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## **QUANTITATIVE ASSESSMENT OF SURFACE RUNOFF FROM A CATCHMENT AREA BASED ON HYDROLOGICAL AND CLIMATIC CALCULATIONS (TATTA RIVER BASIN (YAKUTIA, RUSSIAN FEDERATION) CASE STUDY)**

**Abstract:** The calculation of surface runoff from a catchment area has always been of great interest, especially in land use planning and management, designing of water supply facilities, and the assessment of the negative consequences of water. The reliability of the runoff characteristics obtained serves as the foundation for the effective utilization of water resources. The relevance of a quantitative assessment of runoff from a catchment area becomes evident in the context of climate change observed over the past several decades. The analysis of the extent of the impact of climate change on runoff, in conjunction with anthropogenic activity within a stream basin, facilitates the formulation of appropriate water management measures aimed at the effective management of water resources. In order to determine the runoff, in conditions of insufficiently studied hydrological territories, various methods and modeling methods are used. The most representative data can be obtained through methods that consider the primary natural factors, specifically thermal and moisture resources. It is the thermal energy resources and humidification resources along with azonal factors that have a direct impact on the processes of runoff formation. Therefore, the present investigation is dedicated to evaluating the impact of thermal energy elements and surface humidification of the catchment area on the conditions of runoff formation. The novelty of this work lies in the implementation of a genetic method for determining the primary runoff-forming characteristics, based on the joint solution of water and heat balance equations. This methodology provides a more precise determination of runoff characteristics in the absence of hydrological measurements. The outcomes obtained can also be utilized to reveal the capabilities of hydro-technical utilities during their reconstruction.

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## Introduction

The territory of the Republic of Sakha (Yakutia) has a large number of surface water bodies, the main ones being rivers. Despite significant reserves of water resources, compared to other subjects of Russia, water supply in the Republic of Sakha (Yakutia) remains at a low level. A particularly difficult situation is observed in providing the population with drinking water.

Due to the sharply continental climate, geographical location in the glacial zone, and intricate orographic conditions, the formation of water resources exhibits a diverse nature (Cunha et al., 2022). The channels of small rivers in dry years turn into a chain of shallow bodies of water with a small water reserve after the flood because of significant variations in runoff. The amount of water in the resulting water bodies does not always correspond to the volume of water consumption of settlements or irrigated areas. In this regard, the provision of regular water to all water consumers can only be achieved through the implementation of artificial flow regulation through the construction of water storage reservoirs. Overflowing rivers in high-water years, combined with intense snowmelt in the catchment area, pose a great danger to adjacent settlements (Gautier et al., 2018). A particularly difficult situation arises in regulated stream of rivers.

The availability of runoff characteristics measured over a sufficiently long period, as well as reliable calculated average annual runoff values and costs with varying degrees of security, are the primary prerequisites for superior water resource management within a basin, uninterrupted water supply to consumers, and safeguarding the territory from the devastating consequences of runoff (Kim et al., 2024; Ismayilova et al., 2023).

Changes in the hydrological regime of runoff have been observed everywhere based on hydrometeorological measurements over the past several decades (Wu et al., 2023). The significant influence on the transformation of runoff characteristics can be attributed to both anthropogenic activity and changes in climatic conditions observed in recent years (Thompson et al, 2013). Under the present circumstances, the availability of representative data enables us to qualitatively evaluate the input of the water balance and select the most efficient option for water supply measures for the population. Additionally, it serves as the foundation for designing hydraulic structures with optimal characteristics, ensuring their durability and economic efficacy for a prolonged period. In this regard, in the territory of Western and Eastern Siberia, information on the water resources of rivers and intermittent streams has always been of the greatest value for practice.

The availability of water, as well as the ecological state of the river basin, especially in the middle and lower parts, where water-regulating hydraulic structures are mainly concentrated, are influenced by the representativeness of runoff characteristics and the precision of calculated runoff values. The negative consequences of non-representative runoff characteristics are aggravated during years with typical water content, leading to significant interruptions in water supply in dry years and to catastrophic consequences in water-rich years (Peng et al., 2024).

Frequent recurrence of water problems is precisely related to the poor study of runoff characteristics. A sparse network of hydrologic sections and water gauges on such a huge

territory with diverse natural and climatic conditions, as well as the lack of reliable methods for calculating runoff characteristics, create significant difficulties in studying the water capacity of the catchment basins of the Republic of Sakha (Yakutia) and zoning them according to hydrological characteristics (Khatatbeh & Kim, 2023).

