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FORECASTING GROUNDWATER POTENTIAL ZONES USING GIS FUNCTIONALITY AND ANALYTICAL HIERARCHY PROCESS (AHP)

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This article presents the results of the identification of the spatial distribution of groundwater potential zones using remote sensing data and open geospatial databases as the initial, as well as approaches based on the use of pairwise comparison of spatial parameters by assigning weights based on expert estimates (AHP). Using the GIS functions, seven thematic layers were created with the corresponding attributive information: the layer of the geological structure of the territory; the layer of the geomorphological structure of the territory; lineament density layer; surface slope layer; layer of soil types; land use/land cover layer and drainage density layer, which have been assigned different weights to characterize the strength of their influence on groundwater recharge. The spatial distribution of groundwater reserves was determined by integrating the seven thematic layers and their respective percentages through overlay analysis in an ArcGIS 10.5 environment. Three potential zones of groundwater availability were identified: a zone with very high potential, the area of which was 45.3%, a zone with high potential, occupying 36.8%, and a zone of moderate potential, the area of which was 17.9% of the territory of the Gorki district. The results of the study can be used by both local government bodies and researchers to develop the measures to optimize the groundwater resources management.

Key words: groundwater; factors; forecasting; GIS; analysis of hierarchy.

The Republic of Belarus possesses significant resources of fresh groundwater, which many times exceed the current and future water consumption [1]. However, like any other natural resource, groundwater can be depleted and undergo changes in quality. In this regard, it becomes relevant to determine the factors affecting the accumulation of groundwater, as well as the establishment of zones with different potential of fresh groundwater reserves [2]. Identification of groundwater potential zones occurrences and the mapping of these zones can be performed using both surface and underground (geological and geophysical) research methods [3].

The use of remote sensing data and the functionality of geographic information systems (GIS) together with the methods of mathematical analysis, in particular analytical hierarchy process (AHP), open up new opportunities for hydrogeological research and can significantly speed up and reduce the cost of obtaining the necessary relevant geospatial information [4].

The purpose of this study was to identify and map the spatial distribution of groundwater potential zones using Earth remote sensing and open geospatial databases as input data, as well as using a relatively simple approach to determine such zones based on the use of pairwise comparison of spatial parameters by assigning them weights based on expert judgment.

To achieve the goal of the study, the following tasks were solved:

1) processing the initial data and creating thematic layers with the corresponding attributive information;

2) assessment of the potential for groundwater availability using the analytical hierarchy process;

3) analysis of the sensitivity of factors affecting the replenishment of groundwater resources;

4) combining and transforming geospatial data and creating the resulting vector layer of groundwater potential zones with different availability. Figure 1 illustrates the methodology used to identify and delineate of groundwater potential zones.

