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Importance of using GIS software in the process of application of Analogue terrains and Counter-approach technologies in water resources assessment

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Abstract

The research is devoted to the wider application of GIS technologies in hydrological studies, especially in the assessment of water resources of rivers. Runoff formation is a very complex process that occurs under the influence of multiple factors. Studies show that the more flow-forming factors that are considered in the assessment process, the more accurate and reliable the results are. The practice of studying water resources based on the analogy of observed and unobserved river basins is a widespread approach in hydrology. Previously, analogies created on the basis of one or several predictors did not allow to obtain reliable results in the selection of analogue terrains. Modern scientific innovations have enabled more detailed analysis and modeling of runoff-forming processes. With our proposed method, analog geo-spaces are selected based on the similarity of most components through space information, and assessment is performed using GIS and other multifunctional technologies. Another advantage of the assessment with the new method is the ability to easily restore climate and runoff data for unobserved and extreme regions. Thus, on the basis of basins with hydrometeorological data, it is possible to estimate the water resources of any other unstudied rivers with high accuracy without time-space restrictions. Comparison of the actual and calculated by the proposed method of runoff for most of the river basins of Azerbaijan shows that the error between them was up to 10% in 92 cases out of 100.

1. Introduction

It is impossible to imagine modern scientific research without the use of space imagery and geospatial data. Previously, scientific-experimental researches were mainly carried out by terrestrial visual methods by organizing field expeditions, but now 80-90% of them are performed on the basis of space information. The Earth sciences section is the most widespread field of multi-functional operations performed through geospatial data and GIS technologies. Geoinformation data are also widely used in the field of hydrology, especially in the recovery of hydrometeorological data and the estimation of water resources [1-3].

Space information and GIS technologies are extremely important sources in terms of realizing the 4 important features of modern scientific research (applicability, operativity, interactivity and predictability). Applicability – is a feature that includes the consideration of important scientific results in economics and design. Operativity – means faster execution of research results. This feature is very important from the point of view that the speed of scientific research does not lag behind the pace of development of socio-economic reforms. Interactivity – is a concept that shows the sensitivity and adequacy of research to changing factors. In other words, interactivity reflects how and in what volume the quantitative and qualitative changes in the components will affect the water resources of the territory. Providing interactivity in research is not only limited to monitoring changes in the volume of water resources, but also creates additional chances to eliminate negative manifestations. Predictability – reflects the analysis based on the results of scientific research for territorial and landscape planning, hydraulic engineering design, assessment of the adequacy of the level of water resources, water risk insurance, hydrological forecasting and modeling, etc.

Taking into account the current trends in world science and their need in the Republic of Azerbaijan, we have developed the New Innovative Hydrological Method (NIHM), which is an operational-interactive and sensitive method.

2. Material and Method

Our main goal in the submission is to investigate the role of space images and geoinformation during the restoration of hydrometeorological quantities and the assessment of water resources in unobserved areas. For this purpose, a number of traditional and modern methods were used, as well as our proposed NIHM method. Even during the application of traditional methods, the study processing was carried out completely with modern GIS-technologies [4, 5]. The scientific research process is based on 3 important sources: primary reliable data, modern scientific approach methods and high-precision computing technologies. To obtain accurate results, first of all, it is important to have reliable research materials. During the study, information about most of the factors influencing water resources is collected without physical contact of the territory. LULC data (Land use & Land cover) are obtained on the basis of fragments of multispectral (hyperspectral) satellite images. Various difference indices (NDIs) are used to determine the landscape and soil cover, vegetation density, humidity and aridity of the area. The most important of these are indices for vegetation (NDVI), water (NDWI), build-up (NDBI), urban (UI), erosion and bare soil (NDBaI), salinization (NDSI), drought (NDDI) and humidity (NDMI).

The heigh, slope, aspect indicators of the relief are determined by the digital elevation model (DEM); and using the Hydrology, Surface and Density program in ArcGIS, the morphometric features of rivers and the range of horizontal and vertical fragmentation of the surface are found.

In procces restoring climate data from traditional methods, the methods of Graphical Relationships, Interpolation and Analogy were used; and modern methods, preference was given to Counter-approach and NDI methods. Actual data on the remaining landscape, soil, morphometric, humidity and other components are determined by satellite images. Relationships and natural regularities are defined between the actual indicators of the components in specific physical and geographical conditions. This method is entirely carried out by the application of multifunctional calculation, comparison and probability software in ArcGIS. The data processing is adopted by verifying millions of options and correcting the most reliable quantities, including the influence of complex factors and each different physical-geographical situation.

