Submission date: 1 of July, 2025
Acceptance date: 9 of September, 2025
Publication date: 9 of January 2026

WATER BALANCE ESTIMATION OF RIVER BASINS USING AN INNOVATIVE HYDROLOGICAL TECHNIQUES

ESTIMACIÓN DEL BALANCE HÍDRICO DE CUENCAS HIDROGRÁFICAS MEDIANTE TÉCNICAS HIDROLÓGICAS INNOVADORAS

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Suggested citation (APA, seventh ed.)

Teymurov, M. A., Jabrayilov, E. A., & Mammadov, Z. R. (2026). Water balance estimation of river basins using an innovative hydrological techniques. *Universidad y Sociedad, 18*(1). e5273.

ABSTRACT

The article proposes a novel scientific approach to evaluating the water balance of river basins. The study takes into account the influence of numerous factors affecting water balance, including climatic variables, land cover, and morphometric characteristics of the area. Over the long-term average period, the water balance of river basins is considered as the distribution of atmospheric precipitation into three components: surface runoff, subsurface flow (underground feeding of rivers), and actual evapotranspiration. A comparison between observed data and newly calculated water balance components for more than 70 river basins with diverse physical and geographical conditions shows minimal discrepancies. In 71 cases, the calculation error was within 10%, and in 29 cases, it slightly exceeded this limit. As a case study, the water balance components of the Goychay River Basin for the period 1999–2024 are presented. During this period, out of the total precipitation (587.3 mm), 117.2 mm (19.9%) contributed to surface runoff, 94.9 mm (16.2%) to subsurface flow, and the remaining 375.2 mm (63.9%) to actual evapotranspiration. The proposed approach stands out for its rapid computation mechanism and high accuracy, underscoring its relevance and practical applicability. In addition, the obtained results provide a valuable scientific basis for water resource management, regional planning, and decision-making processes aimed at ensuring sustainable water use under increasing climatic variability.

Keywords: River basin, Water balance, Hydrological methods, Surface runoff, Subsurface flow, Actual evapotranspiration.

RESUMEN

El artículo propone un enfoque científico novedoso para evaluar el balance hídrico de las cuencas hidrográficas. El estudio tiene en cuenta la influencia de numerosos factores que afectan el balance hídrico, incluidos las variables climáticas, la cobertura del suelo y las características morfométricas del territorio. En el período promedio a largo plazo, el balance hídrico de las cuencas se considera como la distribución de la precipitación atmosférica en tres componentes: escorrentía superficial, flujo subsuperficial (alimentación subterránea de los ríos) y evapotranspiración real. Una comparación entre los datos observados y los nuevos valores calculados de los componentes del balance hídrico para más de 70 cuencas con diversas condiciones físicas y geográficas muestra discrepancias mínimas. En 71 casos, el error de cálculo estuvo dentro del 10%, y en 29 casos lo superó ligeramente. Como estudio de caso, se presentan los componentes del balance hídrico de la cuenca del río Goychay para el período 1999–2024. Durante este período, de la precipitación total

(587.3 mm), 117.2 mm (19.9%) contribuyeron a la escorrentía superficial, 94.9 mm (16.2%) al flujo subsuperficial, y los restantes 375.2 mm (63.9%) a la evapotranspiración real. El enfoque propuesto destaca por su mecanismo de cálculo rápido y su alta precisión, lo que subraya su relevancia y aplicabilidad práctica. Además, los resultados obtenidos proporcionan una base científica valiosa para la gestión de los recursos hídricos, la planificación regional y los procesos de toma de decisiones orientados a garantizar un uso sostenible del agua frente a la creciente variabilidad climática.

Palabras clave: Cuenca hidrográfica, Balance hídrico, Métodos hidrológicos, Escorrentía superficial, Flujo subsuperficial, Evapotranspiración real.

