

SURFACE AND GROUND WATERS IN TERRESTRIAL PERMAFROST REGION

DOI: 10.21782/EC2541-9994-2020-1(37-48)

**MODELLING OF RUNOFF FORMATION PROCESSES
AT SMALL MOUNTAIN WATERSHEDS IN THE PERMAFROST ZONE
(BY THE DATA OF THE KOLYMA WATER BALANCE STATION)****O.M. Makarieva^{1,2}, L.S. Lebedeva¹, T.A. Vinogradova²**¹ *Melnikov Permafrost Institute, SB RAS, 36, Merzlotnaya str., Yakutsk, 677010, Russia; omakarieva@gmail.com*² *St. Petersburg State University, Institute of Earth Sciences, 7-9, Universitetskaya nab., St. Petersburg, 199034, Russia*

Based on analysis of the observation data on the active layer characteristics, the distribution of the snow cover, the streamflow and the evaporation processes in the small watersheds of the Kolyma water-balance station, five main types of landscapes representative of the mountainous areas of the North-East of Russia were identified: rocky talus at surface watersheds; mountain tundra and Siberian dwarf pine brushwood at south-facing slopes; mossy and lichenous sparse forests at north-facing slopes; larch forest in the river valleys; larch forest in the river talik zone. For each type of the landscape, the vegetation-soil cover was developed, and the parameters of the Hydrograph deterministic hydrological model were estimated. Modelling of the water balance elements and of the runoff hydrographs was carried out for the Kontaktovy Creek basin (Nizhny gauge, area 21.3 km²) and three microwatersheds representing the main types of landscapes (the Morozova, Severny and Yuzhny Creeks). Calculations were carried out with the daily time interval for the period of 1951–1997. Based on comparison with the observational data, the simulation results were assessed as satisfactory. The novelty of the research consists in the proposed approach of a priori estimation of the hydrological model without using calibration methods. Such an approach is promising for assessing future changes in runoff formation processes and the evolution of frozen ground under conditions of climate change.

The Kolyma water-balance station, Hydrograph hydrological model, runoff, permafrost zone, active layer, landscape, water balance

INTRODUCTION

Climate changes and degradation of permafrost lead to transformation of the hydrological cycle, including changes in the water content of the soils [Quinton *et al.*, 2011], intensification of interflow between ground and surface waters [Walvoord, Kurylyk, 2016], seasonal redistribution of the water balance components [Tananaev *et al.*, 2016; Glotov, Glotova, 2018; Makarieva *et al.*, 2019c]. The quantitative assessments of the impact of changes in the active layer (AL) of the frozen ground on formation of runoff in the future remain undetermined. This is related to the non-linear character of the interactions between the climate and permafrost landscapes [Fedorov, Konstantinov, 2009; Bring *et al.*, 2016]. Due to the limited character of the field observations over the characteristics of heat and water exchange among the landscapes on the vast territories of the permafrost zone, mathematical modeling is one of the methods of investigating the mechanisms of interactions between frozen ground and the processes of runoff formation and prediction of their changes in the future [Makarieva *et al.*, 2018a]. However, it is necessary to develop not only those models which would take into account the conditions of AL changes and the pro-

cesses of runoff formation on different landscapes but also the methods of a priori (instead of calibration) assessment of the parameters of such models [Pomeroy *et al.*, 2007].

The objective of the study was to apply and verify the method of sequential estimation of the parameters of the deterministic hydrological model “Hydrograph” [Vinogradov, Vinogradova, 2010] for the conditions of mountain watersheds of north-eastern Russia, considering the changes in the characteristics of the active layer, differences in the landscapes and the processes of runoff formation on the basis of the observation data from the Kolyma water-balance station (KWBS). First a single soil column is considered as the object of modeling, then sequential transfer of the model parameters on an elementary watershed consisting of elementary slopes is carried out, then on a small watershed, medium-sized and large basins. At each stage, the results of the modeling are verified with the observation data. Such an approach provides more grounds for using the modeling method and verified sets of parameters of the developed model when making calculations for the ungauged watersheds, as well as under conditions of climate changes.