2.1. Study Area

The research area covers the Karabakh region located in the south-west of the Republic of Azerbaijan (Figure 1). The area of the research region is 13732 km^2. The selection of the Karabakh region as a research area is not accidental. Currently, as a result of the liberation of the region from occupation, large-scale socio-economic reforms have been initiated here. However, as a result of being under occupation for more than 30 years, it has created very tense conditions in the region. During this period, no research work was carried out, the infrastructure was completely destroyed, hydrometeorological observation stations did not operate. The mining of a large part of the region, the existence of military conditions in some areas, as well as the harsh mountainous conditions create additional difficulties in research. NIHM method is considered the most reliable research method for precisely such extreme situations. Because with the new hydrological method, it is possible to carry out research without time-space restrictions, without physical contact with the area and without the need for observational data.

Figure 1. Study area

2.2. Complex factors in the formation of water resources

It is known that all the components that make up natural complexes are closely related and interact with each other. These effects occur in a regular manner, and changes observed in any component are reflected in other components as well. Among the natural components, relief, heat and humidity level have a leading effect. During the study, most of the factors that play a role in the flow-formation and the change in the volume of water resources are taken into account. These factors are divided into 3 groups:

1) Inputs that make up the surface cover of the territory. These include landscapes, vegetation density, land use fund, soil cover, granulometric composition of soils, lithology of rocks, etc. belongs to.

2) Morphometric quantities. These include the relief of the area (height, slope degree, exposure of slopes), river basins area, horizontal and vertical fragmentation of the surface, river network density, etc. includes.

3) Climate and humidity factors. These include factors such as air temperature, atmospheric precipitation, actual and potential evaporation, humidity coefficient, maximum water retention of soils, actual soil moisture, hydrological losses, initial abstraction.

Taking into account the frequency of quantitative and qualitative changes within these factors, it is possible to divide them into 2 categories: variable and relative stable factors.

1) Variable factors–are subject to faster changes in terms of quantity within time-space. They include parameters related to climate, landscape and soil moisture: precipitation, temperature, actual and potential evapotranspiration, humidity coefficient, maximum soil water retention, soil moisture, initial abstraction, landscapes, vegetation density, surface horizontal and vertical fragmentation, river network density, etc.

2) Stable factors–although they change little in a certain period of time, they are expressed in different changing values within the space. Based on them, the morphometric quantities of the basin (height, slope, aspects, rivers basin area), as well as the granulometric composition of soils, hydrological soil groups (HSG), water absorption capacity of rocks, etc. includes. In the research process, the stable factors were mainly used in the selection of analogue terrains and in the restoration of components without observed data.

Flow-forming factors can also be combined in 2 groups in terms of obtaining information about them:

1) Geospatial data components that can be obtained through space data. It includes most components, except for some climate data.

2) Restored components based on a database of analogue terrains. It includes some climate indicators.

2.3. Advantages of the new hydrological method (NIHM)

The essence of the NIHM method is the principle of estimating the rivers water resources using runoff coefficients that include the influence of complex factors. The practice of assessing water resources based on runoff coefficients and runoff numbers has a history of hundreds of years [6-8]. Over time, those methods have been modified. At present, as a result of the hybrid of these types of methods, very reliable methods are developed [9-11]. The NIHM method we propose takes into account the advantages of the leading methods and models currently used in the world and also in the basis of the innovative proposals we put forward. The new method, the way of innovative scientific approaches, has an effective role in terms of solving the following important scientific problems: Studying inter-component natural regularities in a wider range. Quantifying relationships between components. Recovering unknown data of components through quantitative indicators of known data of factors (predictors). Process forecasting and modeling based on possible changes in components. Studies show that it is possible to determine and predict the degree of influence of quantitative changes in any component on others in a specific quantitative expression. Since the number of components represented in natural complexes is quite large, and their interaction possibilities are endless, this connection constitutes a very complex mechanism. The study of climate and flow quantities, which are an important component of this mechanism, is more relevant. Because in recent times, the intensity of changes in natural components has increased against the background of global climate changes, and it has left a mark with its negative effects on the reduction of more vitally important water, soil and biological resources. At present, there is an increasing trend of scientific works performed taking into account the influence of complex factors in geographic research, especially in the natural resources assessment. Taking complex factors into account makes it possible to study the effect of each component separately or in combination on the subject of the research, to obtain more reliable results in the assessment of natural resources. Our proposed New Innovative Hydrological Method (NIHM) combines all 4 features of modern research and is of great scientific-practical importance. Assessment of water resources through NIHM is distinguished by a number of important scientific innovations and advantages. The most important issues of them are the following: Implementation of the calculation process completely using spatial information and GIS technologies. Consideration of the influence of most factors affecting the volume of water resources. Minimizing dependence on observational data. Providing operability and interactivity in the assessment process. Absence of spatial and temporal restrictions, that is, the possibility of conducting research in any natural and extreme conditions, at any time period. Ability to restore all components, in the absence of data. High accuracy and reliability of the obtained results. The aprobation of the hydrological assessment through NIHM method has also been highly justified. Research conducted on river basins located in different physical-geographical conditions of the Azerbaijan showed that the error between the actual ratios and the runoff coefficients found by the new method was only 10% in 92 cases out of 100. This shows that the estimation in new innovative ways has a very high reliability.

