

BASEFLOW AS THE UNDERGROUND ORGANIZER AND REGULATOR OF A SINGLE RIVER SYSTEM

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Abstract

Rivers have two nutrition sources: surface runoff and subsurface feeding. Rain and snow water constitute their surface runoff and underground feeding of rivers constitutes baseflow (subsurface runoff). Rivers are fed by surface flow during rainfall cases, and by subsurface ways during dry periods. The surface runoff fraction can be determined by measurements of water discharge at existing hydrological observation stations. Determining the share of groundwater recharge is one of the most difficult areas in hydrological studies, and this process is usually carried out indirectly (hydrograph separation, subtraction of the sum of surface runoff and evaporation from precipitation, etc.). However, studying baseflow is of great importance in terms of assessing the water resources of rivers, regulating and managing the river runoff. The article is devoted to the issue of determining the baseflow share of the rivers, and for this purpose a new formula was proposed. The rivers groundwater feeding of the southern slope of the Great Caucasus mountains, which are the study area, were estimated using the new method, and there was very little error between the actual values and the results obtained with the offered formula. The assessment mechanism with new formula allows for highly accurate estimation of the baseflow of rivers basins under any natural conditions, even in the absence of observational data and without spatial-temporal limitations.

Keywords: Surface runoff, baseflow (subsurface runoff), hydrologic soil groups, hydrograph separation, initial abstraction

I. Introduction

The Republic of Azerbaijan is located in an arid and sub-arid region, so there is a serious water shortage. On the other hand, under the influence of global climate change and human activity, there is a tendency for water resources to decrease. River waters account for more than 80% of Azerbaijan's water resources. Against the backdrop of arid climate, the formation capabilities of river waters are weakening and their gradual depletion is observed. The increase of human activities and the population's demand for drinking water also puts additional pressure on the reduction of water resources. According to estimates, over the past 30 years, the republic's water resources have decreased by 15-25% in various rivers. In such conditions, there is a need for continuous assessment of river water resources. The water resources of rivers consist of their surface and underground flow parts. The formation of natural components, including river flow, in any area depends on the temperature and humidity conditions of the area. Previously, assessments of the humidity of the

area and water balance elements were carried out mainly with precipitation and temperature quantities, but now the direction of scientific approaches has changed significantly. Modern science requires the solution of water-related issues not only in a multi-year period, but also within a more specific time and space. While hydrometeorological indicators can play the role of basic data for assessment in the medium-long term, they lose their importance within a specific time-space framework. In such situations, the level of humidity of the area and the moisture content of the soil become the main factors. That is, when we assess the water balance of the area at any given moment, the precipitation and temperature quantities lose their role as the main factor in that specific situation. Therefore, currently, in order to increase the flexibility and accuracy of hydrological scientific research, there is a tendency to assess the humidity conditions of the area on a multifactorial basis. Research that is inclined to the multifactorial principle gives impetus to a deeper analysis of the humidity conditions of the area and to solve the problem [3, 10].

Thus, in the process of assessing the water resources of rivers, multifactorial and complex analysis of the water balance of river basins is an important detail. The surface runoff of rivers can usually be measured by various methods at hydrometeorological stations. However, the process of groundwater inflow into rivers, determining its share in its nutrition and participation in the study of water balance remains a poorly studied area of hydrology. For this purpose, in the presented article, we have put forward a new scientific approach to calculating the shares of underground feeding of rivers (baseflow). The role of groundwater in the water balance of the territory and in the nutrition of rivers is characterized by the following three important aspects:

- 1) Baseflow as an integral part of a single river system, along with surface runoff.
- 2) As a participant in the water balance of the area and a soil moisturizer.
- 3) As an underground organizer and regulator of rivers runoff.

II. Methods and materials

Satellite images, digital elevation models (DEM) and hydrometeorological observation data from 2000-2024 were used as input research materials. Fragments of Landsat-7 ETM+ and Landsat-8 OLI/TIRS multispectral satellite images were applied to obtain landscape types (LULC) and regions moisture condition. Considering the content of the study, priority was given to indices for vegetation (NDVI, SAVI), bare soil (BSI), build-up (NDBI), urban (UI), water (NDWI) and moisture (NDMI).

The hypsometric indicators of the area (elevation, slope degree, aspects, etc.) were studied using a digital elevation model (DEM-Digital Elevation Model). Surface, Density and Hydrology and other software were applied in ArcGIS to collect morphometric indicators (determination of river basins, flow directions, horizontal and vertical surface fragmentation, density of the river network, etc.).

In areas where observations were not made, the restoration of climatic data was carried out using modern Interpolation and Analogue terrains methods, Counter-approach technology [17].