This study has been conducted in continuation of the works by [Lebedeva et al., 2015; Vinogradov et al., 2015], in which estimation of the parameters of the Hydrograph hydrological model is performed and its applicability to calculating the changes in the active layer thickness is shown for the profile of soils at different landscapes within the KWBS.

OBJECTS OF THE STUDY

The Kolyma water-balance station is the first in the world stationary hydrological station in the zone of continuous permafrost. The station was established in 1948 and was closed down at the end of 1997. The KWBS occupied the territory of the mountain watershed of the Kontaktovy Creek with the area of 21.3 km² in the upper part of the Kolyma River basin (the Magadan region). The combination of the landscapes covered by the KWBS is representative for the conditions of the mountain permafrost zone of the north-east of Russia [Nasybulin, 1976]. This enabled us to use series of data of combined hydrometeorological and special observations of 30–50 years in order to develop and verify models of natural processes taking place on vast territories, which are hydrologi-

cally poorly studied. In this work, materials of the combined and published database of the KWBS were used [Makarieva et al., 2017, 2018b]. Detailed analysis was made of the hydrometeorological conditions of runoff formation on the territory of the KWBS, conducted using the series of observations of maximum completeness, contained in [Lebedeva et al., 2017; Makarieva et al., 2018b]; therefore, only brief information on the physical and geographical characteristics of the station are provided here.

The absolute altitudes of the territory of the KWBS vary from 823 to 1690 m. The major types of landscapes are the rocky talus, mountain tundra and Siberian dwarf pine brushwood, as well as sparse larch wood and larch wood bogged in the creek valleys (Figs. 1, 2). The mean annual air temperature at the Nizhnaya weather station (a.s.l. 850 m) for the observation period of 1949–1997 is -11.3°C , and the mean annual precipitation is 342 mm.

As modeling objects, three microwatersheds of the Yuzhny, Severny and Morozova Creeks were chosen, representing typical landscapes of the KWBS, as well as the entire territory of the station, encompassing the Kontaktovy Creek at the Nizhny gauge.