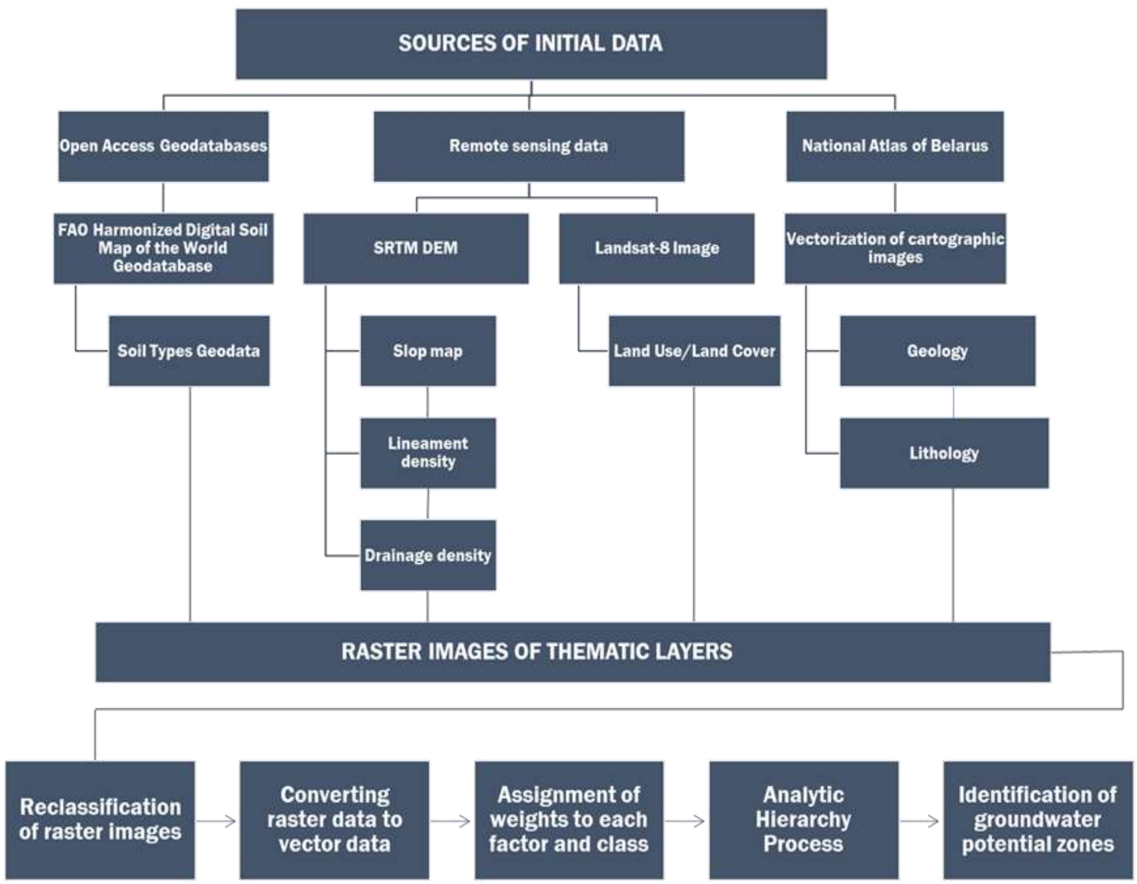

Figure 1 – Flowchart for groundwater potential zones identifying

The studies were carried out in 2020–2021 on the territory of Gorki district of Mogilev region (Republic of Belarus). As the initial data, we used geospatial databases and data of remote sensing of the Earth, which are in the public domain, as well as information provided in the National Atlas of the Republic of Belarus (Table 1).

Table 1 – Initial data and their sources

Data type	**Source**	**Data format**
Digital elevation model (DEM)	Shuttle Radar Topography Mission (SRTM) data (USGS), resolution 30 m	Digital
Drainage density		Raster
Land Use/Land Cover	prepared from Landsat 8 in ArcGIS, spatial resolution 30 m	Raster
Soil	FAO Harmonized Digital Soil Map of the World Geodatabase	Digital
Slope	Developed from SRTM data (Spatial resolution 30 m) in ArcGIS	Raster
Lineament density		
Geology	National Atlas of Belarus, p. 66 [5]	Digital
Geomorphology	National Atlas of Belarus, p. 41 [5]	Digital

Primary data include digital elevation model (DEM) available from the Shuttle Radar Topography Mission (SRTM) and Landsat-8 multispectral imagery. The slope factor was calculated using the 30m DEM based on the maximum rate of change in value from each cell to neighbouring cells. The data related to drainage density were generated indirectly from the slope data.

Seven thematic layers were obtained through GIS functionality: the layer of the geological structure of the study area; the geomorphological structure layer; density layer of local faults (lineaments); surface slope layer; layer of soil types; land use type layer and drainage density layer. These layers, together with their corresponding attributive information, were used to predict the distribution of groundwater potential zones (Figures 2–8).

The AHP method provides for the consideration of a problem or phenomenon as a multilevel hierarchical structure that takes into account the relationship between its elements (factors) [4, 6]. Each element of the hierarchy can represent various tangible and intangible factors, measurable quantitative parameters and qualitative characteristics, objective data and subjective expert assessments [7]. The implementation of this method in identifying groundwater potential zones provided for the sequential passage of the following stages:

1) selection of factors influencing the groundwater potential zones and assigning weights to various thematic layers and their respective characteristics – criteria (building a three-level hierarchy "goal – factors – criteria");

2) creation of a pairwise comparison matrix for all factors affecting the accumulation of groundwater resources, its normalization and calculation the weight of each factor;

