ASSESSMENT OF THE WATER BALANCE OF THE TERRITORY AND RİVERS WATER RESOURCES USING A NEW OPERATIONAL-INTERACTIVE METHOD

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Abstract

A new method (CWBM) is proposed for calculating the water balance of the territory and water resources of rivers. CWBM was developed on the basis of reliable scientific sources (satellite images, GIS-technologies, modern scientific approaches, advanced hydrological models). The following scientific innovations were achieved for the first time in the new method: 1. Considering the soil-water-air environment (SWA) as a single mechanism, the influence of complex flow-forming factors has been studied. 2. It was possible to obtain quantitative expression of the impact of each factor on water resources separately and together. 3. In the research process, time-space restrictions and dependence on observational data have been eliminated. 4. By carrying out 3-stage studies (past, present, future), it is possible to receive prompt and adequate responses to any changes and perform multi-scenario forecasting. 5. In any river basins with different physical-geographical conditions, it is possible to estimate both the total runoff separately and as a sum of the surface runoff and base flow. Comparison of the actual and calculated with CWBM method flow for 113 river basins of Azerbaijan shows that the error between them was up to 10% for 92 and 10-15% for 21 rivers.

Keywords*:* total runoff of rivers, CWBM, hybrid and synthesis methods, Counter-approach technology, analogue terrains

I. Introduction

In recent years, the impact of global climate and landscape changes on the formation and depletion of water resources has further complicated the problems associated with water. This problem is more pronounced in countries with limited inland water resources. Currently, there is no such socio-economic sphere in which it is possible to carry out without taking into account the quantitative and qualitative values of water resources. Population and economic growth rates in the world are quite high. At the same time, climate change and anthropogenic activities quickly affect the volume of water resources. This, in turn, is required the assessment of water resources in ways that allow for operative, interactive and more reliable results. In methodologies, operativity – includes the objectives of the study, not lagging behind the pace of development of the economy and the population, interactivity – assessment in terms of adequacy to changing factors. Conducting research using satellite imagery, GIS and other modern technologies are important features to ensure the reliability of the results obtained. Therefore, in recent years, in the world, especially in countries such as the Republic of Azerbaijan, where there is a shortage of water resources, such methods are widely used. Such methods are often developed on the basis of a hybrid and synthesis of basic hydrologic methods in the world. Hybrid methods, which include the advantages of basic methods, have more advanced capabilities by eliminating their shortcomings [1, 2, 7, 8, 22, 23].

To estimate the water balance of the territory and rivers water resources, we have proposed a new method of CWBM (Complex Water Balance Method). The CWBM was greated based on the advantages of leading hydrological methods widely used in the world, taking into account the specific physical and geographical features of Azerbaijan and as a result of our innovative scientific approaches.

II. Methods and materials

The study area covers the Karabakh region, located in the southwest of the Republic of Azerbaijan. The area of the investigated region is 13732 km^2. Satellite images of different years, a digital elevation model (DEM-Digital Elevation Model) and hydrometeorological observation data were used as the source materials for the research. Data on the landscape-soil fund were obtained on the basis of fragments of multispectral (hyperspectral) satellite images. Height, slope, and exposure measurements were determined using DTM, and river morphometric values were determined using ArcGIS Hydrology, Surface, Density, and other software.

Water balance methods are more reliable sources for estimating the water resources of rivers. It is known that the water balance reflects the distribution of atmosferic precipitation in various spheres (initial abstraction, surface runoff, infiltration, evapotranspiration, etc.). The advantages of the most popular water balance methods in the world were used as basic methods in the development of the CWBM. Among the basic methods, the Rational method is considered more effective – in terms of studying surface runoff; NRCS-CN – soils infiltration capacity and groundwater feeding of rivers; Ponce-Shetty and Lvovich methods – studying the theoretical foundations of water balance [4, 5, 10, 15, 16, 17, 18, 20].

The Rational method is considered one of the most important method for assessing the level of precipitation formation on surface runoff. The formula of the rational method (Rational Equation) is expressed as follows:

$$Q = ciA \quad (1)$$

Here Q–is the water discharge (unit-cubic feet), i–is the amount of precipitation (inch), A–is the area of the study area (acre), c–is the rational (surface) runoff coefficient.