In such conditions, indirect methods must be used to determine runoff characteristics. One of the most optimal approaches to quantify surface runoff from a catchment area is to employ a methodology based on the joint solution of heat and water balance equations. The method of hydrological and climatic calculations allows for the determination of climatic runoff using standard meteorological data. This method involves calculating runoff both in the average year and in years with different levels of availability, as well as the ability to analyze the intra-annual distribution of water balance characteristics. This is especially important in hydrologically unexplored basins.

## **Field of study**

This study proposes using the genetic method to determine the water balance characteristics of the catchment area, based on the hydrological and climatic calculations of V.S. Mezentsev (1957), which are based on studies of the patterns of interaction between heat and moisture. The Tatta River, located in the southern part of the Republic of Sakha (Yakutia), was chosen as the object of the study.

The river basin has an elongated shape from the southeast to the northwest. It is located between the Lena and Amga rivers. It is a left tributary of the Aldan River. The Tatta River has enormous water management importance: it is the main source of water supply for settlements in the Lena-Amga interfluvium of the Republic of Sakha (Yakutia). In high-water years and during spring snowmelt, the river flow increases sharply, which leads to flooding of settlements. An example is the settlement of Ytyk-Kyuyol, which is subject to flooding depending on the water content of the flood. Due to the lack of hydrological observations, the method of hydrological and climatic calculations will be used to quantitatively assess the flow of the Tatta River at the Ytyk-Kyuyol station.

We will begin by studying the patterns of interaction between heat and moisture. Subsequently, we shall ascertain the constituents of the water balance utilizing data obtained from two meteorological stations, namely Churapcha and Ytyk-Kyuyol, located in the Tatta River basin. As the initial meteorological information, we will use observation data for the period from 1970 to 2023.

The Churapcha meteorological station is located in the upper part of the Tatta River catchment basin. Its coordinates are: latitude 62.03° N, longitude 132.60° EL; altitude - 186 m. The Ytyk-Kyuyol meteorological station's coordinates: latitude 62.37° N, longitude 133.50° EL; altitude - 153 m.

## **Materials and Methods**

Since the results of heat balance studies have provided a solid energy base for water balance hydrology, runoff calculations based on the joint solution of water and heat balances provide an accuracy that is sufficient for many scientific and applied purposes (Tusupbekov et al., 2019).

The utilization of this technique to investigate the patterns of interaction between heat and moisture enables us to refine the calculated runoff characteristics based on the available fields of atmospheric precipitation and thermal energy resources of evaporation, while also considering the orographic, soil-geological, and other characteristics of the catchment's structure. The peculiarity of this method is that the runoff characteristics are not associated with the river discharge, and can be used for poorly studied and unstudied hydrological areas (i.e. the runoff regime is determined mainly by climatic data and geographical characteristics).

In the works of V.S. Mezentsev and I. V. Karnatsevich (1969), G.V. Belonenko (1984), I.V. Karnatsevich (1989), the water balance equation for the surface zone and the zone of weathering for a specific year, without considering deep groundwater, is written as:

$$X + W_1 - W_2 = Z + Y, \quad (1)$$

where  $X$  – depth of precipitation for the calculated time interval, mm;  $W_1$  and  $W_2$  – field moisture at the beginning and end of the calculation interval, mm;  $Z$  – evapotranspiration, mm;  $Y$  – total (surface and underground) runoff layer, mm.

For the average long-term period, with a stable water balance situation, the final equation of the water balance of a land area (river basin) takes the form:

$$H = Z + Y \quad (2)$$

where  $H$  – general moisture.

Given that the energy component of evaporation consists of heat energy resources  $T_z$ , which can theoretically be spent to evaporate the maximum possible amount of water  $Z_m$ , the indicator of evaporation of the territory is the ratio:

$$\beta_z = \frac{LZ}{T_z} \quad (3)$$

where  $L$  – evaporation heat. Thus  $\beta_z$ , the ratio characterizing the share of available thermal energy spent on evaporation can vary depending on the humidification in the range  $0 \leq \beta_z < 1$ , approaching zero in dry desert conditions and approaching one in case of oversaturation. Even with thorough wetting, when the surface is completely covered with water, the inequality  $Z_e < Z_m$ , is always satisfied, where  $Z_e$  is the free-water-surface evaporation, mm;  $Z_m$  is the water equivalent of the heat energy resources of evaporation. That is, under natural conditions, the actual evaporation  $Z$  can never reach its theoretical maximum, since part of the energy is inevitably spent on other natural processes (Mezentsev, 1957).