INTRODUCTION

A continuous decline in global water resources is currently being observed worldwide. This trend is driven by both natural factors (such as climate and landscape changes) and anthropogenic influences (human activities). In arid regions - such as those encompassing the Republic of Azerbaijan - the impact of global changes is felt more acutely. This is particularly evident in the depletion of vital natural resources, including increased stress on water availability. One of the most crucial measures for mitigating current and anticipated risks is the implementation of hydrological methods that are sensitive and adaptive to any form of environmental change. In this context, priority is given to methods that rely on synergistic approaches and the integration of multiple techniques (Chandramohan& Vijaya, 2017; Han et al., 2024; Mao et al., 2018; Wang, 2012).

In this study, we propose a new hydrological approach based on these principles. The research is conducted through an innovative and synergistic scientific methodology developed by us, which integrates the strengths of leading global hydrological methods while taking into account the specific natural conditions of the study area. The consideration of complex factors affecting the region's water balance and water resources ensures high accuracy in the obtained results. The proposed research method stands out for its applicability, flexibility, interactivity, and predictive capabilities. It can be implemented without physical contact with the area and without constraints of time or location.

Water balance methods are considered one of the most reliable approaches for assessing a region's water resources. Because these methods employ a comprehensive approach, they allow for more in-depth analysis by accounting for the majority of factors that influence river runoff and water resource formation. As a result, the calculation process requires the inclusion of a greater volume of data. In the past, assessments were often conducted using only one or a few of the factors contributing to the water balance. Today, however, scientific and technological advancements, including satellite data and diverse computational technologies, make it possible to collect information on most components and incorporate them into the calculation process.

The term «water balance» refers to the distribution of atmospheric precipitation falling on a given area into various components, such as surface runoff, infiltration, evapotranspiration, soil moisture, initial water losses, and others. Over long-term periods, the water balance of river basins is characterized by the distribution of precipitation among actual evapotranspiration, surface (overland) runoff, and subsurface flow. Rivers are primarily fed by surface runoff during wet periods, while in dry periods they are sustained mainly by subsurface flow (permeability). The portion of precipitation that contributes to both surface and subsurface flow together constitutes the total river runoff (Lvovich, 1969; Sivapalan et al., 2011).

MATERIALS AND METHOD

The Goychay River Basin was selected as the study area (Figure 1). This region, located within the Greater Caucasus zone of the Republic of Azerbaijan, is characterized by diverse physical and geographical features. The basin covers an area of approximately 1,770 km^2 (1,769.3 km^2 as calculated in GIS). The area's hypsometric characteristics (such as elevation, slope, aspect, etc.) were analyzed using a Digital Elevation Model (DEM). To derive morphometric indicators—including river basin delineation, flow direction of the surface, and stream network density - various tools within the ArcGIS software suite, such as Surface, Density, and Hydrology, were utilized.

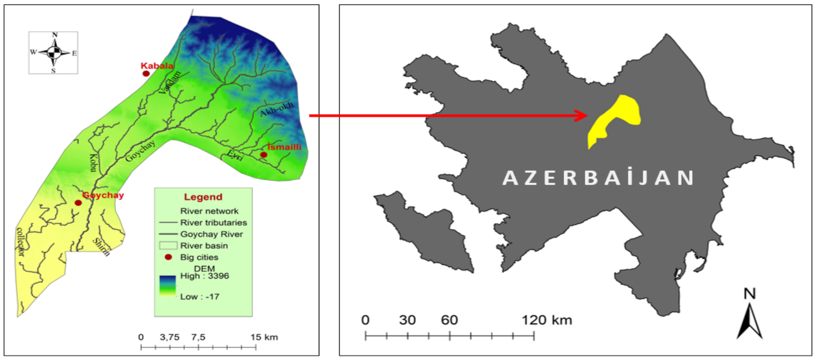

Fig 1. Location and Boundaries of the Goychay River Basin.

Source: Satellite data (DEM) processing by the authors

Hydrometeorological data for the Goychay River Basin were collected from existing measurement stations. Long-term observation records are available for climate data at the Goychay station, and for river discharge at both the Buynuz and Goychay stations. In areas lacking direct observations, climate and runoff data were reconstructed using modern interpolation techniques and spatial analogy methods. Additionally, land surface temperature (LST) indices were used for reconstructing temperature data, while the MODIS (MOD16) dataset was employed to estimate potential evapotranspiration.