To change to the unit of measure for water discharge to m3/sec we proposed a conversion factor (k=0.0000314), which formula was expressed as:

$$Q = k \times ciA \quad (2)$$

The rational coefficient is found on the basis of various types of landscape, hydrological soil groups (HSGs) and slope. Hydrological soil groups (HSGs) – depending on the granulometric composition of soils, their ability to form surface runoff and infiltration is reflected. The NRCS classification defines 12 soil granulometric codes and 4 HSGs (A, B, C, D). From group A to group D, there is a tendency to weaken infiltration and increase surface runoff [21].

In the methodology authored by Lvovich, the annual water balance of river basins is expressed by the concept of "total catchment wetting" (W) and is found by the following equation:

$$W = P - Q_s = U + E \quad (3)$$

Here W – is total catchment wetting; P – atmospheric precipitation; Q_s – surface runoff; U – baseflow; E – actual evapotranspiration from basins surface.

The Ponce-Shetty model is conceptually similar to Lvovich's methodology. According to this model, the total annual runoff of rivers is separated in two stages: fast flow and slow flow. Fast runoff is part of the precipitation that passes into direct surface runoff. The rest of the precipitation is stored as humidification in the basin (W-wetting):

$$P = Q_f + W \quad (4)$$

Stage 2 of the model represents the distribution of wetting (W) to other water balance elements, and this parameter itself is divided into two components:

$$W = Q_b + V \quad (5)$$

Here V – is the water returned to the atmosphere in the form of evaporation, Q^b – is the slow flow (baseflow), the mass of water that is a component of the underground feeding of rivers. It is called "slow" because the groundwater feeding of the river occurs gradually due to precipitation.

Thus, in the Ponce-Shetty model, the rivers total runoff (Q) is expressed as the sum of fast and slow flow, that is, surface runoff and baseflow:

$$Q = Q_f + Q_b \quad (6)$$

Runoff Curve Numbers (CN) used in the SCS-CN method are also indicators defination of the precipitation rate to runoff formation. In this method, the conversion rates of precipitation to runoff are expressed by different runoff curve numbers (CN) at 3 humidity levels (dry, normal, saturated). Unlike the Rational method, an important advantage of the SCS-CN method is that, with the possibilities of determining surface runoff, it simultaneously reflects the infiltration characteristics of the area, especially in terms of assessing the degree of soil moisture. This feature is especially important in content of estimating the share of underground feeding of rivers (baseflow).

In SCS-CN method uses several important components to determine the water balance of an area as: 1) Hydrological losses (L) – is the fraction of precipitation that does not participate in the formation of surface runoff. 2) Maximum soil retention (S) — is maximum water retention capacity of soils in the concrete physical and geographical conditions of the territory. 3) Initial abstraction (I_a) — is part of precipitation spent on various areas before surface runoff formation. 4) Actual soil moisture (F) — is the actual soil water retention under the existing geographical conditions of the area.

The SWA environment consists of hundreds of components. These components are divided into soil, air and water components separately. In terms of their role in the runoff formation and participation in the water balance, it is possible to divide the SWA components into 3 groups:

1) The components that make up the surface cover of the territory. These include LULC (Land-use & Land cover) and HSG (Hydrological soil groups). LULC – is the general description of the surface area, or the sum of natural and human landscapes (vegetation, crops, settlements, bedlands, water bodies, etc.) [3, 9, 14, 19].

2) Morphometric values. It includes the elevation of the area, slope of the terrain, exposure (aspest) of the slopes, basin area, horizontal and vertical fragmentation of the surface, density of the river network, etc. [12].

3) Climatic and humidity factors. These include atmospheric precipitation, air temperature, actual and potential evaporation, humidity coefficient, initial abstraction, maximum soil retention, astual soil moisture, hydrological losses, etc.

The study comprehensively takes into account the majority of factors that play a role in the runoff-formation, and changes in water resources. Both the influence of the majority of components is taken into account, and the assessment is carried out in a complex manner. Therefore, the new hydrologic method was named "Complex water balance method" (CWBM).

As a result of combining the features of the leading basic water balance methods and introducing innovative proposals into the CWBM method, a number of additional advantages have been obtained:

1. In the process of research, it is possible to take into account the influence of most runoff-forming factors.
2. Whole process of research can be carried out without physical contact only based on multispectral (hyperspectral) satellite images of the area.
3. There is no dependence on observational data, and space-time restrictions.
4. CWBM combines 4 main principles of modern scientific studies (applicability, operativity, interactivity, predictability).