2.4. Analogue terrains selection

The most widely used ways when studying the water resources of the ungauged areas were the Counter-approach and Analogue terrains selection. Analogue terrains–are areas with similar physical and geographical conditions between river basins with measurement data and no observations. The functional mechanism of terrains analogy is designed to search unknown elements in areas without data by using the relationship between components (especially in quantitative terms) based on the database of long-term observation areas. The results of long-term observations and artificially created experimental river basins showed that the greater the number of runoff-forming components included in the calculations, the closer the relationship between the components. This thesis showed itself in the higher correlation in the estimation of flow quantities. So, the more similar the physical-geographic conditions in which the flow is formed, if the analogy is made with the maximum number of factors affecting, the flow quantities are closer to each other. The application of the Analogy method was widely used in classical studies. The main goal in this method is to recover any unknown factor(s) based on their relationship with other factors that have measurement data. Until now, the consideration of some factors in the studies conducted in this direction did not allow obtaining very accurate results. At present, scientific and technical achievements, reliable research materials obtained with satellite images have created conditions for a deeper analysis of natural complexes, including climate and flow quantities, which are the subject of our research. The advantage of research conducted in this direction is determined by the fact that it is possible to include most important components of natural complexes in the research process. As a result, it is possible to give mutual connection of all components and at the same time comprehensively assess their impact on various subjects. These types of scientific approaches are mostly used in hydrological studies in terms of flow formation, precipitation-flow mechanism modeling, water balance of the area and water resources assessment. As a result of the simultaneous and comprehensive consideration of the influence of many factors on the flow quantities, it was found that there are very important regularities, and their specific numerical expressions were obtained. When selecting analogue geospaces, no distinction is made for the location of the river basin with measurement data. Thus, the principle of similarity of the same river basin located in the same physical-geographic provinces, different rivers in the same province, rivers located in different provinces and even in other countries can be referred to. At present, it is possible to achieve maximum (sometimes 100%) similarities between river basins through satellite images and modern GIS technologies. Analogue terrains are distinguished not only by the complex factors themselves, but also by their different quantitative and gradational limits. As a result, inter terrain analogy sometimes appears in millions of variants during the processing carried out in ArcGIS various calculation, comparison and probabilistic software. Figure 2 shows analogue terrains in the forested areas of the Karabakh region, distinguished by the combination of the forest with other flow-forming factors.

