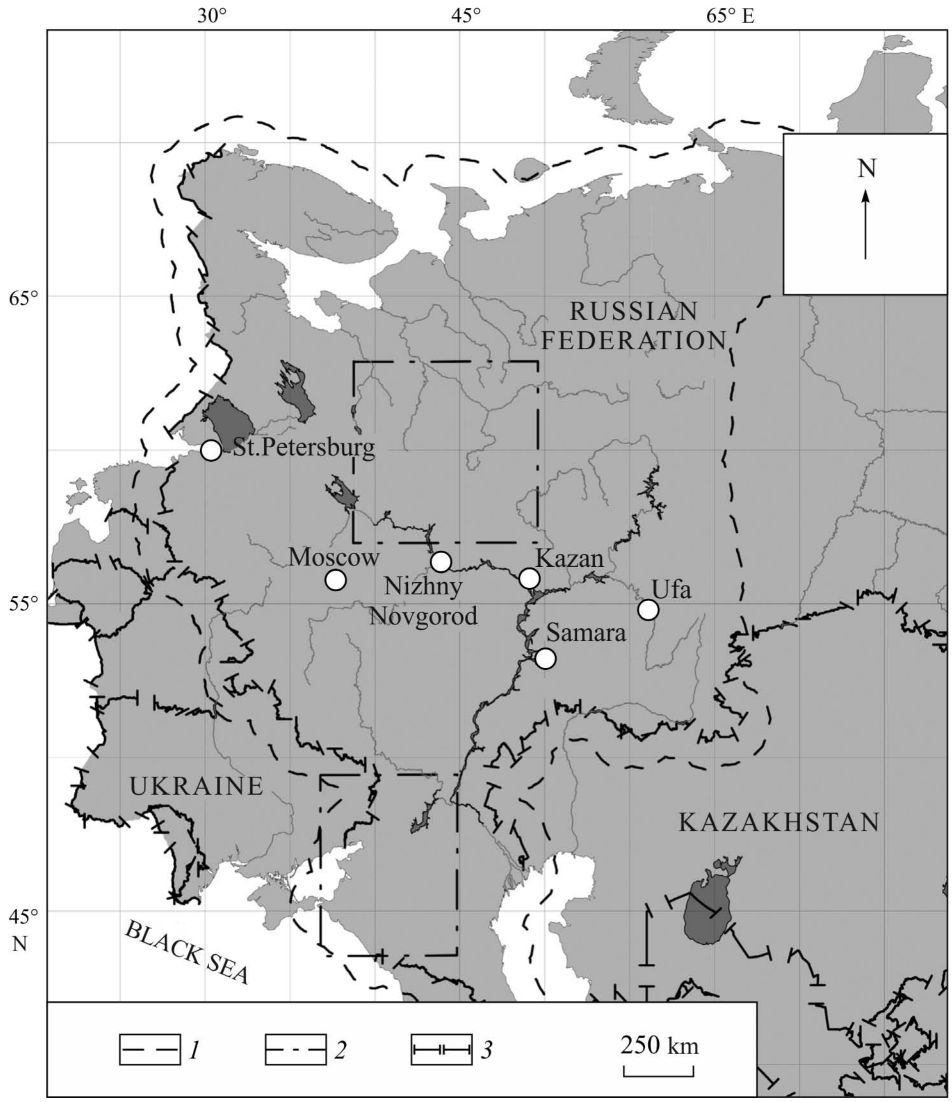

Fig. 1. Schematic map of the study territory. Boundaries: *1* – study region, *2* – test areas, *3* – state borders.

360 thou km^2 in size each (see Fig. 1). Within these areas the basin boundaries were constructed by using the aforementioned terrain models; after that, they were compared with one another and with the geopositioned rasters of the 1:1 000 000 and 1:200 000 topographic maps. Results showed quite a satisfactory quality and a small difference between the boundaries constructed in terms of different DEMs on well-dissected elevated plains. For weakly dissected lowland plains the quality impaired greatly. Therefore, special attention was given to these territories, because within ETR they occupy large spaces. As a result of a comparative analysis, it was assessed in an expert manner that for such complicated (from the standpoint of the automatic construction of the boundaries) topographic conditions the correctly delineated basins make up: 33% in AsterGDEM2, 50% in SRTM (90 m), 54% in GTOPO30, and 60% in GMTED2010. Thus for the test areas the best result within the lowland terrain built of horizontal strata is yielded by the GMTED2010 model.

