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RESULTS OF THE STUDY OF THE GEOECOLOGICAL STATE OF MOUNTAIN RIVER BASINS OF THE SOUTHWESTERN CASPIAN REGION IN 2024

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Abstract. *This paper presents the results of the first phase of a major research project entitled "Dynamics of the Geoecological State of Mountain River Basins in the Northeast Caucasus, Azerbaijan, and Iran under Climate Change and Growing Anthropogenic Pressure." A methodology, concept, and methods for geoecological assessment of mountain river basins have been developed using key areas (small and medium-sized river basins in the Caspian Sea catchment area in Russia, Azerbaijan, and Iran) as examples.*

Key Words: *Mountain rivers, Caspian region, geoecology, basin, climate*

The following scientific results were obtained:

1. The types of nature management and socio-cultural processes in the mountain river basins of Caspian were characterized. It was shown that these types of nature management and socio-cultural processes form the basis for the formation of a matrix of geoecological assessment criteria. A list of criteria for the geoecological assessment of mountain river basins was proposed, based on the integration of remote sensing data and geoinformation modeling. The geoecological assessment criteria developed within the study were structured according to landscape contours.

2. The morphometric characteristics of the river basins of small and medium-sized rivers in the Northeast Caucasus, Azerbaijan, and Iran were identified and analyzed using GIS technologies. Basin boundaries were determined using DEMs and topographic maps and various geometric parameters of the basins were measured. At the current stage of scientific and technological development, the use of GIS technologies and DEMs is an effective method for identifying river drainage basins and calculating their morphometric parameters.

Although 90 m/pixel DEMs have lower accuracy, they can be used in modeling drainage basin delineation when higher resolution DEMs cannot accurately capture total runoff and build up.

The list of key morphometric parameters calculated for river basins in key areas shows minor differences, suggesting the feasibility of further use of all DEMs. The exception is the 90 m/pixel DEM, which often performs better in modeling than some 30 m/pixel DEMs. For the study area, the Copernicus 30 m DEM is optimal and, in some cases, the Copernicus 90 m DEM or SRTM 30 m DEM, where the use of the Copernicus 30 m DEM is associated with basin delineation errors.

3. Based on this data set, a matrix of criteria for geoecological assessment of the Caspian region's territory was developed as a basis for geoecological assessment of various landscape types. The matrix is based on 34 criteria describing the morphometric characteristics of the relief, seismicity, avalanche hazard, mudflow hazard, anthropogenic landscape transformation, KIZA, surface water and soil pollution, and others.

4. A methodology for geoecological assessment of the Caspian region's mountain river basins was developed. Despite the integrity of the drainage basin as a geoecological unit, its assessment criteria should vary depending on the landscape zones that make up the basin. The methodology for geoecological assessment of mountain river basins is based on two main postulates: the operational-temporal unit of study is the boundaries

of the transformation of sociocultural processes and the operational-territorial unit of study is the landscape zones.

5. A partial assessment of several geoecological assessment criteria in the Caspian region was conducted. Large-scale landscape field studies were conducted, and pollution of water, bottom sediments, soils and vegetation was assessed. The highest nitrogen dioxide and aerosol index levels were recorded in the Kheraz and Gorgan river basins. This suggests that these basins are most susceptible to atmospheric pollution among those considered. Significant concentrations of carbon monoxide were also detected in the Gorgan River basin. Maximum ozone levels were found in the Sunzha River basin.

Analysis of changes over time revealed that the COVID-19 pandemic has significantly impacted the distribution of pollutants. Correlation analysis revealed that altitude is a key factor influencing the distribution of pollutants such as carbon monoxide, ozone and the aerosol index. Population density is more strongly associated with the distribution of nitrogen dioxide. The distribution of other substances is more complex and involves different distribution mechanisms.

The study area is part of the alpine-type relief zone of the Eastern Caucasus, which encompasses early Alpine folded structures composed of Lower and Middle Jurassic shale strata. Systems of deeply dissected mountain ranges and intermontane depressions are well developed. The overall geomorphological structure is determined by the folded structures and the Alpine longitudinal faults that bound them. The formation of secondary landforms, superimposed on tectonic forms, is associated with late Quaternary glaciation and erosion-denudation processes. Modern glaciation is confined to certain of the highest mountain ranges.