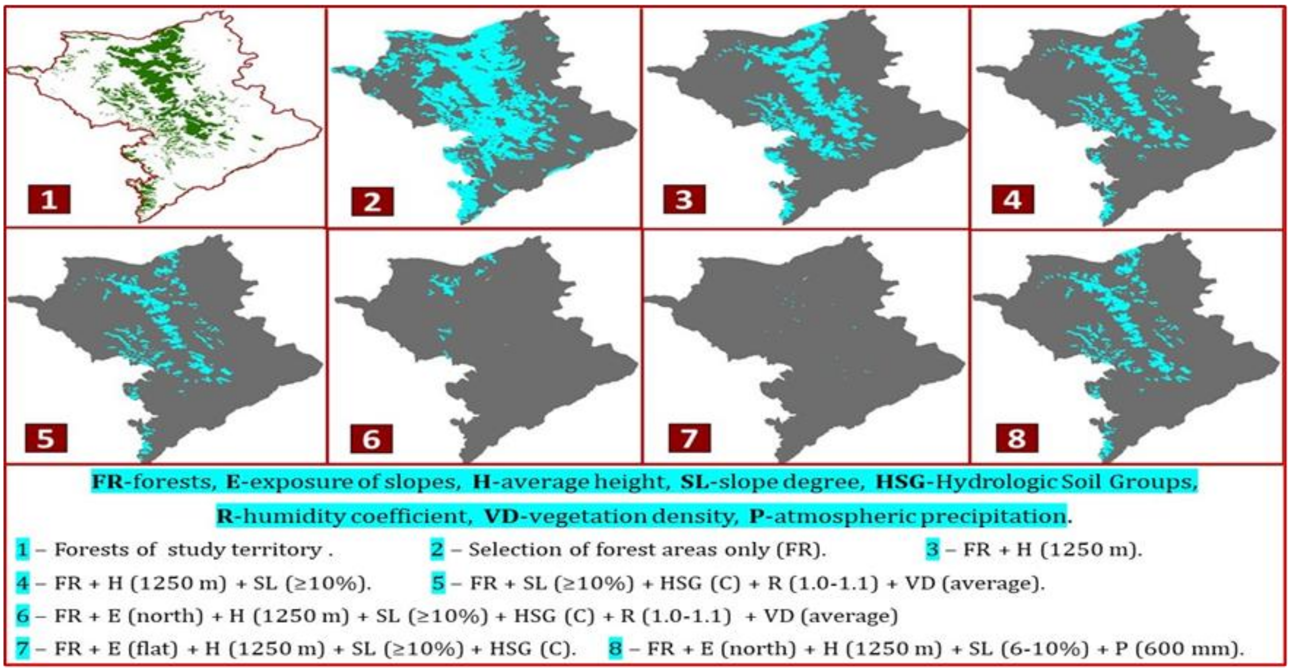

Figure 2. Selection of analogue terrains with the joint participation of various factors.

As the intraspecies diversity of components and their quantities change, the number of similar spaces (polygons) decreases. Using ArcGIS program, the number of similar polygons in the Karabakh region, separated only with the participation of forests, was 388506. Each time a new predictor was added to the processing, the number of analogue terrains changed as follows: average elevation – 142141, slope – 71536, humidity coefficient and vegetation density – 12268, exposure (north) – 1728, flat surfaces – 26 (Table 1).

Table 1. Number of analogue scenarios obtained participating forest landscape with other components.

Picture no	Analogue polygons count	Components participated in analog spaces and their amounts
2	388506	FR (only the forest)
3	142141	FR + H (1250 m)
4	71536	FR + H (1250 m) + SL (≥10%)
5	12268	FR + SL (≥10%) + HSG (C) + R (1.0-1.1) + VD (average)
6	1728	FR + E (north) + H (1250 m) + SL (≥10%) + HSG (C) + R (1.0-1.1) + BS (average)
7	26	FR + E (flat) + H (1250 m) + SL (≥10%) + HSG (C)
8	9969	FR + E (north) + H (1250 m) + SL (6-10%) + P (600 mm)

2.5. Counter-approach technology

The Counter-approach technology is based on the fact that if most of the flow factors are known, the unknown parameters are recovered from the database of available factors. In other words, when using Counter-approach technology, the research process is performed from the end to the beginning.

This study way is mostly used in climate data recovery. A suitable place and time to compare is selected. Factual climate data is collected. In the GIS processing database, it is converted into polygons (areas) with Interpolation and Reclassify programs. Analogue terrains are selected with the Select by Attributes program, and the compatibility of the locations is defined using the Weighted Overlay Influence (Fuzzy) software.

As an example, the Table 2 shows the restoration of rainfall in the area, taking into account the influence of some important factors. These factors included forest landscape, vegetation density, soil infiltration capacity (HSG), humidity level of the area (R) and slope (M).

Table 2. Restoration of precipitation data (m)

Vegetation cover density	Humidity level (average)		Humidity level (high)		
	HSG “C”	HSG “D”	HSG “C”	HSG “D”	HSG “D”
	M ≥ 10%	M = 6-10%	M ≥ 10%	M = 6-10%	M ≥ 10%
Bare soils	543.1	514.9	651.9	624.8	517.8
Poor vegetation	542.9	548.8	622.0	618.8	522.1
Fair vegetation	549.6	558.4	614.9	620.5	528.9
Dense vegetation	545.1	553.8	618.6	617.4	532.4

3. Results and Discussion

As mentioned, the water resources of rivers are estimated using runoff coefficients that change under the influence of complex factors. In the study, the process of assessing water resources is carried out according to the following algorithm:

1) Based on observational data and space information, the data of the flow-forming components is collected.
2) Collected data are jointly processed in the ArcGIS database through various software.
3) The specific physical and geographical conditions in which the runoff coefficients obtained with the measurement data are formed are investigated.
4) Runoff coefficients are determined for each different geographical conditions corresponding to the variability of flow-forming factors.
5) Runoff coefficients obtained by finding analogue terrains are also applied to unexplored areas.
6) The water resources of any area are estimated based on the equal distribution of runoff coefficients on the territory (runoff layer).