For selecting the electronic map of ETR rivers suitable for our level of generalization we examine the sources of publicly available information regarding the hydrographic network (VMap, OpenStreetMap, CCM 2.1, Ecrins, and HydroSheds) differing in coverage and detail. As the initial map of the hydrographic network, we used the 1:1 000 000 vector map of water bodies of the Russian Federation (the updated DCW map), namely: the layer of water bodies represented by polygons, and the layer of water bodies represented by polylines at the map scale. This study used all information contained on these layers, except for information on the location of channels. A preprocessing involved verifying the topology (geometry) of the layers and generated so-called skeletons of rivers represented by polygonal features by transforming river channels to linear forms.

The preparation of the terrain model seeks to create a unified mosaic using the array of fragments of the GMTED2010 model, resampled to the working raster and reprojected into the working projection, specify a correspondence between the terrain model and the hydrographic network map used, and to eliminate local "kettles" that are present in the initial model.

The Albers Equal-Area Conic projection was used for geopositioning, with the parameters: central meridian – 45; 1st standard parallel – 64; 2nd standard parallel – 52; grade parallel – 0; eastward displacement – 8 500 000; northward displacement – 0, and datum – WGS84. The parameters of the working raster (the regular grid covering in projection the study territory), used for representation of input data, model calculations and presentation of results, were selected in the course of a number of experiments. As a result, the 200×200 m cell was selected, and the size of the rasters processed totaled more than 212 million cells including about 130 million within the boundaries of the study territory. The selection of such a cell size can be considered optimal for the following reasons: 1) its spatial detail of analysis is somewhat higher than the scale of investigations, which permits the undesirable effects caused by crude estimations to be avoided at this stage; 2) it suffices to exclude most of the possible topological errors when passing from the 1:1 000 000 vector model of the hydrographic network to the raster model, and 3) it can be used to process raster data of such volumes with modern computing resources and technologies.

The GMTED2010 model is available in fragments. We used nine fragments which were then "sewn together" into a single mosaic, resampled to the working raster and reprojected into the target projection. The resulting DEM was updated by using the map of the hydrographic network of the territory. Preliminarily, the vector layers of the hydrographic network were rasterized to the working raster; the updating was carried out in accordance with the technique reported in [24, 25] and improved in the course of the investigation. The essence of this technique is thus: the terrain model is updated so that the values of the elevation marks in the cells of the regular grid pertaining to water bodies decrease monotonically from source to mouth. A next stage of preparing the terrain model involved eliminating local "kettles", that is, the regions of closed depressions on the territories not pertaining to water bodies. This operation was done by the known technique described in the national [26] as well as the foreign [27] literature.

RESULTS AND DISCUSSION

Constructing the basin boundaries in the automatic mode. The updated model of topography and the raster model of the hydrographic network were used in constructing the boundaries of the river basins for the entire study territory, and in generating a corresponding electronic vector map. The boundaries were delineated in the automatic mode using the algorithm implemented in the Whitebox GAT software product [28]. A series of test calculations were carried out preliminarily within the areas with different topographic features. The basins were delineated planarly, that is, not only the basins of small rivers (at the scale used, they were first-order streams) but also their interbasin spaces. At this stage it was necessary to solve a number of technical problems associated with a large volume of data arrays (rasters) to be processed, as well as enhancing the resources of the computer facilities.

For assessing the quality of the result obtained, special attention was given to the accuracy of identifying the basin boundaries. For this purpose, various errors (artifacts of automatic identification) were analyzed. A verification of the accuracy of identifying the basin boundaries used six areas with different morphogenetic type of topography within the Republic of Tatarstan and Belgorod and Kursk oblasts. For these territories the boundaries of river basins were determined (and then vectorized) in an expert manner (i. e. by a traditional manual method). Next, the GIS tools were used to compare the features (the basins of the same rivers) obtained in the automatic mode and in the expert manner. The coincidence of area characteristics, and also the "correctness" of the geometry of the boundaries was assessed. Fig. 2 shows an example of the fragment of such a coincidence for Kursk oblast. Based on the findings, it was established that in the selected test areas the mean difference between the indicators of the basin areas as identified automatically and in the expert manner made up 3.6%. For the areas with weakly dissected lowland topography this error does not exceed 5%, while in the areas with relatively dissected, elevated topography it makes up about 2%. Such a quality of the automatic construction of the basin boundaries for the cartographic model thus developed may be considered quite satisfactory.

Correction of the boundaries. The result from constructing the basin boundaries in terms of the DEM in the automatic mode is represented as the vector layer of polygonal features (river basins and interbasin spaces). The inaccuracies and errors in identifying these features may be arbitrarily subdivided into geometrical and topological. Both of them are the consequence of solving the problem of constructing the boundaries in terms of the raster model of data. The manifestation of the geometrical inaccuracy may imply that the vector geometry is represented as accurate as the linear size of the resolution cell of the working raster, while the polyline that represents the boundary consists of pairwise orthogonal segments. This can be corrected by using the procedures of smoothing the polylines.