5. Restoration of indicators of any SWA component without observational data is possible with high accuracy.

6. Important time-related challenges in the assessment have been eliminated and an estimate of the water balance has been achieved in any time interval (in rainfall event, short-term and long-term periods).

III. The sequence of the study fulfillment

The essence of the new method (CWBM) is the principle of assessing the water balance and water resources using runoff coefficients that include the influence of complex runoff-forming factors. In most modern basic methods of water balance, studies are carried out mainly for local areas under conditions of high humidity or stormwater runoff at the moment of rainfall. On the other hand, total runoff of rivers is calculated unilaterally. That is, surface runoff and baseflow are studied separately, and this does not allow simultaneously estimating the total volume of river runoff. Thanks to the CWBM, a number of shortcomings of existing hydrological methods have been eliminated. As a result, it is possible to assess the total runoff of rivers both directly from the coefficients reflecting the total runoff, and by estimating the surface and underground fedding separately and summing them up. Another important advantage obtained is that there are no restrictions on the size of the study areas and time period.

Runoff formation is a very complex process. Until now, due to the influence of a number of factors, the formation of runoff and the assessment of water resources did not allow obtaining reliable accurate results. At present, scientific achievements have created conditions for a deeper analysis of runoff formation and the atmospheric-runoff process. Thus, as a result of simultaneous and comprehensive consideration of the influence of most factors, it was found that there are very important patterns in the distribution of runoff coefficients. 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% scales, and in multilinear regression equations with a high correlation coefficient, and graphical relationships, and some by calibration.

The process of correction of runoff coefficients is carried out according to following algorithm:

1. Daily long-term observational data on climate and runoff of hydrometeorological stations located in river basins with different physical and geographical conditions were collected.

2. Data on other complex factors impacting the runoff in these river basins were obtained from satellite images.

3. The available data of hydrometeorological observations and indicators of other runoff-forming factors are collected and processed jointly in the GIS database.

4. Based on observations and space data, the distrubution of factual runoff coefficients and data of components influencing it over river basins are comprehensively investigated.

5. Possible situations are considered, on the basis of the combined impact of complex climatic, landscape and other factors, and runoff coefficients are found for each different situation.

6. The data of runoff-forming components corresponding to the obtained runoff coefficients are determined, the same (or close intervals) coefficients are grouped and corrected.

7. The possibility of applying the obtained correction coefficients to analogues terrains without observational data is checked and the most reliable results are selected.

One of the important advantages of the CWBM is the possibility of assessing the water balance in the territories without observational data. For this purpose, flow-forming factors are obtained in different ways:

a) Most of the factors can be obtained directly from satellite imagery. These include landscapes, land-use, soil cover, granulometric composition of soils, HSGs, horizontal and vertical fragmentation, aspects, elevation, slope, basin area, river network density, humidity level of area, etc.

b) Some of the climate and humidity quantities are obtained indirectly ways. In this case, the relationship of climate quantities with known components is taken as a basis. For this purpose, various components that are more sensitive to changes in climate quantities are applied.

To restore climatic factors in the unobserved territories, a number of traditional and modern methods are used. Among the traditional methods, preference was given mainly to methods such as Graphic relationship, Interpolation and Analogy; and from modern methods to Counter-approach technology and NDIs (Normalized difference indices).

Counter-approach technology (CAT) is based on the fact that if the majority of factors are known, unknown values are restored from the database of available factors. In other words, in the method of CAT, the research process is carried out from the end to the beginning. A suitable place and time for comparison is selected, the influence of factors is verified individually or in combination.

Against the background of climate change, the most serious changes are felt in the humidity level of the territory, landscape, soil types and vegetation density. It was determined that, there is a very high correlation relationship between the quantitative changes of these factors and the values of climatic parameters. As a result, using different NDIs and CAT, it was possible to restore climatic data corresponding to different indicators of soil-vegetation cover and humidity level of the territory.