Runoff coefficients were fully analyzed by applying multiple software for calculation, comparison and probabilistic analysis in GIS. In the processing, the influence of complex factors and various physical and geographical situations was taken into account, multidimensional options were checked, and the most reliable runoff coefficients with corrections were adopted. The results of obtained runoff coefficients were verified both in the ArcGIS program in the form of a trend in 100% Influence scales, and in multilinear regression equations with a high correlation (determination) coefficient, and some by calibration.

The rivers water resources are considered the total runoff, which is the sum of their surface and underground feeding. Some components have a positive impact on surface runoff, others on groundwater (baseflow). Their cumulative effect is manifested in completely different quantities of runoff coefficients.

A number of important components of the study area (Karabakh) obtained with satellite imagery, DEM processing, and interpolated climate data using ArcGIS software.

3.1. Determination of river basin components

The river network of the study area is obtained using ArcGIS Hydrology software [12] . Through this program, it is possible to determine the directions and accumulation points of the surface flow, the rivers length, the river network density, the area and boundaries of the basins, etc. (Figure 3).

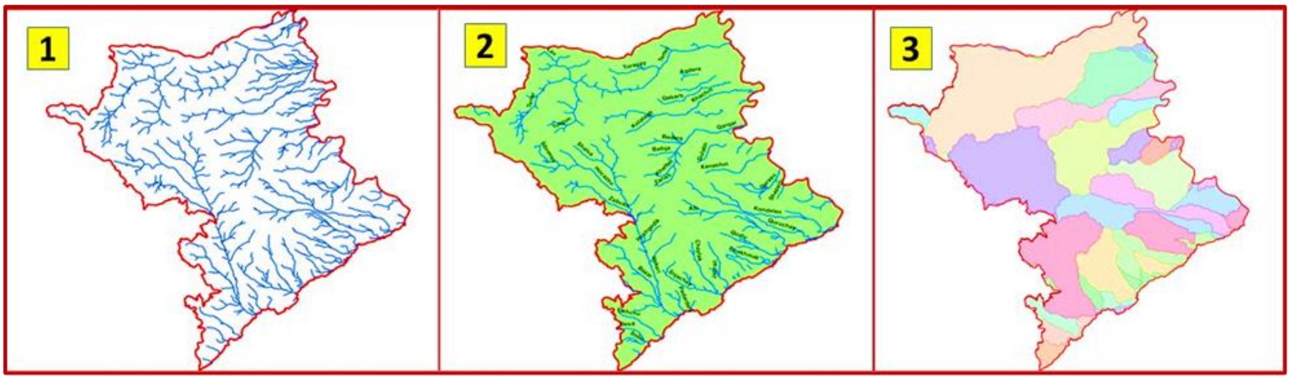

Figure 3. River basin components: 1–Flow accumulation, 2–River network, 3–Rivers basins separation.

3.2. Determination of geomorphological components

The geomorphological characteristics of the area play an important role in the formation of rivers water resources. Components from this group include topographic and hypsometric indicators of the area (relief, average height, slope, aspects, horizontal and vertical fragmentation of the surface, etc.) (Figure 4). An increase in height and slope degrees to an increase in surface runoff and a decrease in baseflow (underground fedding of rivers) [13, 14]. The aspest (steepness of the slopes) also has a strong influence on the flow coefficients. Precipitation and runoff ratios are expressed in high values, especially on the north-facing slopes. The high horizontal fragmentation of the surface increases the rivers network density. On the contrary, if the vertical fragmentation is too great, the fall of the river increases, which has a negative effect on rivers density [15].