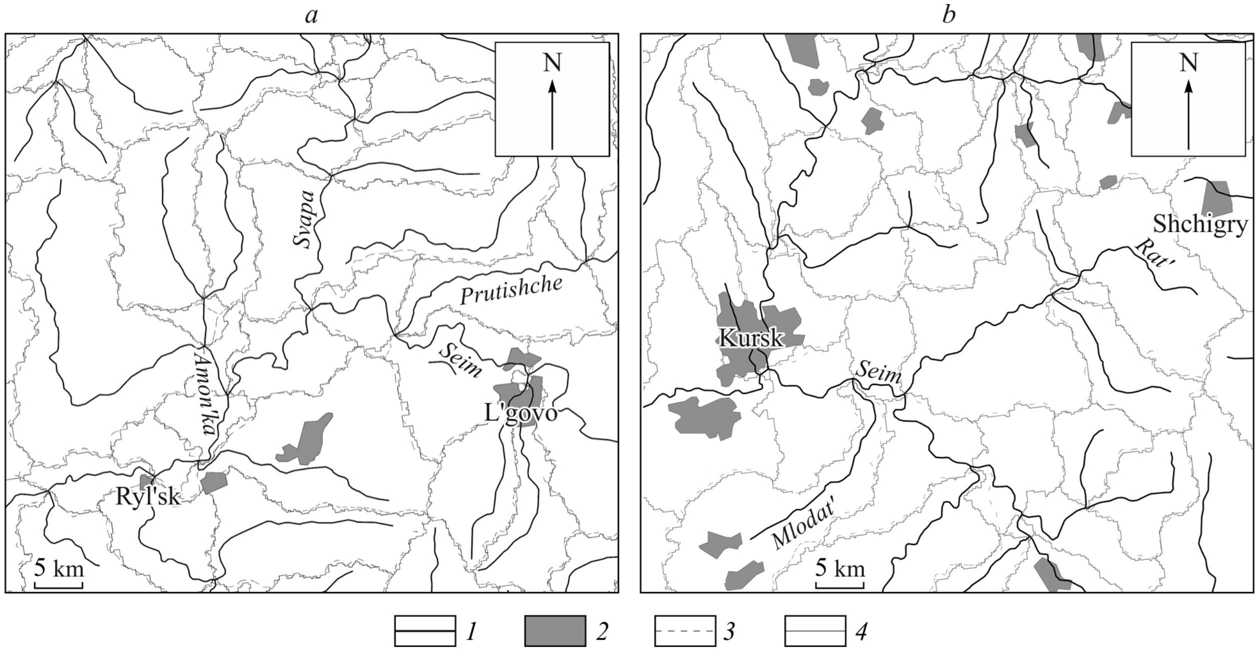

Fig. 2. Comparison of the river basin boundaries in Kursk oblast for lowland (*a*) and elevated (*b*) topography.
1 – rivers; *2* – settlements; boundaries of river basins: *3* – identified from topographic maps, *4* – identified by using DEM-based automatic technique.

Topological errors imply are apparent from the discrepancies in the vector geometry of the features of the basin layer and the features of the hydrographic network layers; more specifically, the basin boundaries running nearby the mouths of the rivers traverse them (in the case of a correct behavior, the basin boundaries must "converge" to the end node of the polyline that represents the river).

If the resulting layer of the river basins is used for cartographic representation only, then such errors can be neglected when constructing maps at the scale of investigation (1:1 000 000). If, however, the resulting layer is used in spatial analysis, then such errors must be eliminated. They can severely complicate or even render impossible the employment of a number of methods as well as distorting results of a subsequent spatial analysis. In the present case, most of topological errors were corrected in the automatic mode, in ArcGIS, for example. About 5% of topological errors were corrected in the manual mode.

Thus the 1:1 000 000 electronic map of first-order river basins was created for the ETR. A fragment of the map is shown in Fig. 3. The map is represented by a vector layer of polygonal features. A total of 63 553 basins of rivers and their interbasin spaces are identified on the map. The basins differ greatly in their areas (the standard deviation 9800). The minimum, maximum and mean areas are 0.3 km^2, 1951.1 and 68 km^2, and the quantile with the 99% level is 459 km^2.

The resulting map for the boundaries of river basins forms the basis for the generation of the base of geodata for the territory. In the process of systematizing information of hydrological gauging stations it was established that only 3206 stations on ETR had been doing observations for more than 10 years, whereas 1657 stations (nearly 40% of their total number) had had a very short observing period insufficient for obtaining reliable statistical characteristics. Of 3206 gauging stations, 2070 have carried on hydrological observations for the last 40 years. On the other hand, 319 stations are located on the streams, the area of the surface catchment of which exceeds 100 thou km^2. Such basins, as a rule, occupy several natural zones and compensate the zonal features of the runoff. Therefore, observations from such gauging stations should be used with caution. According to a preliminary assessment, 1763 out of 3026 stations had information on the river discharge, and these stations were included in the hydrological database. After that, the structure of the geospatial database was developed, which integrated data on the water flow and sediment yield in the rivers. The base incorporated information, such as the spatial (coordinate) referencing of the gauging stations, and the introduction of the values of main characteristics of the gauging stations and the parameters observed for the period of their operation.