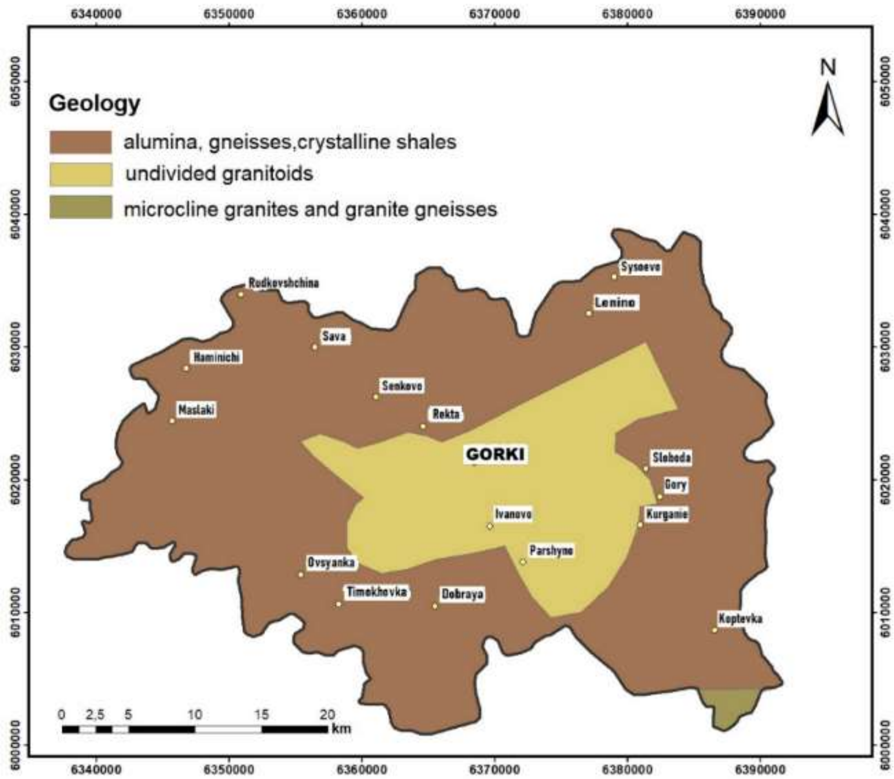

Figure 2 – Geology map of Gorki district

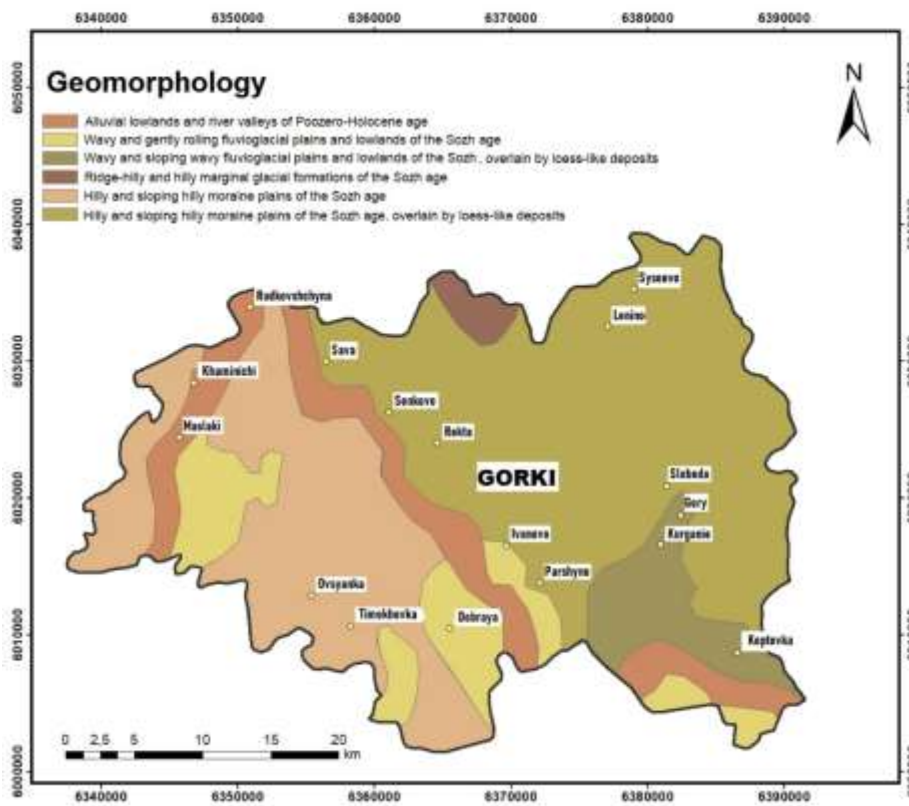

Figure 3 – Geomorphology map of Gorki district

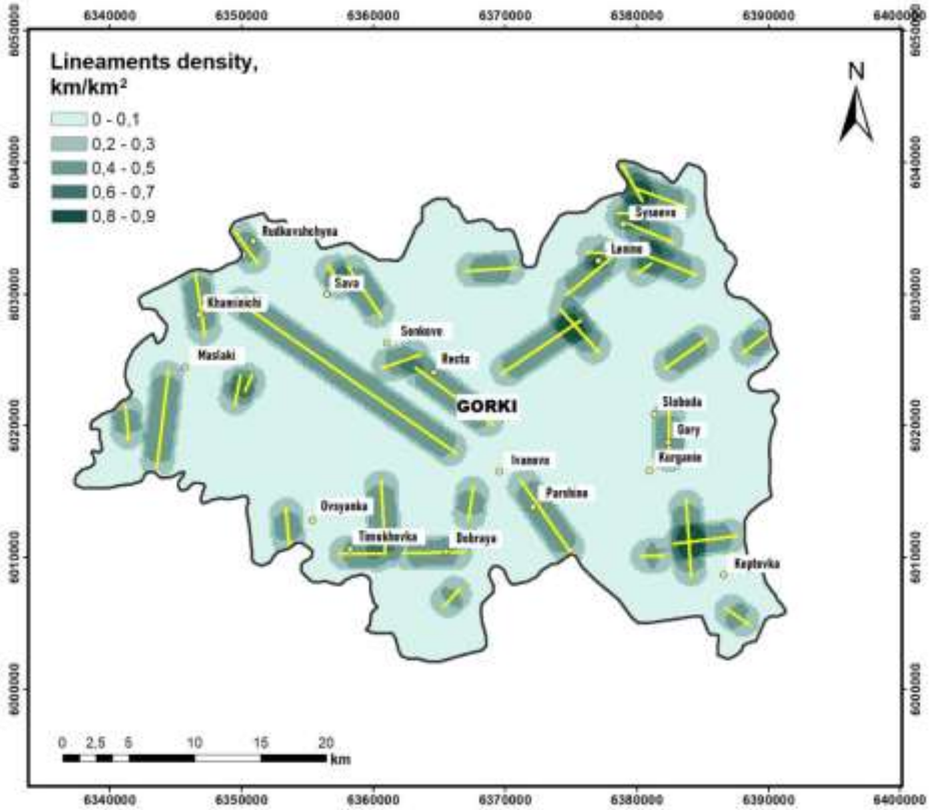

Figure 4 – Lineament density map of Gorki district