Another important condition for conducting research in unobserved areas is the selection of analogue terrains with based on actual data. When choosing a analogue locations, a high degree of similarity (sometimes 100%) was achieved. This is due to taking into account complex runoff-forming factors. The ArcGIS Select by Attributes software was used to select analogue terrains, and Weighted Overlay (Fuzzy) Influence was used to determine the level of compatibility.

For example, Fig.1 is shown analogue terrains of river basins with different physical and geographical conditions, such as medium dense forests (50-75%), average height (1000-1200 m), slope degree (>15%), hydrological soil group (C), high humidity level (R>0.85), precipitation (700-750 mm), aspect (north-east).

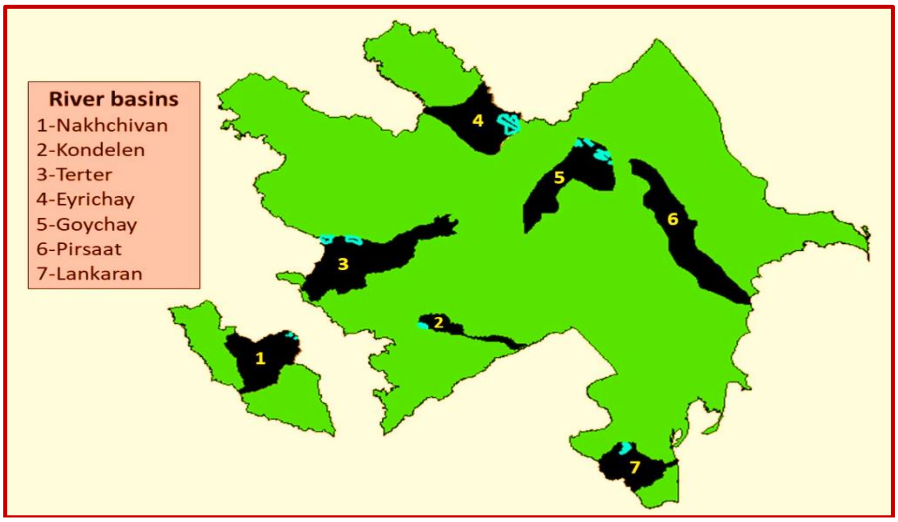

Fig. 1: *Selection of analogue terrains in river basins with different natural conditions*

As can be seen from the figure, in the Pirsaat basin (6 in the figure) no analogue areas to other river basins were found under these conditions. Therefore, if necessary, an analogy is made with other conditions and within smaller areas.

The approbation of the SWBM method has been highly justified. Comparison of actual runoff values and calculated with SWBM for 113 river basins of Azerbaijan with different natural conditions and sizes shows that the error between them was up to 10% for 92 basins and 10-15% in the rest. These results show that the SWBM method has a very high reliability, and it is considered reasonable to apply it to areas without observational data.

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 1 presents the total runoff coefficients for some LULC types for average vegetation densities (50-75 %), with a moderate humidity level (R=0.45-0.80), according to the HSG "B" and 3 degrees of slope.

Table 1: *Changes of total runoff coefficients for different LULC types*

LULC (Land-use & Land cover)	HSG (Hydrologic Soil Groupe) – B		
	Humidity level, average		
	Slope degree, %		
	≤ 6	6 - 10	≥ 10
Dense forests and gardens	0.13	0.14	0.16
Subalpine and alpine meadows	0.34	0.38	0.43
Rare forests (forest-meadow landscapes)	0.24	0.29	0.34
Arid forests and shrubs	0.08	0.095	0.125
Subnival and nival areas	0.49	0.52	0.56
Cultivated areas	0.05	0.075	0.10
Residential areas (settlement-25-30%)	0.065	0.08	0.11
Residential areas (settlement-60-65%)	0.28	0.36	0.41
Residential areas (settlement-85-90%)	0.76	0.79	0.81
Streets (asphalt paved)	0.80	0.82	0.84
Pastures	0.23	0.34	0.45
Water bodies (lakes and reservoirs)	0.32	0.27	0.23
Dry steppes and semi-deserts	0.055	0.075	0.12
Impervious areas and bedlends	0.66	0.68	0.70

The water balance and water resources of the rivers were estimated on the basis of the runoff coefficients with the obtained average values of their distribution over the territories.