The database consists of several tables. The first table contains data on the location of gauge stations and their characteristics: the name of the main river, the distance

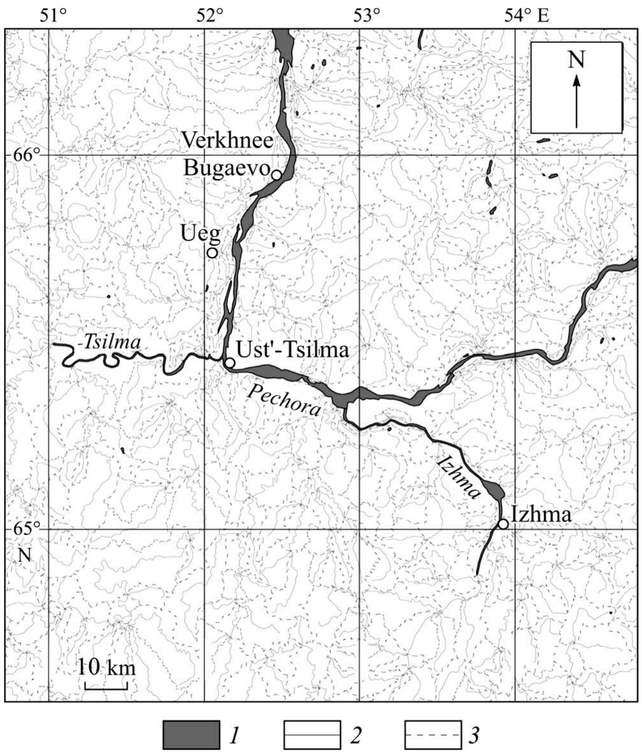

Fig. 3. Fragment of the map for the basins in European Russia.
1 – areal water bodies; *2* – rivers; *3* – basin boundaries.

from the source and from the mouth, the level of zero of gauge, the system of altitudes, jurisdiction of regional administrations of Rosgidromet (Federal Service for Hydrometeorology and Environmental Monitoring), the dates of opening and closing, the length of the observing period, the gauge station code according to the national coding system for gauge stations operated by Rosgidromet, the river code according to the numbering scheme of water bodies of the State Water Register, and the volume number of annual and long-term issues of hydrological information concerning a particular gauge station. The summary table includes data on the values of different kinds of discharge (mean annual water/sediment discharges, the specific rate of water flow, and the sediment-production rate) for all years of observation. The third table contains statistics describing the observation series obtained at gauge stations for the runoff of water and sediments (the normal runoffs, the mean long-term specific rate of flow, extreme values of flow, etc.) as calculated for the entire observing period available. The fourth table is designed for storage of information on morphometric characteristics of the catchment (the area, the mean altitude, the slope, and the degree of channelization). The fifth table contains information on natural and anthropogenic formation conditions (the forest and lake percentage, swampiness, and ploughness). The values of these indicators were introduced according to information contained in the volumes of hydrological reference books. Results of an automatic processing of the DEM will be used in introducing the other characteristics of topography (such as extreme altitudes) as well as in replenishing the missing (in reference books) data. Furthermore, the fifth table provides for storage of information regarding the climatic belt, the natural (landscape) zone, the type of topography, the lithological composition of superficial rocks that are dominant on the catchment.

We believe that this information can help to achieve a number of goals: to determine a dependence of the formation and functioning of small river systems and their catchments on landscape-geographical conditions of European Russia, map the regularities of the liquid and solid runoff, estimate the degree of anthropogenic load on the basins, and to carry out an integral assessment of their geoecological state.

CONCLUSIONS

The GIS technology tools were used to construct the electronic vector map of small river basins and their interbasin spaces for a large territory of Russia, its European part. The map, obtained by automatic tools, displays first-order river basins for a given level of generalization (sc 1:1 000 000). The GMTED2010 model was used as the DEM. Analysis of foreign and national cartographic products for river basins at such a scale for the study territory reveals that there are no satisfactory analogs.

A total of 63 553 basin geosystems was singled out on the territory, with their area averaging 68 km^2. The verification of the accuracy of delineating the basin boundaries showed a good agreement between the areal and geometric characteristics of the method with expert approach used. The basin geosystems thus identified are operational-territorial units with respect to which the geospatial database is generated, which characterizes the natural-resource potential of the European territory of Russia.

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