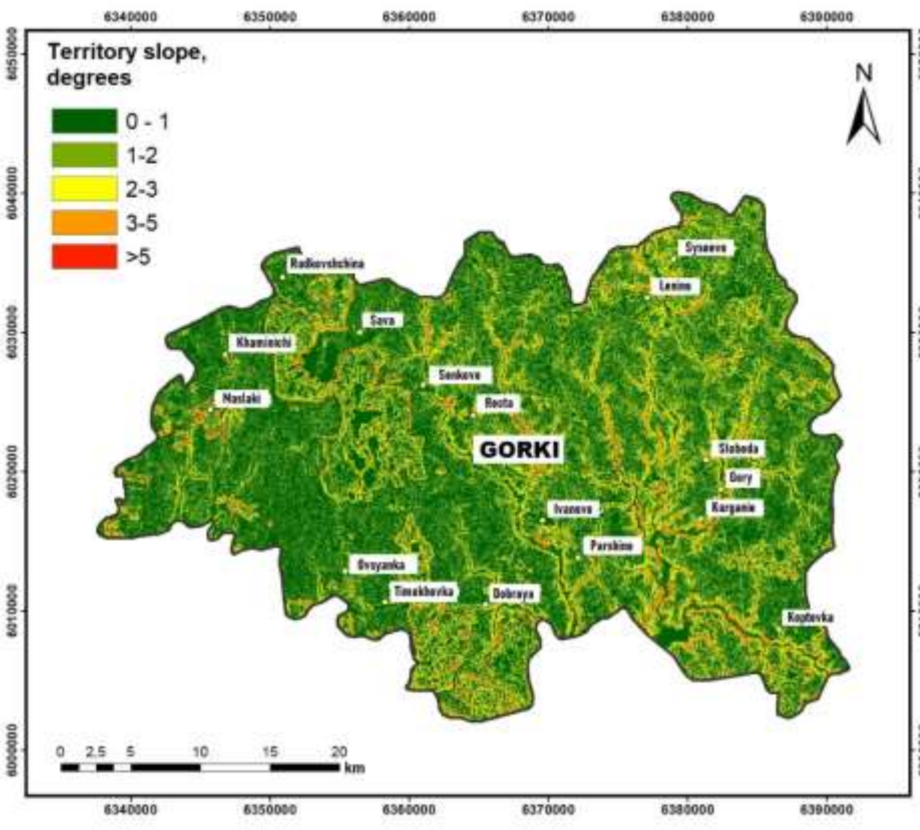

Figure 5 – Slope map of Gorki district

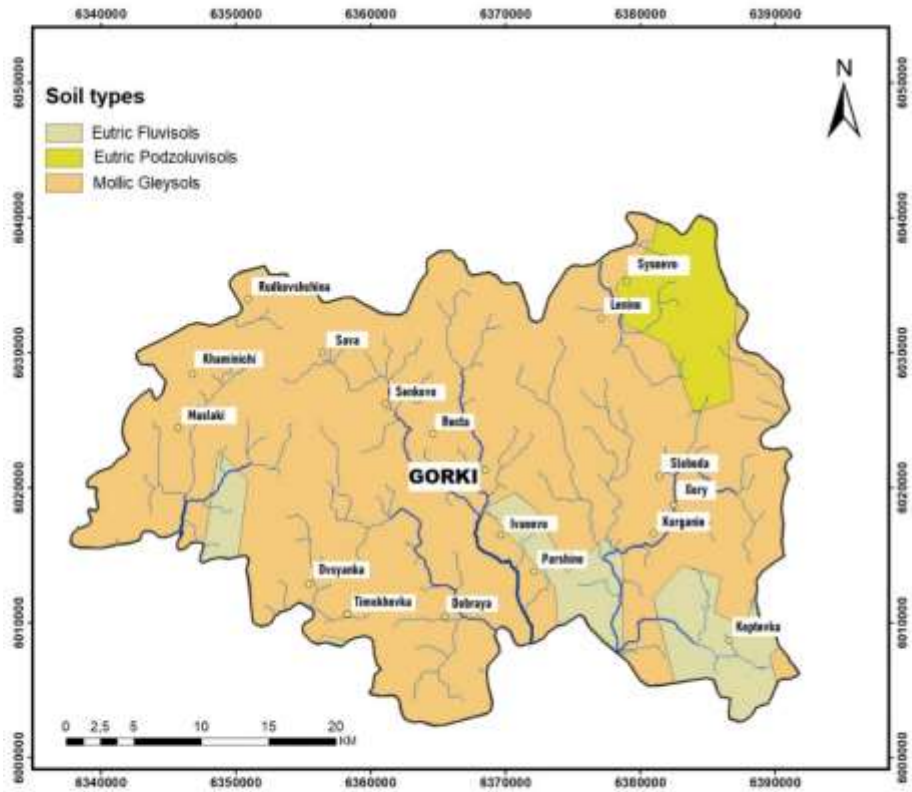

Figure 6 – Soil map of Gorki district

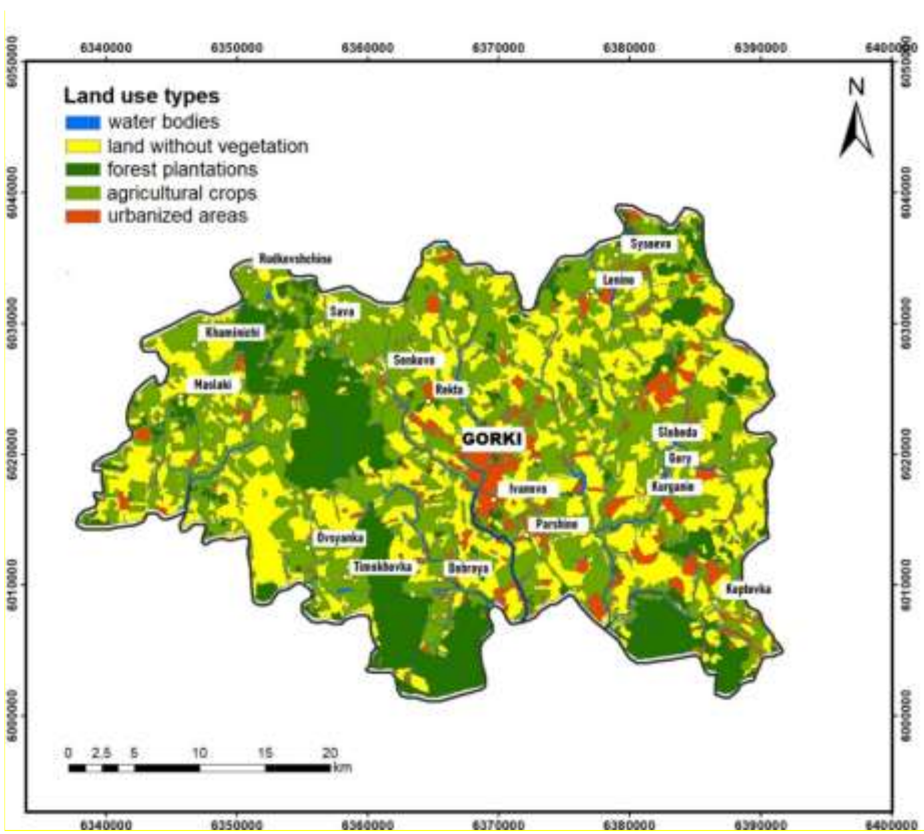

Figure 7 – Land use map of Gorki district