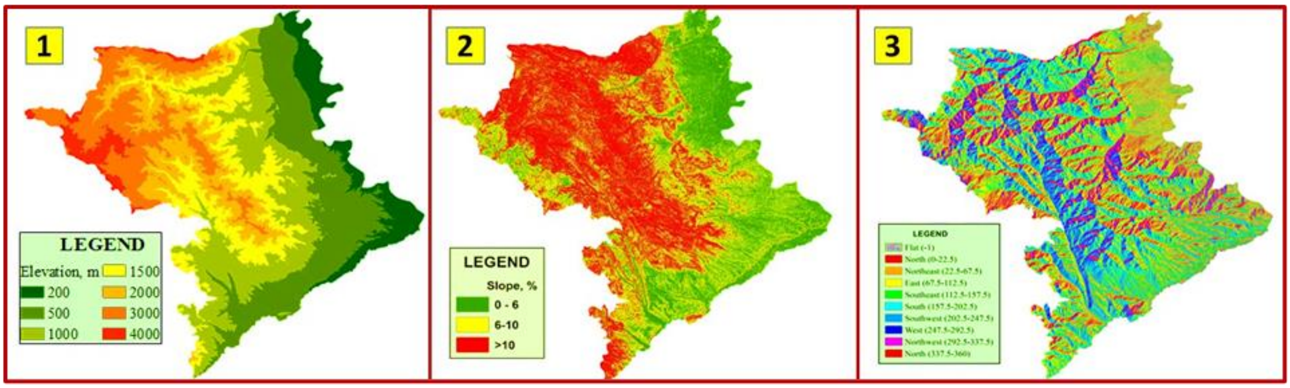

Figure 4. Geomorphological components: 1–Average height, 2–Slope, 3–Aspect.

3.3. Determination of surface cover components

The most important components that make up the surface cover of the territory are LULC (Land-use & Land cover), vegetation density, granulometric composition of soils, HSG (Hydrological soil groups), etc. belongs (Figure 5).

LULC is the sum of natural and anthropogenic landscapes characterizing the general appearance of the surface cover of the territory. (vegetation cover, water bodies, residential areas, cultivated areas, wetlands, roads, industrial facilities, bare soils, etc.) [16, 17]. The influence of landscape types and their density on rivers runoff is quite complex. Some types of landscape (forests, meadows, wetlands, closed water bodies, rural settlements, crops, etc.) have a positive effect on underground flow, and others have a positive effect on surface runoff (deserts and semi-deserts, dry steppes, nival-subnival areas, pastures, bare lands, etc.) has an effect.

As the density of vegetation growth, their water retention capacity also increases. As a result, this causes the water to slow down in the basin and increase the share of precipitation spent on underground fedding of rivers.

The physical and hydrological characteristics of the soil cover also play a significant role in the flow generation. In this sphere of study, it is important to evaluate the infiltration capacity of soils depending on their granulometric composition and porosity [18]. The so-called "Hydrological soil groups" (HSGs), which reflects the permability capacity of soils, is currently a widely used indicator during hydrological assessment. HSGs–is an indicator reflecting the surface runoff and infiltration capacity of soils.

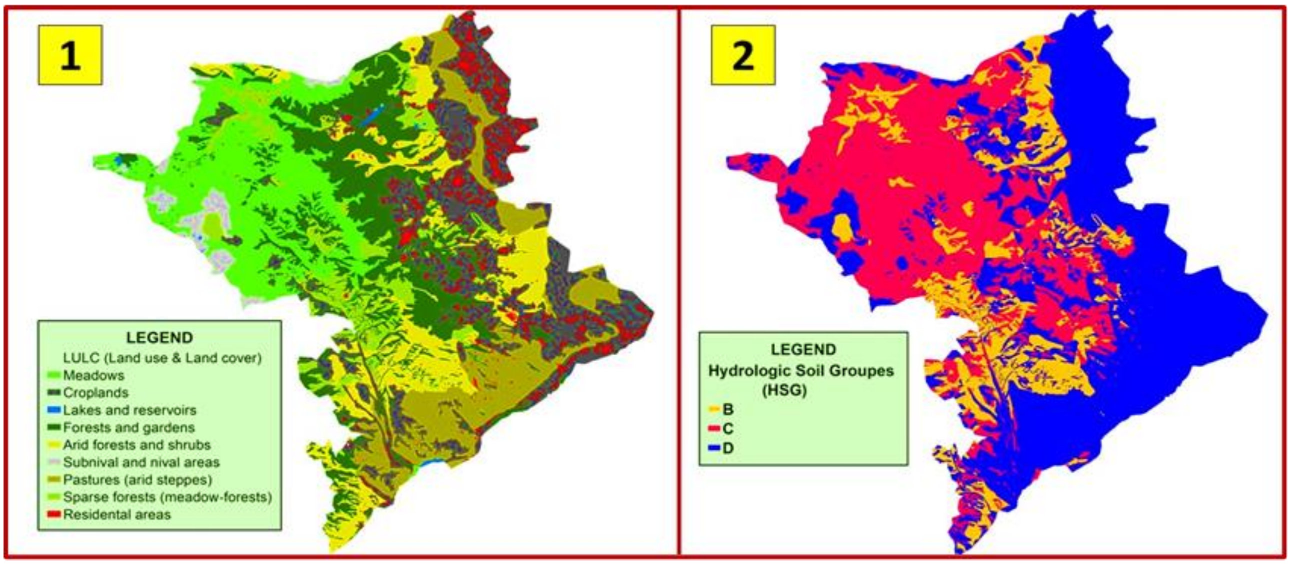

Figure 5. Surface cover components: 1–LULC (Land use & Land cover), 2–HSG (Hydrologic Soil Groups).