An indicator of the moisture content of an area over any period of time is the ratio of moisture and heat resource

$$\beta_H = \frac{LH}{T_Z} \quad (4)$$

Soil moisture is an indicator of the humidity of an area (Reynolds, 1970). Changes in soil moisture are mainly associated with climatic conditions (Mallet et al., 2020). The moisture content of soils in the autumn period significantly affects the hydrological processes of the flood period, forming a runoff from the surface of catch basins (Grillakis et al., 2016). At the same time, when determining the runoff in the average long-term interval, taking into account the stability of soil moisture in an average year, we take  $W_1 - W_2 = 0$ , then the annual moisture factor will take the form:

$$\beta_x = \frac{L(X)}{T_Z} = \frac{X}{Z_m} \quad (5)$$

Analyzing the dependence of evaporation on heat and moisture resources in differential form, V.S. Mezentsev (1957) proposed a general form of the equation for the relationship between water and heat balance, where  $n$  is a parameter depending on the physical and geographical conditions of runoff formation.

Taking into account the notations, the equation will take the form:

$$\beta_Z = \frac{T_Z}{L} \left[ 1 + \left( \frac{L(X + W_1 - W_2)}{T_Z} \right)^{-n} \right]^{-1/n} \quad (6)$$

## Results

The equation system of the hydrological-climatic calculation method facilitates the computation of total evaporation, soil moisture, on-site runoff, and soil moisture deficit for studied intervals of an average year and a continuous series of successive intervals of specific years (Rouhier et al., 2017).

Calculations of water balance elements using the constraint equation required generalization and analysis of observed data on atmospheric moistening and consideration of the structural features of the catchment surface, determination of calculation parameters and characteristics of the structural features of the catchment area in parametric form. For a specific year, the evaporation energy resources were determined using an empirical formula based on the average monthly air temperature values.

The initial data on natural moistening pertains to the monthly amounts of measured atmospheric precipitation (Hiyama et al, 2023), to which corrections for wetting and wind undercount (coefficient  $k_2$ ) were implemented. As winter frozen precipitation accumulates in the form of snow cover for a duration of five months, only a small portion, equivalent to the height of the water evaporation layer during the winter period, participates in the evaporation

process. The remaining portion is added into the snowmelt process (Mayr et al., 2013) and precipitated during April – the first warm month. There is no runoff during the winter half-year due to deep freezing of soils in the territory under consideration.

The correction factors for precipitation due to wind undercount were introduced as follows: in dry winters and winters with average winter precipitation, the  $k_2$  corrections of the Yakutia Hydrometeorological Service were applied; and in snowy winters, the  $k_2$  values given in the Climate Data Sheet, were reduced to 1.0 (for the snowiest winter, the correction factor was taken to be equal to 1.0) in inverse accordance with the value of winter precipitation (Mezentsev & Karnatsevich, 1968).

The energy part in the calculations is represented by the water equivalent of the energy resources evaporation  $Z_m$  - the maximum possible evaporation - the layer of water that could evaporate if the heat resources  $T_z$  were spent only on evaporation. The  $Z_m$  values were determined using empirical formulas, where the sums of positive air temperatures appear as an argument (Tusupbekov et al., 2020). Hence, the data preparation commenced with an examination of the average air temperatures for every month of each year. Then, the sum of the average monthly temperatures was calculated for each year and the annual  $Z_m$  value in mm of water layer was determined using the formula.

The results of calculating the water balance elements based on precipitation and temperature data from the Churapcha and Ytyk-Kyuyol meteorological stations are presented in Tables 1 and 2.

*Table 1. Calculation of water balance elements in an average year for Churapcha station.*

Average year	$X$	$Z_m$	$V_1$	$V_2$	$V_{avg}$	$Z$	$Y$	$\beta_H$	$H$	$dH$
Winter	51	42	0,560	0,68	0,63	18	2	0,50	19,99	-20,01
04	15	29	0,68	0,73	0,71	15	2	0,59	17,12	-11,73
05	21	100	0,73	0,56	0,63	44	5	0,50	49,62	-50,20
06	36	150	0,56	0,45	0,50	50	3	0,35	52,46	-97,76
07	38	163	0,45	0,45	0,45	47	2	0,30	49,34	-113,95
08	43	138	0,45	0,46	0,46	41	2	0,31	42,69	-95,64
09	31	85	0,46	0,48	0,47	26	1	0,32	27,43	-57,71
10	25	23	0,48	0,563	0,53	8	1	0,38	8,85	-14,21
Year	263	729	0,56	0,55	0,55	249	19	0,41	267,50	-461