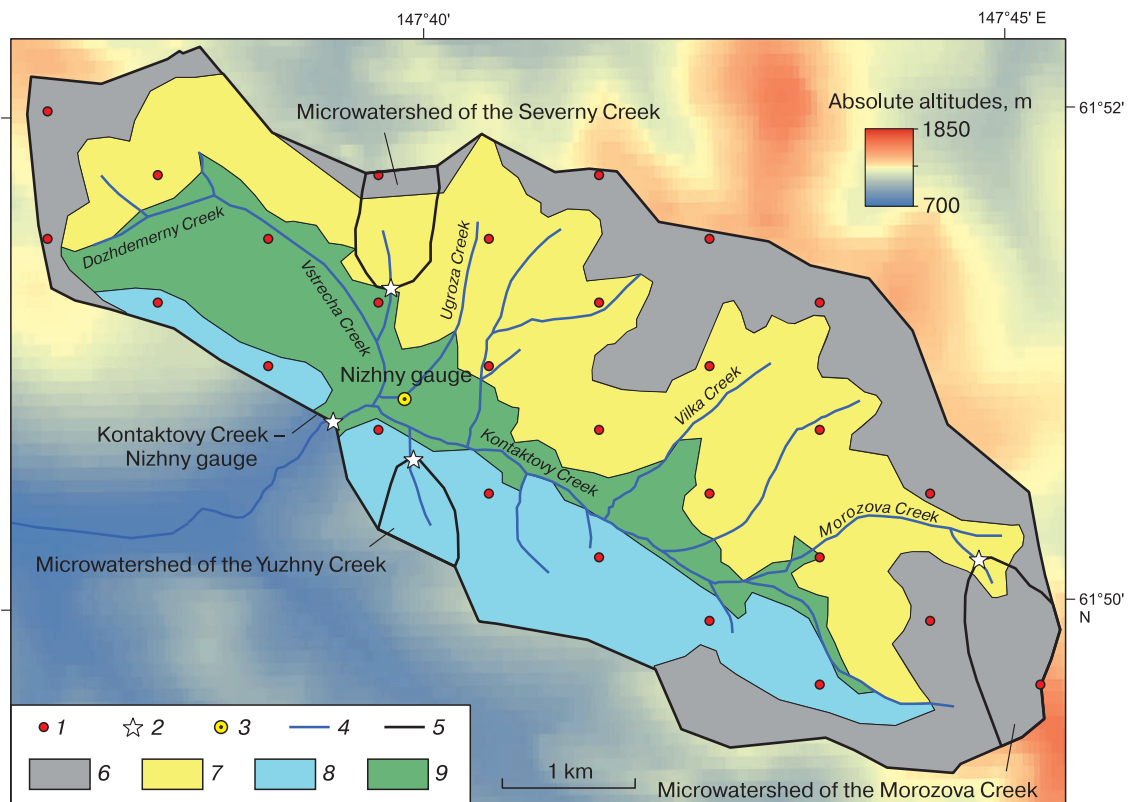


Fig. 1. The scheme of the Kolyma water balance station.

1 – representative points (RP); 2 – hydrological gauges; 3 – meteorological station; 4 – the river channel network; 5 – watershed boundaries; 6–9 – runoff-formation complexes (RFC): 6 – rocky talus, 7 – mountain tundra, Siberian dwarf pine brushwood on the southern slopes, 8 – sparse larch forest on the northern slopes, 9 – larch forest in river valleys, including the zone of suprapermafrost taliks.

The Morozova Creek is the right tributary of the Kontaktovy Creek. The watershed with the area of 0.63 km² is fully covered by blocks and clastic rocks (Fig. 1, 2, *a*). the altitude range is 1200–1690 m, and the maximum sloping reaches 50°. The mean annual runoff depth for the period of 1969–1997 amounts to 453 mm, and the annual runoff coefficient (*R*), calculated as the ratio of runoff and precipitation, reaches 95 %.

The Severny Creek is the left tributary of the Vstrecha Creek, which runs into the Kontaktovy Creek. The watershed with the area of 0.33 km² is covered almost exclusively by the Siberian dwarf pine brushwood of the medium and high degrees of crown density (Fig. 1, 2, *b*). The soil cover is irregular. Most of the slopes (70 %) have the southern aspect, and 30 % have the south-eastern and south-western aspects. The mean inclination is 21°, its maximum value reaches 40°. The maximum and minimum watershed altitude marks are 1300 and 880 m.

The Yuzhny Creek is the left tributary of the Kontaktovy Creek. The watershed with the area of 0.27 km² is covered by sparse larch wood with sparse bush, alder wood, and Siberian dwarf pine brushwood, which becomes denser along the talweg (Fig. 1, 2, *c*). The solid soil cover is represented by sphagnum mosses with participation of lichens

[Boyarintsev *et al.*, 2006]. The maximum and minimum altitude points of the Yuzhny Creek watershed are 1110 and 917 m. The valley slopes primarily face north-east and north-west. The average slope is 17°.

The water balance of the watersheds of the Severny and Yuzhny Creeks differs significantly from the Morozova Creek. The mean annual values of the annual runoff depth were found to be only 227 mm (*R* = 56 %) and 193 mm (*R* = 51 %) for the Severny and Yuzhny Creeks for the periods of 1958–1997 and 1960–1997, respectively.