According to the granulometric composition, 12 soil codes and 4 HSGs are separated (A, B, C, D). From group A to group D, there is a tendency to weaken infiltration and increase surface runoff in soils [19]. For each soil code and soil group, the granulometric content and porosity level were determined separately. This is a very important condition for determining the infiltration capacity (the share of underground feeding of rivers)of the area . Usually, this indicator is given in the form of the infiltration coefficient (the part of precipitation spent in baseflow).

3.4. Determination of climate and humidity components

In traditional methods, when calculating water resources, temperature and precipitation data were usually taken as the basis of climate indicators. In the new methods, the assessment is carried out based on the general humidity level of the study area. Scientific experiments show that assessment of water resoces with only temperature and precipitation data does not give very complete results. Because the rivers runoff can be high even in high temperature conditions. Or there may be no runoff formation even during high rainfall events. The precipitation-runoff relationship necessarily depends on the humidity level of the territory at the time of rainfall and in the multi-year period. For this reason, more than 10 parameters are currently used in assessing the climate-humidity level of the area [20]. These are indicators that reflect both the humidity level of the air and the soil. In the process of assessment by air components such as temperature, precipitation, actual and potential evaporation, humidity coefficient, relative humidity; and from soil components such as soil infiltration rate, maximum soil water retention, actual soil moisture, initial abstaction, etc. are widely used. Some important climate-humidity factors of the study area are shown in Figure 6.

In the CWBM method, the influence of components on runoff is assessed in a complex way, both separately and together. When determining runoff coefficients, not only the factors themselves are necessary, but also their intraspecific diversity, different quantitative indicators. For example, the density of vegetation, soil moisture level, population settlement rate, various gradations of slopes and heights, aspects, each different values of the climate-humidity components were also extracted. Every other situation appears as a new runoff coefficient. The multiplicity of runoff coefficients is due to taking into account complex runoff-forming factors and each specific situation. To facilitate the use of the method, runoff factors are given based on more important variable factors. These factors include 5 components and their variable values: precipitation, LULC (Land-use & Land cover), HSG (hydrological soil groups), slope, moisture level of the area (coefficient humidity). Thus, in determining the total runoff factor, each type of LULC is taken into account along with their vegetation density; each different rainfall amount, 3 degrees of slope (<6, 6-10, >10%); HSG into 4 groups (A, B, C, D) and humidity of the territory into 3 levels (low, medium, high). Other relative stable runoff-forming coefficients were mainly used to compare basins, to identify analogue terrains, to assess the ratio of components relationships, to select moisture level, and for other purposes.

As an example, Table 3 shows the trend of changes in multi-year total runoff coefficients with changes in slope, Hydrological soil groups (groups A and D) and humidity level (R) in forested areas with average vegetation density (50-75%).

The water resources of the Karabakh region according to the NIHM method were estimated at 1804 million m^3 in 2022. According to the assessment, the average total runoff coefficient of the Karabakh rivers was equal to

0.2625; that is, 73.75% of precipitation did not participate in the runoff formation. The share of surface runoff was 47.9%, and that of underground runoff (baseflow) was 51.2%.