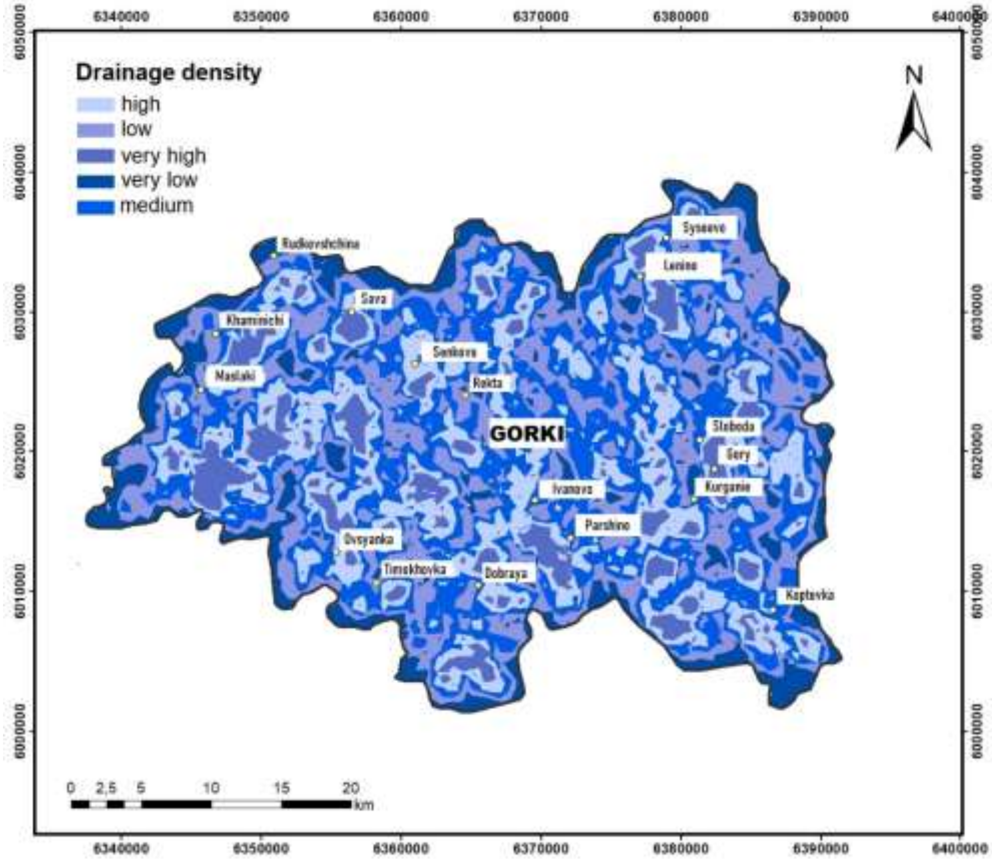

Figure 8 – Drainage density map of Gorki district

3) calculation of the magnitude of the relative total weights of the factors affecting the accumulation of groundwater resources, and the magnitude of the maximum eigenvalue of the consistency vector λ_{max} for ranking the influence of the factors;

4) assessment of the consistency of the weights matrix of influencing factors by determining the value of the consistency index CI and the consistency ratio CR [2].