The Rational method was used to study surface runoff, the NRCS-CN method was used to study the infiltration capacity, the Penman-Monteith method was estimated to research evapotranspiration, the Ponce-Shetty and Lvovich methods were used to study the theoretical foundations of water balance. [4, 12, 14, 15, 21].

When studying the soil-water mechanism with NRCS-CN methods, the following water balance elements are usually assessed:

1) Hydrological abstract (or hydrological water losses) – the part of precipitation that does not turn into surface runoff. In other words, the entire part of precipitation that does not turn into surface runoff is considered abstract losses. Its content reflects the part of precipitation spent on soil moistening, infiltration and evapotranspiration. Hydrological abstract is denoted by L and is calculated by this formula.

$$L=P-Q_s \quad (1)$$

Here, P – is atmospheric precipitation, Q_s – is surface runoff.

2) Maximum soil water retention – indicates the maximum water retention capacity of the soil of the area under specific physical-geographical conditions and is denoted by S . The functional relationship between the maximum retention (S), precipitation (P) and surface runoff (Q_s) is calculated by the following formula:

$$S = 5 \times [P + 2Q_s - (4Q_s^2 + 5PQ_s)^{1/2}] \quad (2)$$

3) Initial abstraction – is the fraction of precipitation that is spent on various areas before surface runoff is formed and is denoted by I_a . Initial abstraction plays the role of a preparatory stage for surface runoff, that is, it shows the share of it spent on losses (filtration, accumulation in depressions, transpiration by the plant surface, initial evaporation from the soil, etc.) after the onset of precipitation until the runoff occurs. The $I_a = \lambda S$ relationship reflects the state of precipitation transformation into runoff under various natural conditions. Here λ is the initial abstraction coefficient. $I_a = 0.2S$ is assumed for average (normal) humidification conditions, $I_a = 0.3S$ for arid areas, and $I_a = 0.1S$ for extreme moisture conditions. [1, 11, 26, 28].

4) Factual soil moisture – indicates the actual humidity content of the soil at the time of observation, that is, the amount of water in it. Factual soil moisture is indicated by F and is expressed as follows:

$$F = P - Q_s - I_a \quad (3)$$

5) Antecedent Moisture Condition (AMC) – reflects the moisture content of the area on the eve of precipitation. The word "antecedent" ("antecedent") indicates how the weather conditions were in terms of humidity (dry, hot, humid, rainy) in the days before the onset of precipitation. The territories are divided into 3 AMC conditions according to the moisture conditions. In the USDA classification, the amount of precipitation (P) in the last 5 days is usually taken as the main criterion when assessing AMC conditions. If the precipitation in the last 5 days is 12-28 mm, it is considered normal moisture (AMC II). When precipitation is less than 12 mm, AMC I (dry) conditions are accepted, and when it is more than 28 mm, AMC III (moist) conditions are accepted [5, 19, 20].

III. Results and discussion

The role of groundwater in river flow is mainly manifested in its regulatory function, in its role as a source of nutrition for the river during dry periods without precipitation. This has also been proven by monitoring changes in precipitation and water discharge in several areas of Azerbaijan with different natural conditions. Comparison of data from hydrometeorological stations in the same area has shown that in most cases, maximum water discharge is not observed in rivers in the first days of precipitation. This is explained by the fact that precipitation is used for soil moistening and initial abstraction in these first days. On rainy days, flow occurs mainly through the surface, while groundwater recharge is more pronounced in the dry period, especially 5-10 days after precipitation. Although groundwater recharge manifests itself gradually and evenly, since infiltration increases after relatively heavy precipitation, the activity in groundwater recharge is relatively high during the first 5-10 days after precipitation, and gradually weakens in the subsequent period, which in turn results in a decrease in soil moisture.

Depending on the physical and geographical conditions of the area, baseflow share is at different levels, sometimes even higher than the surface nutrient part. So far, in scientific studies, the share of the underground feeding of the rivers and its role in the formation of the river runoff have been assessed in three ways:

1) By comparing river basins with similar morphometric indicators, but sharply differing in geological structure and water discharge.

2) By separating the hydrographs of rivers according to their nutrient sources.

3) By applying the remaining part to the underground nutrition after calculating the surface runoff and evaporation quantities in the water balance.

The method of finding the share of the underground feeding of rivers by hydrograph separation is the most widespread method in hydrology. This method has been widely used both in the former post-Soviet space and in hydrological studies in the USA and the West European countries. With some exceptions, in this method, the river's baseflow shares are usually calculated by the volume of water covered by the lowest levels of water discharge in the hydrographs [7, 9, 16, 27].

One of the difficulties in studying baseflow is that in most cases its share is determined by quantitative indicators of the remaining part after calculating other water balance elements. It is known that precipitation falling on river basins in the multi-annual term is found by separating it into 3 components: [8, 23].

$$P = Q + U + E \quad (4)$$

where: P – atmospheric precipitation, Q – surface runoff, U – baseflow (underground feeding of rivers), E – actual evapotranspiration.