Source: Authors, based on the analysis of meteorological observations

$X$  – atmospheric precipitation layer for the calculated time interval, mm

$Z_m$  – maximum possible evaporation, mm;

$V_1$  – relative soil moisture at the beginning of the calculation interval,

$V_2$  – relative soil moisture at the end of the calculation interval,

$V_{avg}$  – averaged relative soil moisture over a time interval;

$Z$  – total evaporation, mm;

$Y$  – total (surface and underground) runoff layer, mm;

$\beta_H$  – total moisture coefficient, mm;

H – total moisture, mm;  
dH – soil moisture deficit for the calculated time interval, mm.

Table 2. Calculation of water balance elements in an average year for Ytyk-Kyuyol station.

Average year	X	Zm	V <sub>1</sub>	V <sub>2</sub>	Vavg	Z	Y	β <sub>H</sub>	H	dH
Winter	49	40	0,75	0,82	0,79	21	7	0,70	28,13	-11,87
04	13	0	0,82	1,03	0,95	0	0	0,92	0,00	0,00
05	26	62	1,03	0,85	0,92	36	18	0,88	54,45	-7,15
06	33	132	0,85	0,59	0,69	60	16	0,58	76,05	-55,89
07	45	161	0,59	0,50	0,53	54	8	0,39	62,69	-98,00
08	63	120	0,50	0,53	0,52	39	6	0,37	44,72	-75,41
09	40	42	0,53	0,60	0,57	15	3	0,43	18,11	-23,70
10	22	0	0,60	0,75	0,69	0	0	0,57	0,00	0,00
Year	284	556	0,75	0,71	0,71	225	59	0,61	284,15	-272

Source: Authors, based on the analysis of meteorological observations

X – atmospheric precipitation layer for the calculated time interval, mm

Zm – maximum possible evaporation, mm;

V<sub>1</sub> – relative soil moisture at the beginning of the calculation interval,

V<sub>2</sub> – relative soil moisture at the end of the calculation interval,

Vavg – averaged relative soil moisture over a time interval;

Z – total evaporation, mm;

Y – total (surface and underground) runoff layer, mm;

β<sub>H</sub> – total moisture coefficient, mm;

H – total moisture, mm;

dH – soil moisture deficit for the calculated time interval, mm.

Annual precipitation fluctuates from 170 to 380 mm for Churapcha station, and from 192 to 410 mm for Ytyk-Kyuyol station. The annual sum of Zm varies for Churapcha station from 547 to 838 mm, and for Ytyk-Kyuyol station from 511 to 795 mm. In the long-term, the evapotranspiration follows the precipitation. The runoff, which is exclusively formed in spring (April-May) is subject to seasonal fluctuations, ranging from 3 to 51 mm for the Churapcha station and 15 to 100 mm for the Ytyk-Kyuyol station.

Despite the small difference in precipitation in an average year (about 7%), the Churapcha meteorological station is 24% better supplied with heat energy resources than Ytyk-Kyuyol, which affected the value of total evaporation and the runoff layer.

The use of the hydrological and climatic calculation method allowed us to reveal in greater detail the degree of intra-annual change in heat and water balance elements in an average year. According to tables 2 and 3, the greatest heat resources are observed in June, which leads to a decrease in soil moisture and an increase in moisture deficit. The maximum total evaporation occurs in June, when the values of total moisture content reach their greatest values. Despite the significant difference in the annual value of the runoff layer at two meteorological stations located in different parts of the catchment area, the synchronicity of changes in their values with a maximum in May and a minimum at the beginning and end of the warm period is observed in the intra-annual distribution.

Based on the hydrological and climatic calculations (Belonenko & Tusupbekov, 2014), the runoff values from the surface of the catchment area with different levels of probability were determined. The calculation results for the Ytyk-Kyuyol are presented in Table 3.

*Table 3. Values of the runoff layer of different probability in Ytyk-Kyuyol.*

Probability, $P$ , %	Modulus Code, $k$	Runoff depth, $Y_{P\%}$ , mm	Discharge, $Q_{P\%}$ , $m^3/c$
50	0,930	49	11,24
60	0,843	45	10,19
70	0,758	40	9,16
75	0,715	38	8,64
80	0,669	35	8,08
90	0,563	30	6,80
95	0,487	26	5,88
99	0,369	20	4,46

Source: compiled by authors.