The spatial distribution of groundwater reserves was determined by integrating the seven thematic layers and their respective percentages through overlay analysis in an ArcGIS 10.5 environment [8].

Values in the input raster layers were reclassified into a common evaluation scale of 1 (very good), 2 (good) and 3 (moderate). This was done by multiplying the cell values of each factor class by the factor weight and summing the resulting cell values to produce a map of potential recharge zones [4, 9], as summarized in Equation (1):

$$GWPZ = \sum_{i=1}^{n} W_i * R_i = (GE_R GE_W + GM_R GM_W + LD_R LD_W + SL_R SL_W + ST_R ST_W + LU_R LU_W + DD_R DD_W) \quad (1),$$

where $GWPZ$ is the groundwater potential zone; W_i is the weight of each thematic layer; R_i is the rating of each class of each thematic layer; the subscripts R and W refer, respectively, to the factor class of a thematic layer and its percent influence on recharge.

The choice of a three-level rating scale is due to the fact that the study area does not belong to either arid or semi-arid zones.

Table 2 reports the final weights of the factors governing GWPZs. The factor of the geological structure of the territory has the maximum weight, which determines the porosity and permeability of aquifers. These aquifers, in turn, influence the generation and distribution of groundwater recharge.

Table 2. – Ranks and weights assigned to the criteria of factors based on the results of applying the Analytical Hierarchy Process (AHP)

Factor	Factor criterion	Rank	Analytical Hierarchy Process		
			Weight	Weighted rating	Total weight
Geology (GE)	Alumina, gneisses, crystalline shales	3	0.35	1.05	2.10
	Undivided granitoids	1		0.35	
	Microcline granites and granite gneisses	2		0.70	
Geomorphology (GM)	Hilly and sloping hilly moraine plains of the Sozh age	3	0.24	0.72	5.04
	Alluvial lowlands and river valleys of Poozero-Holocene age	6		1.44	
	Wavy and gently rolling fluvioglacial plains and lowlands of the Sozh age	5		1.20	
	Wavy and sloping wavy fluvioglacial plains and lowlands of the Sozh age, overlain by loess-like deposits	4		0.96	
	Ridge-hilly and hilly marginal glacial formations of the Sozh age	1		0.24	
	Hilly and sloping hilly moraine plains of the Sozh age, overlain by loess-like deposits	2		0.48	
Lineament density (LD)	Very high	5	0.16	0.80	2.40
	High	4		0.64	
	Medium	3		0.48	
	Low	2		0.32	
	Very low	1		0.16	
Slope (SL)	0-1	5	0.11	0.55	1.65
	1-2	4		0.44	
	2-3	3		0.33	
	3-5	2		0.22	
	> 5	1		0.11	
Soil type (ST)	Eutric Fluvisols	3	0.07	0.21	0.42
	Mollic Gleysols	2		0.14	
	Eutric Podzoluvisols	1		0.07	
Land use type (LU)	Water bodies	5	0.05	0.25	0.75
	Urbanized territories	1		0.05	
	Forest plantations	4		0.20	
	Land without vegetation	2		0.10	
	Agricultural crops	3		0.15	
Drainage density (DD)	Very high	1	0.03	0.03	0.45
	High	2		0.06	
	Medium	3		0.09	
	Low	4		0.12	
	Very low	5		0.15	

The geomorphological features of the studied region were divided into 6 categories with weights varying from 1 to 6. Alluvial lowlands and river valleys of the Poozero-Holocene age, occupying 11.1% (142.41 km^2) of the territory, as well as undulating and gently rolling fluvioglacial plains and the lowlands of the Sozh age, occupying 10.9% (141.12 km^2) of the territory, are characterized by the maximum potential for the availability of groundwater.

To check the correctness of the theoretical assumption about the influence of one factor or another on the formation of groundwater resources, the dynamics of the sensitivity index *S* was analysed when one or several thematic layers (factors) were removed from the raster image obtained by the weighted overlay method. It was found that the smallest variation in the sensitivity index is associated with the simultaneous removal of the drainage density factor as well as land use and soil type factors (Table 3).