Mechanical weathering of rocks and sheet denudation play a significant role in shaping the modern topography. The area is characterized by a very high degree of erosional dissection of the terrain and is highly affected by modern exogenous processes. This highly dissected terrain facilitates the formation and development of mudflows, avalanches, erosion, and landslides. Landslides are the most prevalent.

It has been established that the highest anthropogenic transformation indicators are found within the Karachay and Gorgan river basins. Low anthropogenic transformation indicators are found in the Atachay and Sulak river basins. The highest anthropogenic transformation indicators are located within the flat parts of the river basins, which have been developed for a long time and where a developed infrastructure and settlement system have been established. The lowest transformation indicators are characteristic of highlands covered by natural forest and meadow vegetation. All river basins under consideration have seen increases in average population size and population density. The most pronounced increases in population density are observed in the Gorgan and Sunzha river basins, while the most pronounced increases in population size are also observed in the Gorgan and Sunzha river basins.

6. An analysis of meteorological station data and reanalysis data in the basins of small and medium-sized rivers in the study region was conducted. Taking into account data from meteorological stations for the period from 1961 to 2023, three main time periods with their own trends in meteorological parameter changes are distinguished: Period 1 (1961-1981), Period 2 (1982-2004), and Period 3 (2005-2023). There is a very high correlation (0.99) between the reanalysis data and meteorological station data on average annual air temperature. There is a high correlation (0.77) between the reanalysis data and meteorological station data on annual precipitation. Temperatures along the Dagestan, Azerbaijan and Iranian coasts of the Caspian Sea have increased most rapidly over the past 19 years (2005-2023), with average long-term temperatures increasing by an average of 1.1°C. Precipitation along the Dagestan, Azerbaijan, and Iranian coasts of the Caspian Sea has decreased precisely during this most recent period (2005-2023), with average long-term precipitation values decreasing by an average of 35 mm. Distribution maps of average long-term values of the studied meteorological parameters were constructed within the catchment areas of the western and southern coasts of the Caspian Sea, as well as within the studied river basins.

Zones corresponding to the presence of climatic anomalies in the study areas were identified. The higher the surface level relative to sea level, the more pronounced the positive anomalies in average long-term air temperatures become. Negative anomalies of average long-term air temperatures within the study area are present in all altitudinal zones except the nival zone (above 3000 m).

Maps of anomalies of long-term average values of the studied meteorological parameters were constructed within the contours of the western and southern coasts of the Caspian Sea, taking into account altitudinal zonation, as well as within the studied river basins. The spatial distribution of long-term average temperature

anomalies is as follows: negative statistical temperature anomalies are confined to the Caucasus Mountains, while positive anomalies are confined to the Elbrus Mountains and the southeastern coast of the Caspian Sea. Positive anomalies of long-term average precipitation were identified at all levels of altitudinal zonation for all time periods. The spatial distribution of long-term average precipitation anomalies is as follows: the largest zones of positive precipitation anomalies are found on the northern slopes of the Caucasus Mountains, as well as within the southern and southwestern coasts of the Caspian Sea. Negative precipitation anomalies are found in small areas along the southern boundary of the Caspian Sea drainage basin, closer to the northern slopes of the Elbrus Mountain range.

Temperatures corresponding to these anomalous values have increased over the past 63 years: positive anomalies of mean long-term temperatures from 2005 to 2023 increased by an average of 1.6°C, while negative anomalies increased by an average of 0.9°C, compared to the first time period (1961 to 1981). Negative anomalies of mean long-term precipitation are detected only at altitudes of 2000 m and above. The volume of mean long-term precipitation values corresponding to these anomalous values has decreased over the past 63 years by an average of 18 mm for positive anomalies and by 41 mm for negative anomalies, when comparing data samples from the three time periods.

Positive temperature anomalies among the studied river basins are found only within the Gorgan River basin. Negative temperature anomalies among the studied river basins are found only within the southern part of the Sulak River basin. Positive anomalies in mean long-term precipitation are found only within the Sunzha River basin and slightly north of the Kheraz River basin.