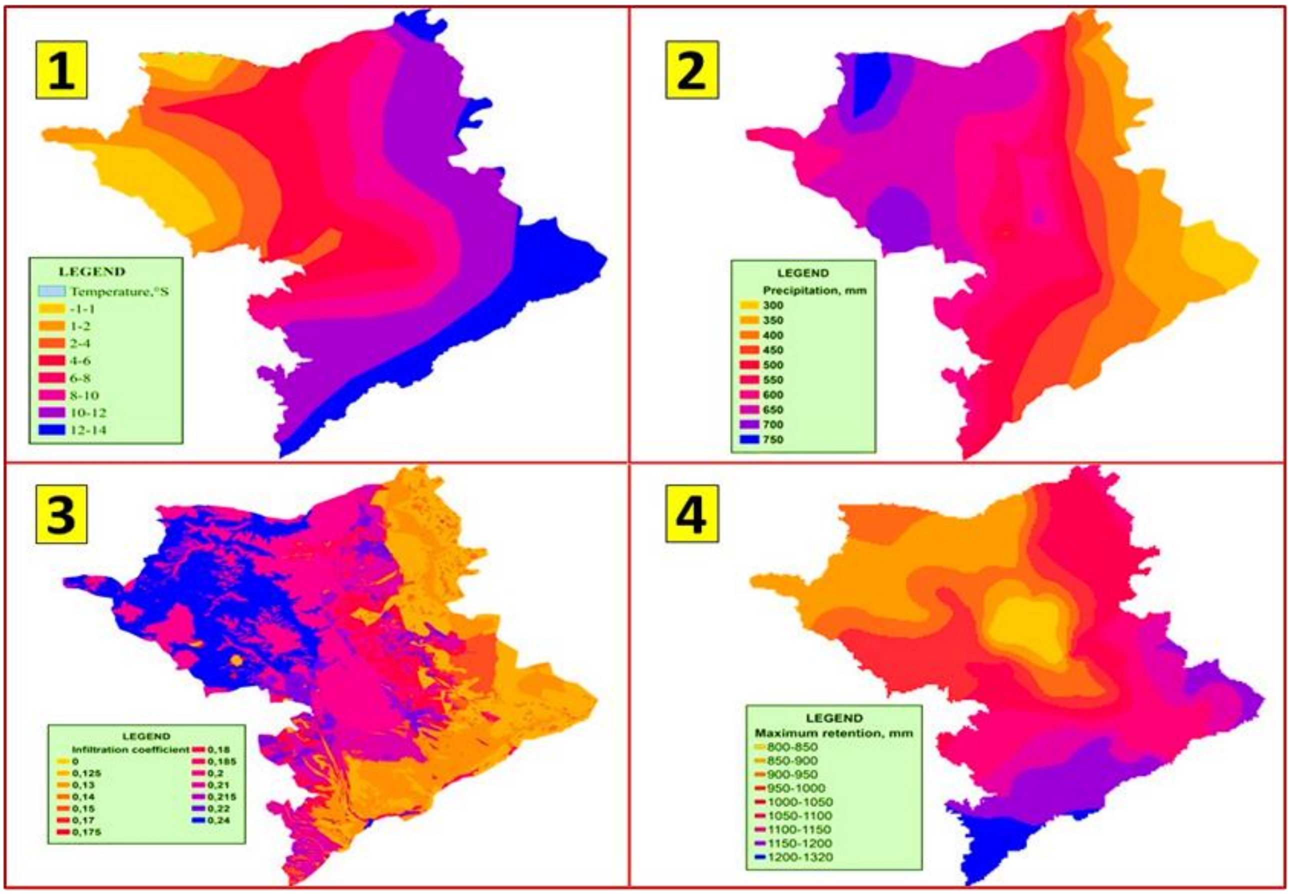

Figure 6. Climate-humidity components: 1–Air temperature, 2–Precipitation, 3–Infiltration coefficient, 4–Maximum soil water retention.

Table 3. Variation of multi-year total runoff coefficients in forested areas.

Humidity condition	Slope, %		
	≤ 6	6 - 10	≥ 10
	Hydrological soil groups – A		
Poor humidity, (R≤0.45)	0.145	0.155	0.175
Moderate humidity, (R=0.45-0.85)	0.17	0.23	0.265
High humidity, (R≥0.85)	0.19	0.265	0.31
	Hydrological soil groups – D		
Poor humidity, (R≤0.45)	0.175	0.19	0.23
Moderate humidity, (R=0.45-0.85)	0.25	0.31	0.345
High humidity, (R≥0.85)	0.28	0.355	0.43

4. Conclusion

Currently, the world's fresh water resources are rapidly decreasing. Assessment of water resources is very important in terms of water supply of the economy and population, protection of the existing ecosystem, territorial planning and solving other problems. Through our proposed new innovative method (NIHM), the entire research process is performed without space-time limitations based on satellite images of the area and GIS technologies. CWBM is an innovative and operative-interactive method. The results obtained with it are distinguished by their sensitivity and adequacy to any changes, being of high accuracy. The advantages of the new method make it urgent to promote it and expand the use of its application possibilities.

The following scientific innovations were applied for the first time during the assessment of flow-forming factors and water resources: 1. Simultaneous application of new different scientific approaches in the processing process, such as Counter-approach technology and Analogue terrains selection. 2. Participation of complex flow-forming factors in the selection of analogue areas. 3. Adding new predictors such as vegetation density, aspect (exposure of slopes), horizontal fragmentation of the surface, humidity level of territory to the process of selecting similar places. 4. Assessment the impact of each of the flow-forming factors on water resources both separately and together. 5. Separate calculation of the natural and anthropogenic impact on the change in the volume of water resources, etc.

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Author contributions

Rza Mahmudov: Conceptualization, Methodology, Writing-Original draft preparation, Editing **Movlud Teymurov:** Data curation, Software, Validation, Investigation

Conflicts of interest

The authors declare no conflicts of interest.

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