In the research process, preference was given to the Ponce-Shetty and Lvovich methods for studying the theoretical foundations of the water balance; the Rational Method for estimating surface runoff; and the SCS-CN (Soil Conservation Service Curve Number) method for determining the infiltration capacity of the area and the soil moisture content (Mishra, 2004; Tailor, 2016; Thompson, 2006).

The NDI (Normalized Difference Index) method is primarily used for collecting and reconstructing factors that can be derived from satellite imagery and other forms of remote sensing data. Given the focus of the study, priority was given to indices related to vegetation (NDVI, SAVI), bare soils (BSI), built-up and residential areas (NDBI), urbanization (UI), water bodies (NDWI), and moisture content (NDMI) (Vani & Mandla, 2017; Zheng et al., 2021).

Over the long-term average period, the water balance of rivers involves the partitioning of precipitation into three main components (1) (Lvovich, 1969; Ivezic et al., 2017; Ponce & Shetty, 1995;):

$$P = Q+U+E \qquad (1)$$

where: P – precipitation, Q – surface runoff, U – infiltration, E – actual evapotranspiration.

In the research process, the estimation of the components of the water balance in the study area was carried out in the following sequence:

1) Climate data were collected from the databases of measurement stations. In data-deficient areas, a combination of traditional and modern methods was employed to reconstruct the missing values.

2) To estimate the surface runoff of rivers, the Rational Method was used as the base approach. Region-specific runoff coefficients were determined based on the influence of local hydrological factors.

3) The contribution of subsurface flow (groundwater recharge) to river runoff was calculated using a formula proposed by the authors, based on the SCS-CN (Soil Conservation Service Curve Number) method.

4) The amount of actual evapotranspiration from the basin surface was determined by subtracting the sum of surface and subsurface runoff from the total precipitation.

Since the water balance reflects how precipitation is distributed across various components, the first step in data-deficient areas is to reconstruct precipitation values. For this purpose, preference was given to methods such as graphical correlations, interpolation, counter-approach, and analogue terrains technologies (Colenbrander, 1980; Guo et al., 2022; Makhmudov et al., 2025).

In classical scientific approaches, interpolation methods typically relied on graphical correlations based on the similarity of one (or occasionally a few) components. However, this often did not allow for the generation of highly accurate results. In contrast, contemporary interpolation methods—carried out through the use of GIS and other multifunctional technologies—enable more precise and comprehensive research across broader spatial domains. The same can be said for the analogy method. While the modern analogue terrain approach adheres to the general theoretical principles of the classical method, it introduces a significantly more advanced and qualitative methodology. «Analogoue terrains» refer to river basins with and without observational data that share similar physical and geographical conditions. The operational mechanism of spatial analogy is based on identifying comparable areas between the study site and gauged basins through a multifactorial analysis. The measurement data from these analogous basins are considered acceptable proxies for the study area (Makhmudov et al., 2025).

The runoff coefficients used in the ***Rational Method*** are parameters that reflect the proportion of precipitation converted into surface runoff (Lapides et al., 2021; Teymurov, 2022). These coefficients are calculated based on a combination of factors such as soil moisture conditions, precipitation, basin elevation and slope, landscape types, vegetation density, soil texture, and infiltration capacity.

The Rational Method is expressed by the following equation (2):

$Q = k \times ciA$ (2)

where: Q – river discharge (m^3/s), i – precipitation amount (mm), A – catchment area (km^2), c – runoff (rational) coefficient, k – conversion factor used to express the result in m^3/s from the original u;'''nits (k=0.0000314) (Bengtson, 2011; Yu et al. 2020).

In the ***NRCS-CN method***, the curve numbers (CN) are not only used to estimate the conversion of precipitation into runoff but are also widely applied to assess infiltration levels and the overall moisture condition of the area. Based on several parameters employed in the NRCS-CN method, we proposed the following formula to estimate the subsurface flow (groundwater contribution) of rivers (Mammadov & Teymurov, 2019), (equation 3):

$\mathbf{Q_u} = (L \times)$ (3)

where: Q_u — subsurface flow component contributing to river discharge (in mm).