The study in the presented article covers the years 1998-2021. The studies used hydrometeorological data and fragments of satellite images relating to this period. According to

2021 data, the results of some runoff factors obtained using space information and ArcGIS programs are shown in Fig.2.

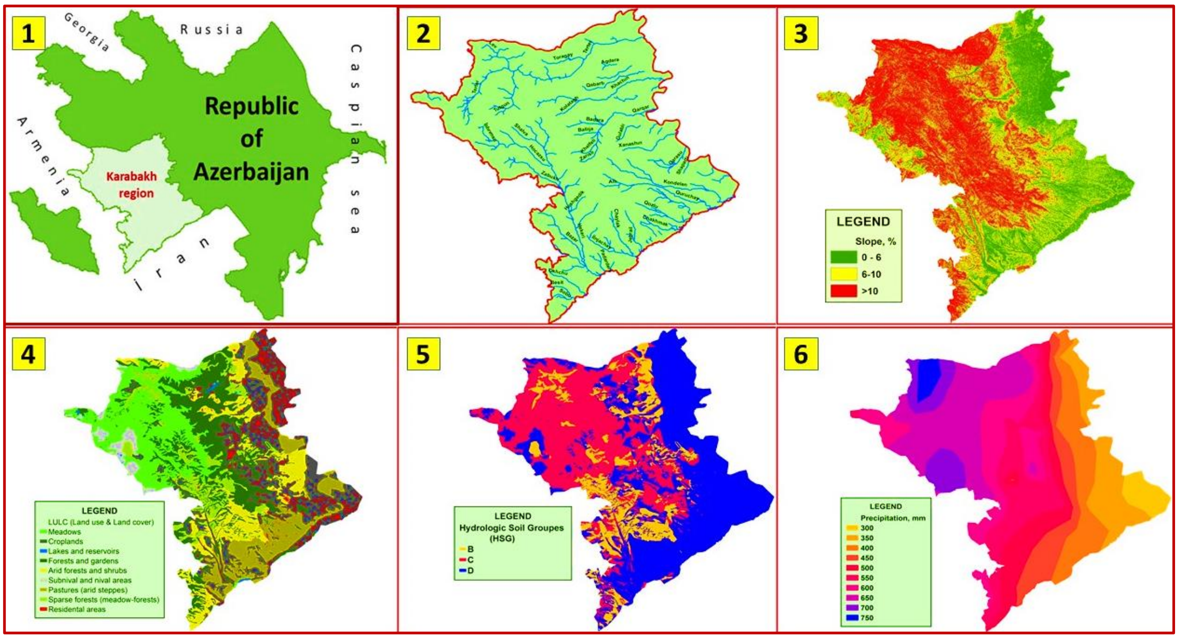

Fig. 2: *1–Study area (Karabakh region). 2–River network. 3–Elevation. 4–LULC (Land-use & Land cover). 5–HSGs (Hydrological soil groups). 6–Precipitation.*

Below presented the results of the most important runoff-forming factors of the study area obtained as a result of processing satellite imagery and GIS technologies.

1. Some types of landscape (urbanization, bare soils, semi-deserts and dry steppes, subnival-nival areas, forest-shrub) seriously affect the total flow of rivers by increasing the share of surface runoff, while others (forests, lakes, meadows, arable lands) increase the share of groundwater runoff (baseflow). The most important factors in the formation of surface runoff are the humidity level and slope degree at the time of precipitation; and in baseflow, vegetation density, hydrological soil groups and soil moisture rate. Table 2 shows the changes in the main LULC types in the region for the studied period.

Table 2: *Changes of main LULC types for the period 1998-2021 (MD-meadows, CA-cultivated areas, WB-water bodies, DS-dry steppes, FR-forests, FS-forest-shrubs, SN-subnival-nival, MF-meadow-forests, ST-settlements)*

Years	LULC (Land-use & Land cover), км^2								
	MD	CA	WB	DS	FR	FS	SN	MF	ST
1998	2871	3255	42.58	1456	3104	1428	262.4	959	357.1
2021	2486	3571	37.08	1662	2623	1648	324.2	1015	368.1
Difference, %	-13.4	+8.85	-12.9	+12.4	-15.5	+13.3	+19.1	+5.52	+2.98

2. Against the background of climatic changes, especially with an increase in temperature, the humidity level of the area decreases [6, 11, 13]. This, in turn, affects the vegetation density and the runoff coefficients. Compared to 1998, the area of bare soils in 2021 increased by 1099.5 km^2 (30.3%), the area with a weak vegetation cover by 467.9 km^2 (9.84%). The area of plots with medium density of vegetation decreased by 905.5 km^2 (19.3%), and areas with high density by 658.9 km^2 (28.9%).