Table 3. – Sensitivity analysis of the elimination of factors affecting the replenishment of groundwater resources

Factor that was not taken into account and its designation	Sensitivity index, S (Average value)	Standard deviation	Variation coefficient
DD	1.76	0.44	25.0
DD + LU	3.97	0.75	18.9
DD + LU + ST	7.20	1.28	17.8
DD + LU + ST + SL	4.42	3.13	29.9
DD + LU + ST + SL + LD	15.67	5.38	34.3
DD + LU + ST + SL + LD + GM	19.39	10.84	55.9

The identification of GWPZ was accomplished based on the rates and weights of the seven thematic layers according to Equation (2):

$$GWPZ = 0{,}35GE + 0{,}24GM + 0{,}16LD + 0{,}11SL + 0{,}07ST + 0{,}05LU + 0{,}03DD \quad (2),$$

Results of the GWPZ mapping are shown in Figure 9.

Three potential zones of groundwater availability were identified: a zone with a very high potential, a zone with a high potential and a zone with a moderate potential, the area of which amounted to 45.3%, 36.8% and 17.9% of the territory of the Gorki district.

The results obtained suggest that the combined use of remote sensing data and GIS functionality is an effective tool for predicting potential groundwater occurrence zones without performing expensive hydrogeological studies. The results of the study can be used by both local government bodies and researchers to develop the measures to optimize the groundwater resources management in order to protect them and provide rational utilization.

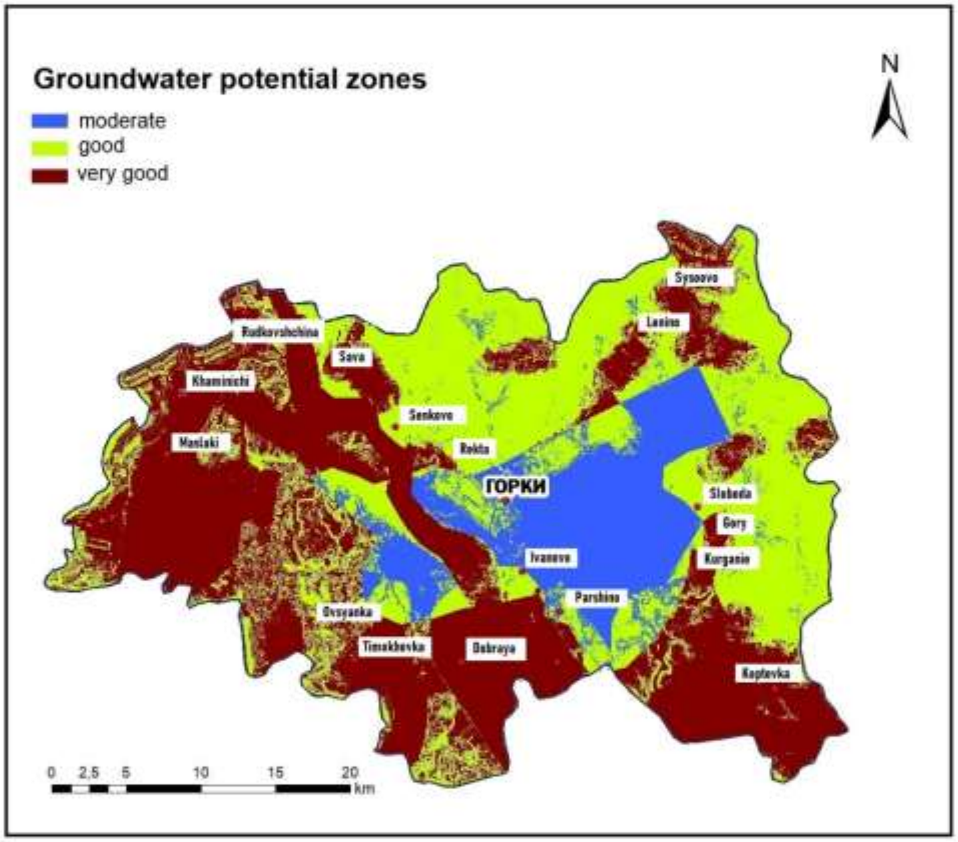

Figure 9 – Groundwater potential zones of the Gorki district which identified using AHP method

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