L — hydrological losses, representing the portion of precipitation not converted into surface runoff (in mm), and is calculated as the difference between total precipitation (P) and surface runoff (Q_s) (equation 4):

$\mathbf{L = P - Q_s}$ (4)

S — maximum soil retention, reflecting the soil's storage capacity under existing physical-geographical conditions (in mm), and is related to precipitation (P) and surface runoff (Q_s) as follows (equation 5):

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

F — actual soil moisture (in mm), representing the volume of water currently stored in the soil, and is expressed as (equation 6):

$\mathbf{F = P - Q_s - I_a}$ (6)

I_a — initial abstraction (in mm), representing precipitation losses that occur before the onset of surface runoff, including water absorbed during soil wetting, infiltration, evaporation, surface depressions, and interception by vegetation. It is calculated as (equation 7):

$\mathbf{I_a} = \lambda \mathbf{S}$ (7).

where λ – is the abstraction coefficient, which depends on the moisture conditions of the area (Moglen et al., 2022; Zhang, 2019).

RESULTS-DISCUSSION

The Rational and SCS-CN methods are traditionally applied during precipitation events and over localized areas. However, recent scientific advancements now enable their application under various natural conditions without spatial or temporal limitations.

In this study, we have comprehensively considered the influence of most factors contributing to runoff formation, water balance, and changes in water resources. These factors can be grouped into three categories:

1. Surface cover characteristics – This includes landscape types (LULC), soil cover, lithological structure, soil texture, and hydrologic soil groups (HSG). HSG is an indicator that reflects the infiltration capacity of soils. There are four HSG categories, ranked in order of decreasing infiltration capacity as follows: A, B, C, and D.

2. Hypsometric and morphometric components – This category includes parameters such as average elevation, slope, aspect, basin area, river length, horizontal and vertical dissection, rivers network density, and others.

3. Climatic and moisture-related factors – These refer to components that define the region's thermal and moisture regime, such as temperature, precipitation, actual and potential evapotranspiration, humidity index, actual soil moisture, maximum soil water retention, hydrological losses, initial abstraction, and so on.

As an example, Table 1 presents annual runoff coefficients for three slope classes within certain LULC types in areas characterized by moderate humidity levels (R = 0.45–0.85), medium vegetation density (50–75%), and Hydrologic Soil Group B.

Table 1: Variation in Long-Term Total Runoff Coefficients under the Influence of Different Factors.

Soil designation	Hydrologic soil group – B Moisture level, average Slope Gradient, %		
	≤ 6	6 - 15	≥ 15
Forests and gardens	0.13	0.14	0.16
Subalpine and alpine meadows	0.34	0.38	0.43
Forest-meadow mix landscapes	0.24	0.29	0.34
Arid woodlands and shrublands	0.08	0.095	0.125
Subnival and nival regions	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 80-95 %)	0.76	0.79	0.81
Pastures	0.23	0.34	0.45
Semi-deserts and dry steppes	0.055	0.075	0.12
Badlands and bare lands	0.66	0.68	0.70

Source: The data were obtained through the authors' own calculations in GIS using multifunctional technologies.

The application of the new method has proven to be highly effective. For 72 river basins located in various physical-geographical conditions across the Republic of Azerbaijan, the margin of error between actual and newly calculated water balance components was found to be within 10% for 51 rivers, between 10–15% for 12 rivers, and above 15% for only 9 rivers (Makhmudov et al., 2023).

As an example, the following section presents the process of assessing the water resources of the Goychay River Basin using the new method. The study period covers the years 1999–2024. Based on satellite data for the year 2024, several runoff-related factors for the Goychay Basin were mapped using ArcGIS, as shown in Figure 2.