The sharply continental climate of the Republic of Sakha (Yakutia) predetermines significant changes in runoff in different years. According to calculations for the Tatta River at the Ytyk-Kyuyol station, the value of the runoff variation coefficient in an average year is 0.6. In such conditions, determining the runoff in low-water and high-water years becomes a priority for water management organizations. The results obtained in Table 3 show the degree of change in runoff in low-water years of varying availability.

## Discussion

Calculations conducted on the basis of the constraint equation of heat and energy and water resources enabled the obtain of runoff values in an average year and in a low-water year with varying estimated probabilities. The runoff regime in calculations using the method of hydrological and climatic calculations is described genetically in connection with the processes of redistribution of atmospheric and soil moisture by the active layer of the earth's surface. One significant advantage of the method is that the equations solely encompass quantities regarding which there exists mass information.

The runoff calculation was based on the data from two meteorological stations located in catchment areas with different runoff formation conditions. One of them, Churapcha station, is located on the left bank of the river with a smooth relief, while the other, Ytyk-Kyuyol station, is located on the steep right bank of the river with high ground levels, where the runoff formation conditions differ from those on the plain. The runoff layer value in an average year at Churapcha station was 19 mm, and at Ytyk-Kyuyol station - 59 mm.

During the process of calculating the maximum flow utilizing heat energy resources and atmospheric moistening data, the maximum flow rate of 1% of the probability was determined, resulting in a value of 155.64  $m^3/s$ .

In order to assess the reliability of the obtained values, an analysis of the results of previously conducted studies was performed. In accordance with the findings of P.F.

Fedorov (2005), an in-depth examination was conducted on the state of the hydroelectric complex cascade on the Tatta River in the Ytyk-Kyuyol settlement section. When designing hydraulic structures, taking the IV hazard class, the discharge capacity of the cross regulators was calculated for a verification flow rate of 1% of probability, and the result was obtained equal to 62.9 m<sup>3</sup>/s. Subsequently, during operation, the insufficiency of the discharge capacity of the hydroelectric complex was revealed when passing the maximum flow rates of the spring flood. Preliminary calculations performed by P.F. Fedorov showed that with the dimensions of the flow section of the cross regulator obtained in accordance with the flow rate of 62.9 m<sup>3</sup>/s, the excess of the theoretical height of the highest water level (HWL) when passing a flood of the estimated probability of 1% will be 2.4 m. It is not difficult to infer that in this particular scenario, the structure will not stand.

In 2010, V.S. Malgin conducted calculations to determine the maximum flow rate of the Lebyagene River, the primary tributary of the Tatta River, which joins from the right bank above the settlement of Ytyk-Kyuyol. After conducting calculations based on the highest historical levels, it was determined that the maximum flow rate was 107.83 m<sup>3</sup>/s. This value confirms the error made in the calculations of the hydraulic performance of the Tatta River cross regulators at the settlement of Ytyk-Kyuyol.

## **Conclusion**

Hence, the methodology employs hydrological and climatic calculations of water balance elements to ascertain the value of runoff by incorporating the interaction between heat and moisture. Furthermore, it clarifies the calculated runoff characteristics based on the available fields of precipitation and thermal energy resources of evaporation, taking into account the orographic, soil-geological, and other characteristics of the catchment basin's structure.

The obtained data demonstrates that the amount of runoff is contingent upon the conditions of its formation and cannot be determined for the entire catchment area.

The peculiarity of this method is that the runoff characteristics are not tied to the river discharge, and can be used for poorly studied and unstudied hydrological areas (i.e. the runoff regime is determined mainly by climatic data and geographical characteristics).

Since the results of heat balance studies have provided a solid energy base for water balance hydrology, runoff calculations based on the joint solution of water and heat balances provide an accuracy that is sufficient for many scientific and applied purposes.

An important area of application of this method is the forecast of changes in river water content under conditions of changes in long-term climatic characteristics. Modeling of runoff formation conditions taking into account different climatic scenarios is a priority area for water management organizations both in terms of water supply and protection of territories and national economic facilities from water disasters.

Despite the fact that the territories are better equipped with meteorological information compared to hydrological information, the network of meteorological stations and posts is currently underdeveloped. There exists no single meteorological point within

the catchment area of numerous small basins. The use of meteorological elements of adjacent territories can affect the quality of the results obtained. However, meteorological observations are much simpler and require less expense than hydrological ones.

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