The trend over the three time periods under consideration is a decrease in the distribution of positive temperature anomalies within the river basins. Over time, temperatures corresponding to anomalous values increased: positive anomalies in mean long-term temperatures by 1.9°C and negative anomalies by 0.7°C, when comparing data samples from the three time periods (within the river basins). Negative anomalies in mean long-term precipitation are not found for any of the time periods under consideration. By the most recent time period (2005-2023), the area covered by positive anomalies in mean long-term precipitation values within the Sunzha River basin decreased, while it increased near the Kheraz River basin. Over time, the volume of mean long-term precipitation values corresponding to positive anomalies decreased by 46 mm when comparing data samples from the three time periods (within the river basins).

7. An air pollution assessment in the study region was conducted using remote sensing data from the Sentinel-5P satellite. The Sentinel-5P satellite, with its high spatial resolution and global coverage, has become an important tool for atmospheric monitoring and analysis of pollution dynamics over large areas. The use of the GEE cloud platform made it possible to process large volumes of satellite data and conduct detailed analysis. The Google Earth Engine cloud computing platform was used for high-quality processing of large volumes of satellite imagery. Using JavaScript code, the average values were filtered and extracted, which were then analyzed and graphically presented in ArcGIS. The processing results were used to study the interannual and intraannual dynamics of the aerosol index, nitrogen dioxide, ozone, carbon monoxide, formaldehyde, sulfur dioxide and methane. Based on the obtained data, distribution maps of these pollutants for the Caspian region for 2018-2023 were compiled and correlation diagrams were constructed between pollution indicators and geographic environmental factors in the studied river basins.

8. From August to October 2024, expeditionary research was conducted in the basins of small and medium-sized mountain rivers (Sulak, Ulluchay, Sunzha, Karachay and Atachay) in Russia and Azerbaijan. This study collected samples of soil, terrestrial vegetation, water, and bottom sediments along the rivers. Laboratory analyses of soil, terrestrial vegetation, water and bottom sediment samples were conducted to determine the concentration of heavy metals and microelements, as well as soil samples for pH, total nitrogen content, petroleum products, organochlorine pesticides and microflora abundance. An electronic database of laboratory analyses was compiled.

9. The spatial structure and current state of the landscapes of small and medium-sized mountain rivers in the study region were studied. Two landscape classes are widespread in the studied area of the Northeastern and Southeastern Caucasus: 1) flat and foothill-hilly, 2) mountainous. Within the flat and foothill-hilly landscapes, three types are distinguished: flat arid, flat and hilly warm-temperate and moderate semi-arid; foothill-hilly warm-temperate and moderate semi-humid; hydromorphic and subhydromorphic. Within the mountain class of landscapes, the following types are distinguished: mountain moderate humid, mountain moderate

semi-humid, mountain moderate semi-arid, mountain cold-temperate, high-mountain meadow, high-mountain subnival, and glacial-nival. These types fully reflect the structure of altitudinal landscape zonation not only in the aforementioned regions but also on the entire northern macroslope of the Greater Caucasus.

Landscape maps of the landscape types and subtypes of the Northeastern and Southeastern Caucasus, as well as landscape maps of the basins of the small and medium-sized mountain rivers studied, have been compiled. Landscape mapping carried out in river basins will form the basis for further study of the current geoecological state of these basins in the context of dynamic climate change, the impact of exodynamic processes and the intensification of anthropogenic pressure on the mountain and lowland geosystems of the region.

10. As part of the task of developing a concept for modeling the spatiotemporal dynamics of the geoecological state of landscapes in mountain river basins of the Caspian Sea catchment using artificial intelligence (AI) methods, a review of domestic and international literature on the use of AI in geoecology was conducted and a comparative analysis of existing methods was performed. A concept for a new model of the spatial-temporal dynamics of the geoecological state of landscapes in small and medium-sized river basins was developed, aimed at identifying homogeneous regions over large territories. This methodology proposes using an artificial neural network (ANN) trained using a metric learning approach with self-supervised learning in the MoCo (momentum contrast) method to assess the differences between sample objects. This allows for a more statistically reliable and objective calculation of the measure of difference, taking into account the complex interrelations between ecosystem characteristics. To implement zoning, it is proposed to cluster the data collection, consisting of individual landscape elements that completely cover the territory subject to the region identification procedure. This clustering is proposed using a modern neural network approach based on the SPICE method, which allows for the efficient identification of homogeneous areas based on the calculated differences.

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