The average elevation of the Goychay River Basin was determined to be 767.9 meters, and the average slope was 24.8%. Smooth surfaces accounted for only 7.9% of the area based on slope aspect distribution. The northern and "north-facing" slopes—where runoff tends to be more active—covered 34.8% of the basin, while southern and "south-facing" slopes accounted for 36.2%. The density of the river network is 0.832 km/km^2 when all valleys are considered, and 0.063 km/km^2 when only valleys longer than 100 meters are taken into account. Based on Hydrologic Soil Groups (HSG), Group A soils occupied 0.65% of the area, Group B – 39.6%, Group C – 29.5%, and Group D – 30.3%. Figure 3 illustrates the key climatic and moisture-related components affecting the water balance of the Goychay Basin, including air and soil moisture conditions.

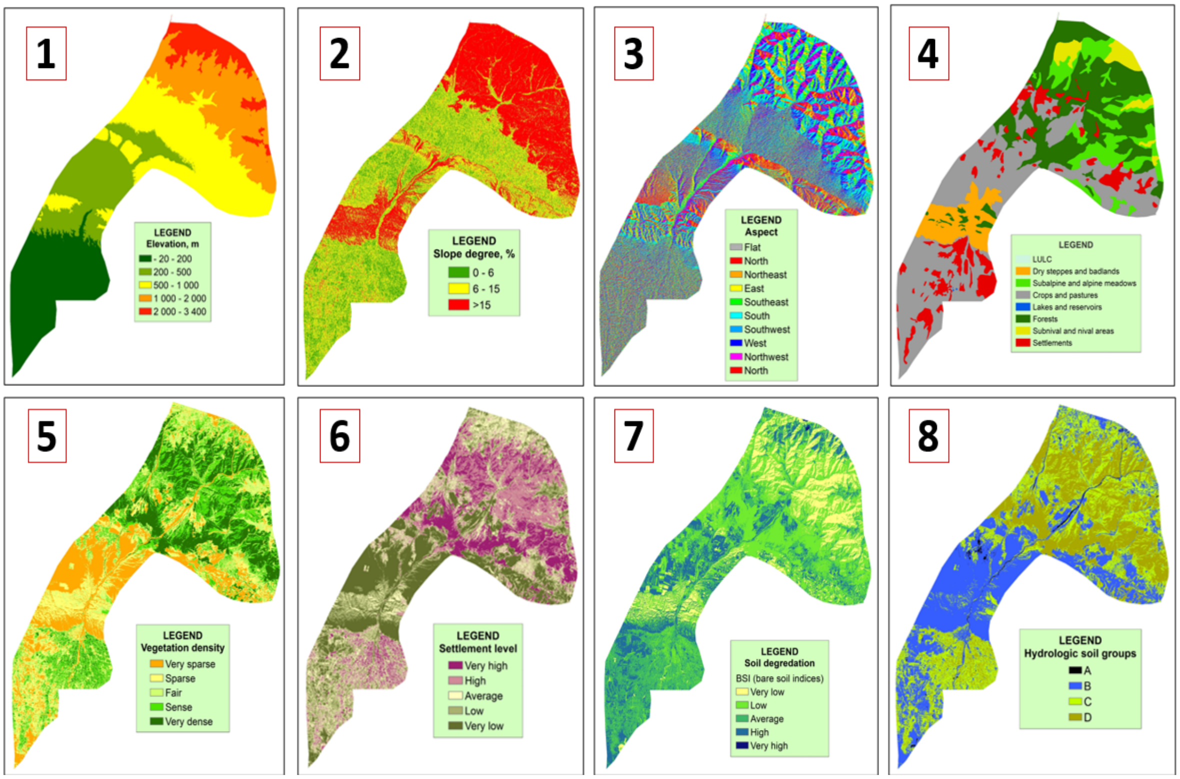

Fig 2. Maps of selected runoff-related factors derived from satellite imagery: 1 – Elevation; 2 – Slope; 3 – Aspect; 4 – LULC (Land Use/Land Cover); 5 – Vegetation Density; 6 – Population Settlement Level; 7 – Soil Degradation; 8 – HSG (Hydrologic Soil Groups)