Observations are usually made on the water discharge of surface runoff on the elements of the river water balance. Observations on infiltration (baseflow) and actual evaporation data are a minority. In the former post-Soviet space, including Azerbaijan, when assessing water balance elements, surface runoff was usually determined by data from observation stations, and groundwater flow was determined by hydrograph separation. The remaining part of the precipitation was considered to be spent on actual evapotranspiration.

As can be seen, very serious calculation errors were observed when assessing the water balance of the area. Thus, at least two of the three components of precipitation (infiltration and evaporation), and sometimes all three, including surface runoff, were calculated without relying on measurement data.

The baseflow of rivers is a parameter that depends largely on the geological-lithological structure of river basins and the rocks permeability capacity. The concept of "Hydrologic Soil Group" (HSGs) is a very important parameter in the study of soil-water relations, especially in the field of assessing the infiltration level of the area. HSGs are classified based on the granulometric composition of soils, reflecting the infiltration capabilities of soils and the potential to create surface runoff. According to the NRCS classification, 4 HSGs (A, B, C, D) are distinguished and 12 soil codes are defined within them according to their mechanical composition.

Table 1: Infiltration rate changes depending on soils granular texture

Soil texture types	Percent of slope				
	0-4%	5-8%	8-12%	12-16%	Over 16%
	Infiltration rate, inches/hour				
Coarse Sand	1.25	1.00	0.75	0.50	0.31
Medium Sand	1.06	0.85	0.64	0.42	0.27
Fine Sand	0.94	0.75	0.56	0.38	0.24
Loamy Sand	0.88	0.70	0.53	0.35	0.22
Sandy Loam	0.75	0.60	0.45	0.30	0.19
Fine Sandy Loam	0.63	0.50	0.38	0.25	0.16
Loam	0.54	0.43	0.33	0.22	0.14
Silt Loam	0.50	0.40	0.30	0.20	0.13
Silt	0.44	0.35	0.26	0.18	0.11
Sandy Clay	0.31	0.25	0.19	0.12	0.08
Clay Loam	0.25	0.20	0.15	0.10	0.06
Silty Clay	0.19	0.15	0.11	0.08	0.05
Clay	0.13	0.10	0.08	0.05	0.03

From group A to D, a tendency for infiltration to weaken and runoff to increase is observed in soils. Hydrological soil groups are distinguished from each other by taking into account the

predominance of a mixture of sand (S), silt (Si), loam (L) and clay (C) in the soil composition. Since the sand-clay composition plays a major role in water filtration, the amount of sand and clay plays the main transitional quantity between soil types. For type A soils, the amount of sand is more than 50%, the amount of clay is 0-10%, in group B, sand is 20-50% and clay is 10-20%, in group C, sand is 40-60%, clay is 20-40%, and in type D, sand is 20-30%, and clay is more than 40-60% [13].

The changes in permeability capacity depending on the granular composition of soils are reflected in Table 1 [22].

The basic methods mentioned above play a leading role in the world in the field of assessment of various components of water balance elements (surface runoff, infiltration, evaporation). Currently, it has become possible to obtain most of the information about the components that affect the water balance elements from satellite space information. On the other hand, there are GIS and other multifunctional software that allow studying the impact of components on water balance elements. For this reason, perfect methodologies are created based on the internal modification of the existing water balance methods themselves and their synthesis. Such methods, in addition to incorporating the advantages of the basic methods, serve to eliminate the shortcomings existing in them and have more advanced features [2, 6, 18, 24, 25].

In our research, we have proposed a new method to calculate the share of baseflow by combining the advantages of hydrological methods that play a leading role in the world. As mentioned, the atmospheric precipitation (P) falling on the basin is spent on surface runoff, baseflow and evapotranspiration over a multi-year period. In the NRCS-CN method, the part of precipitation spent on surface runoff (Q) is found through CN numbers reflecting the existing natural conditions. The remaining part of precipitation (L) that does not turn into surface runoff goes to actual soil moisture (F) and evapotranspiration (E): $L=F+E$. According to the NRCS-CN method, actual soil moisture is expressed as $F=P-Q-Ia$ equation. On the other hand, according to the method, the ratio of the actual soil moisture (F) to the maximum soil water retention (S) is equal to the ratio of hydrological losses to precipitation: $F:S=L:P$.

As can be seen, as the fraction of surface runoff (Q) in precipitation decreases, the share of infiltration and evaporation in the remaining hydrological losses (L) increases. Also, as Q decreases and S increases, the share of evaporation (E) in maximum retention (S) is risen compared to the infiltration (F) indicator.