3. During the specified period, as a result of processing the NDWI (Normalized difference water indices), a decrease in the area of closed water bodies (lakes and reservoirs) by 12.9% was noted.

4. The distribution of the hydrological soil group (HSGs) over the region showed that the areas with group "B" are 15.1%, with "C" – 36.4%, with "D" – 48.5% in 2021. These indicators were equal to 12.8, 41.3 and 45.9% in 1998 respectively.

5. Vertical fragmentation of the territory is an important parameter for calculating rivers fall and surface runoff; horizontal fragmentation to estimate river network density and base flow. The total length of valleys with a length of more than 20 m area was 33067 km, the density of the river network was 2.02 km/km^2. These values for valleys longer than 50, 100 and 200 m are 11,362 km and 0.74 km/km^2; 2928 km and 0.21 km/km^2; 768 km and 0.054 km/km^2 respectively.

Vegetation density	1998.07.22.		2021.08.06.	
	Area		Area	
	км^2	%	км^2	%
Water bodies	42.6	0.31	37.1	0.27
Bare soils	2526.8	18.4	3626.3	26.4
Sparse vegetation	4284.7	31.2	4752.6	34.6
Medium Vegetation	4682.9	34.1	3777.4	27.5
Dense vegetation	2197.3	16.0	1538.4	11.2

6. The maximum height of the study area is 3696 m, the minimum height is 49 m, the average height is 1127.2 m. The average slope of the terrain turned out to be 13.4%. Plots with a slope of less than 6% accounted for 30.4%, with a slope of 6-10% –31.6%, more than 10% –38.0%.

7. The greatest exposure of slopes throughout the entire territory of the study region is oriented to the east (15.4%) and north-west (14.2%). The least oriented parts are flat surfaces (0.13%) and north-east (9.46%).

8. During 1998-2021 there have been serious changes in climatic factors, the humidity level has significantly decreased. Analysis of the moisture (NDMI) and drought (NDDI) indices of the study area also showed a decrease of 5.6% in areas with high humidity, but an increase of 8.4% in areas with low humidity.

IV. Results

Table 3 shows a comparison of the elements of the water balance and the volumes of water resources received for the Karabakh region as a result of staged studies for 1998-2021.

Table 3: *Comparison of changes in the water balance components and water resources for 1998-2021*

Components of the water balance		1998	2021
1	Atmospheric precipitation, P, mm	572.0	547.3
2	Air temperature, t, C°	8.28	8.51
3	Potential evaporation, M, mm	801.6	829.2
4	Factual evaporation, E, mm	415.2	422.7
5	Humidity coefficient, R	0.71	0.66
6	Maximum soil water retention, S, mm	1162.8	1189.7
7	Initial abstraction, I_a, mm	312.8	330.7
8	Actual soil moisture, F, mm	196.3	216.6
9	Hydrologic losses, L, mm	494.8	478.5
10	Rational runoff coefficient, c	0.3025	0.2904
11	Average runoff curve number (CN)	68.6	69.7
12	Total runoff, Q_t, mm	157.92	143.65
13	Surface runoff, %	48.9	47.9
14	Baseflow, %	51.1	52.1
15	River discharge, m^3/sec	67.53	57.28
16	Water resources, million m^3	2.127	1.804

Water resources of the Karabakh region using of the CWBM, were estimated at 2.127 km^3 in 1998 and 1.804 km^3 in 2021. In total, over the specified period, water resources decreased by 15.2%. It was determined that out of this 7.04% decrease in water resources in 1998-2021 accounts for climatic, and 8.16% - for the role of human activities and other factors.

According to assessment, the average total runoff coefficient of the Karabakh rivers in the period up to 2021 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 baseflow – 51.2%. The level of direct surface runoff of falling rainfall was only 12.6%, and in the remaining 87.4% part of the rainfall was spent on other areas of the water balance (initial abstraction, infiltration, evapotranspiration, etc.).

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