Souce: Satellite data processing by the authors

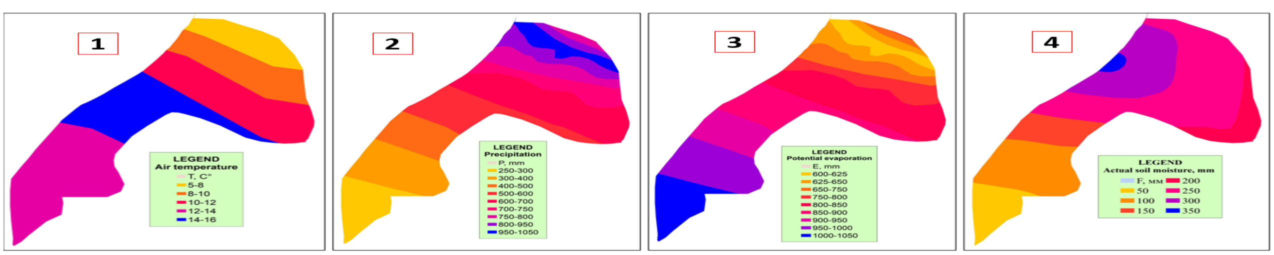

Fig 3. Key climatic and moisture indicators affecting runoff: 1 – Temperature; 2 – Precipitation; 3 – Potential evapotranspiration; 4 – Soil moisture.

Source: Based on data from hydrological stations

For the Goychay Basin, during the period from 1999 to 2024, the average runoff coefficient was c=0.3612, and the average annual precipitation was i=587.3 mm. Using the Rational Method formula, the estimated river discharge (Q) was calculated to be 11.79 m³/s:

$$Q = k \times ciA = 0.0000314 \times 0.3612 \times 587.3 \times 1769.3 = 11.79 \text{ m}^3/\text{sec}.$$

In this study, the variation of the water balance components in the Goychay Basin over the period 1999–2024 was also analyzed (Table 2).

Table 2: Changes in Water Balance Components of the Goychay River Basin during 1999–2024

Components	1999	2024	Difference, %
Precipitation, mm	642.3	587.3	–8.56
Temperature, C°	11.2	12.5	+10.4
Potential evaporation, mm	839.4	879.4	+4.55
Actual evaporation, mm	398.0	375.2	–5.73
Humidity coefficient	0.764	0.667	–12.7
Hydrological losses, mm	511.5	470.1	–9.01
Initial abstraction, mm	237.8	277.6	+14.3
Maximum soil retention, mm	1012.1	952.8	–5.86
Actual soil moisture, mm	224.6	192.5	–14.2
Runoff coefficient	0.3803	0.3612	–5.02
Total river runoff, mm	244.3	212.1	-13.2
Surface runoff, mm	130.8	117.2	–10.4
Subsurface flow, mm	113.5	94.91	–16.4
River discharge, m3/sec	13.57	11.79	–13.12

Source: The data were taken from existing hydrometeorological stations, and for areas without observations, they were reconstructed by the authors using various methods.

During the period 1999–2024, notable changes were observed in the distribution of annual precipitation across the three main components of the water balance (surface runoff, subsurface flow, and actual evapotranspiration) in the Goychay River Basin. In 1999, the distribution of annual precipitation (642.3 mm) among surface runoff, subsurface flow (permeability), and actual evapotranspiration was 20.4%, 17.7%, and 61.9%, respectively. By 2024, the distribution of precipitation (587.3 mm) among these water balance components had shifted to 19.9%, 16.2%, and 63.9%, respectively (Figure 4).