Fig. 1: River basins of the southern slopes of the Greater Caucasus Mountains

Thus, the F:S ratio expresses the share of infiltration in the maximum water retention conditions of soils. However, the maximum water retention quantity includes all other losses that are not included in the initial abstraction, evaporation and surface runoff. Since the water balance

elements, in turn, are determined by atmospheric precipitation, we have proposed to calculate the baseflow share of rivers as the F:S ratio of the quantity

$$U = (L \times \frac{F}{S}) \quad (5)$$

here, U – is the share of groundwater feeding of rivers (in mm), L – is hydrological losses (mm), F – is the factual soil moisture (mm), S – is the maximum water soil retention (mm).

In order to study the groundwater flow in the river's feeding, the southern slope of the Greater Caucasus Mountains located within the Republic of Azerbaijan was selected as the study area (Fig.1).

Table 2 shows the main water balance elements of the rivers of the southern slopes of the Greater Caucasus.

Table 2: Main water balance elements of the Greater Caucasus rivers: P-precipitation, Q_s-surface runoff, L-hydrological losses, S-maximum retention, Ia-initial abstraction, F-factual soil moisture.

River	P mm	Q _s mm	L mm	S mm	Ia mm	F mm
Mazym	735	222.7	512.3	860.2	172.1	340.2
Balaken	843	236.4	606.6	1056.4	211.3	395.3
Katekh	893	266.8	626.2	1058.5	211.7	414.5
Tala	798	244.3	553.7	925.1	185.0	368.7
Mukhakh	827	262.7	564.3	926.0	185.2	379.1
Qapychay	632	202.5	429.5	701.9	140.4	289.1
Kurmukh	865	331.2	532.8	794.7	158.9	373.9
Kashkachay	641	167.7	473.3	850.9	170.2	303.1
Shin	655	206.5	448.5	738.7	147.8	300.7
Kish	728	225.3	502.7	835.5	167.1	335.6
Dashagil	822	292.6	529.4	821.0	164.2	365.2
Kungut	789	252.9	536.1	876.0	175.2	360.9
Eyrichay	670	158.7	511.3	960.9	192.2	319.1
Alijan	618	63.5	554.5	1421	284.2	270.3
Turyanchay	822	122.4	699.9	1583	316.6	383.3
Goychay	742	118.4	623.6	1375	412.5	211.1
Girdiman	936	187.4	748.6	1511	453.3	295.3
Aksu	648	102.9	545.1	1204	421.4	123.7
Pirsaat	314	66.3	247.7	488.9	171.1	76.6
Jeyrankechmez	238	17.7	220.3	620.1	217.0	3.3
Sumqayit	229	20.7	208.3	554.9	194.2	14.1

The groundwater feeding rates of the Greater Caucasus rivers have previously been estimated by various authors based on observational data and by hydrographs separation. A comparison the actual parameters and values obtained by new formula is given in Table 3.

Table 3: Comparison of the actual and new calculated values of the groundwater nutrition share of the rivers of the southern slope of the Greater Caucasus

Rivers	Underground feeding of the rivers		
	Factual, mm	Calculated with new method, mm	Difference, %
Mazym	183.2	202.6	+9.57
Balaken	198.2	226.9	+12.6
Katekh	261.3	245.2	-6.16
Tala	238.2	220.7	-7.35
Mukhakh	210.4	231.0	+8.92
Kapychay	165.7	176.9	+6.33
Kurmukh	254.1	250.4	-1.46
Kashkachay	143.1	168.6	+15.1
Dashagil	262.4	235.5	-10.3
Eyrichay	181.3	169.8	-6.34
Alijan	98.6	105.4	+6.45
Turyanchay	187.7	169.4	-9.74
Goychay	90.8	95.7	+5.12
Girdiman	129.4	146.3	+11.6
Aksu	60.7	56.0	-7.74
Pirsaat	36.2	38.8	+6.70
Jeyrankechmez	0.81	1.07	+24.3
Sumqayit	19.6	5.29	+3.45

IV. Conclusion

In our study, the baseflow (subsurface flow share) of the rivers of the southern slope of the Greater Caucasus Mountains located in the Republic of Azerbaijan was assessed. The baseflow of the river estimated by the formula we proposed were also compared with the traditional hydrograph separation method, which is the most popular in this field so far. At the same time, they were also compared with the subsurface flow shares measured at several gauged points. The application of the most modern scientific methods and studies conducted in the GIS environment allowed us to obtain very reliable results. It was found that there was a very slight difference between the quantities of the baseflow of the river obtained by the new approach we proposed and the results obtained by the actual and hydrograph separation of the rivers. Thus, in 73 cases this difference did not exceed $\pm 10\%$, and in only 27 cases the error was slightly higher than 10%. These provide grounds for using this method to determine the baseflow of rivers located in any physical-geographical conditions where there is no hydrometeorological data or insufficient observation input.

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

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