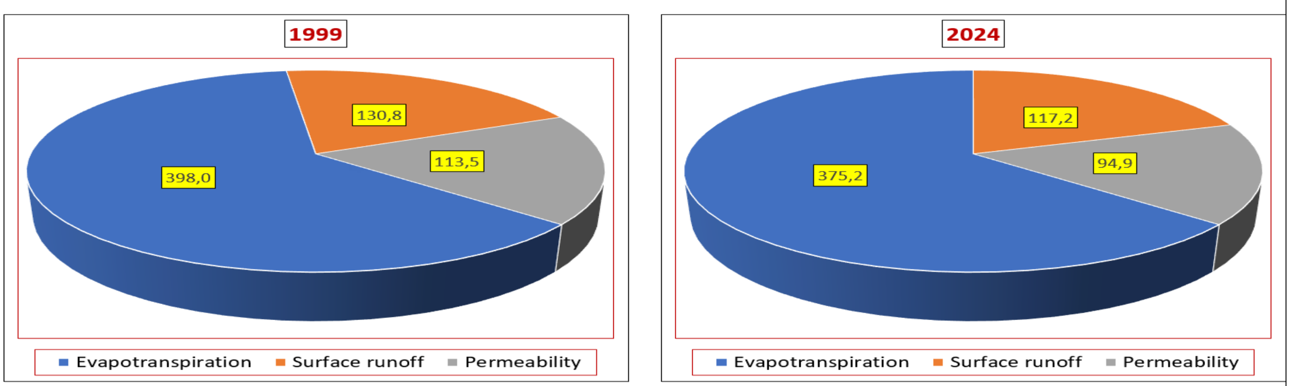

Fig 4. Distribution of precipitation across water balance components in the Goychay river basin for the years 1999 and 2024.

Source: Based on authors' calculations.

The increasing aridity of the climate in the river basin has led to a rise of up to 6% in actual evapotranspiration. The surface and subsurface flow regimes of the Goychay River have also undergone significant changes. Between 1999 and 2024, surface runoff in the river's total flow decreased by 13.6 mm, while subsurface flow declined by 18.6 mm. Consequently, the share of subsurface flow in the total runoff dropped from 46.5% to 44.7%. The main reasons for the increase in surface runoff during the study period were the compaction of the land surface due to increased aridity and the decline in infiltration capacity resulting from vegetation loss.

From a broader perspective, the identified changes in the structure of the water balance of the Goychay River Basin have important implications for water resource management and regional development. The observed increase in actual evapotranspiration and the concurrent reduction in both surface and subsurface runoff indicate growing pressure on available water resources under conditions of increasing climatic aridity. Such trends directly affect agricultural productivity, drinking water supply, and ecosystem stability, particularly in regions where river basins serve as the primary source of freshwater for local communities and economic activities.

The proposed methodological approach offers practical advantages for addressing these challenges, as it allows for rapid, reliable assessment of water balance components across river basins with diverse natural conditions. This makes the method especially valuable for decision-makers, planners, and water management authorities in developing adaptive strategies aimed at sustainable water use, drought mitigation, and long-term planning under climate variability. By integrating hydrological accuracy with operational efficiency, the approach strengthens the link between scientific research and societal needs, supporting evidence-based management of water resources at both basin and regional scales.

CONCLUSION

During the study period (1999–2024), the climatic and moisture conditions in the Goychay River Basin were generally unfavorable for the water balance components. Both atmospheric and soil moisture levels declined significantly, which in turn contributed to the depletion of water resources. Over this period, the amount of precipitation in the basin decreased by 8.56%, the air humidity index by 12.7%, and actual soil moisture by 11.2%. Overall, during the long-term average period up to 2024, 61.9% of the total precipitation (587.3 mm) in the Goychay River Basin was lost to actual evapotranspiration (375.2 mm) without contributing to runoff. The portion of precipitation that contributed to total runoff amounted to only 212.1 mm (38.1%), of which 117.2 mm was surface runoff and 94.91 mm was subsurface flow.

Beyond the quantitative assessment, the results highlight important implications for water resource management and sustainable regional development in arid and semi-arid river basins. In this respect, the proposed hydrological approach represents a practical and efficient tool for assessing water balance dynamics, supporting informed decision-making, adaptive planning, and the development of strategies aimed at mitigating water scarcity under ongoing climatic variability.

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CONFLICTS OF INTEREST:

The authors declare that there are no conflicts of interest.

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