The variety of the combinations of the characteristics of landscapes, microclimate and soil-and-vegetation cover determines the behavior of the AL characteristics (depth, water-ice content, temperature) and the runoff formation processes. For example, in the wet larch forest in creek valleys during snow melting, when soils are frozen, surface runoff is formed, and in the summer season, when frozen soil thaws, significant runoff losses occur due to wetting of the moss and lichen cover and transpiration, and subsurface runoff is formed. The thaw depth in the bogged depressions is 20–50 cm. In the rocky talus zone, the soil profile consists of debris of clay shale of different sizes and is characterized by low values of maximum water-retaining capacity and of the ice content. Due to deposition of rock, such grounds re-

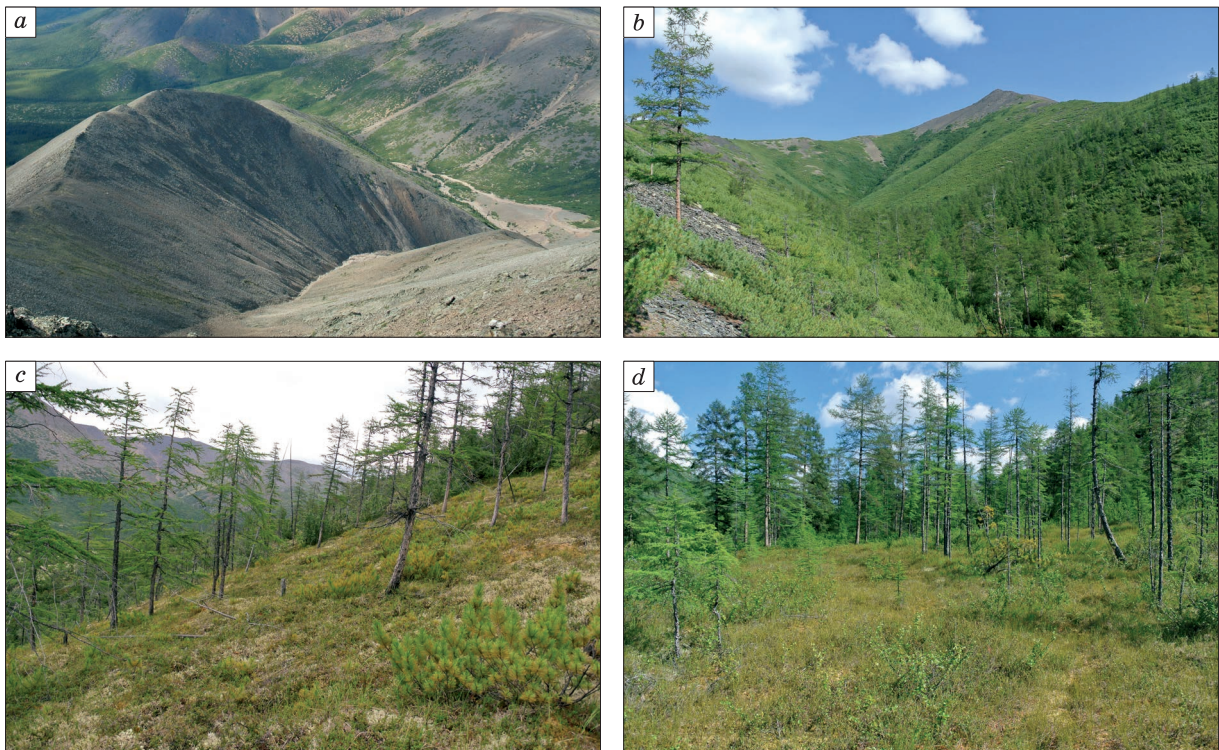


Fig. 2. The landscapes of the Kolyma water balance station:

a – rocky talus, Morozova Creek; *b* – mountain tundra, Siberian dwarf pine brushwood, Severny Creek; *c* – mossy and lichenous sparse larch forests, Yuzhny Creek; *d* – larch forests, the valley of the Kontaktovy Creek. The photo by O.M. Makarieva, August 2016.

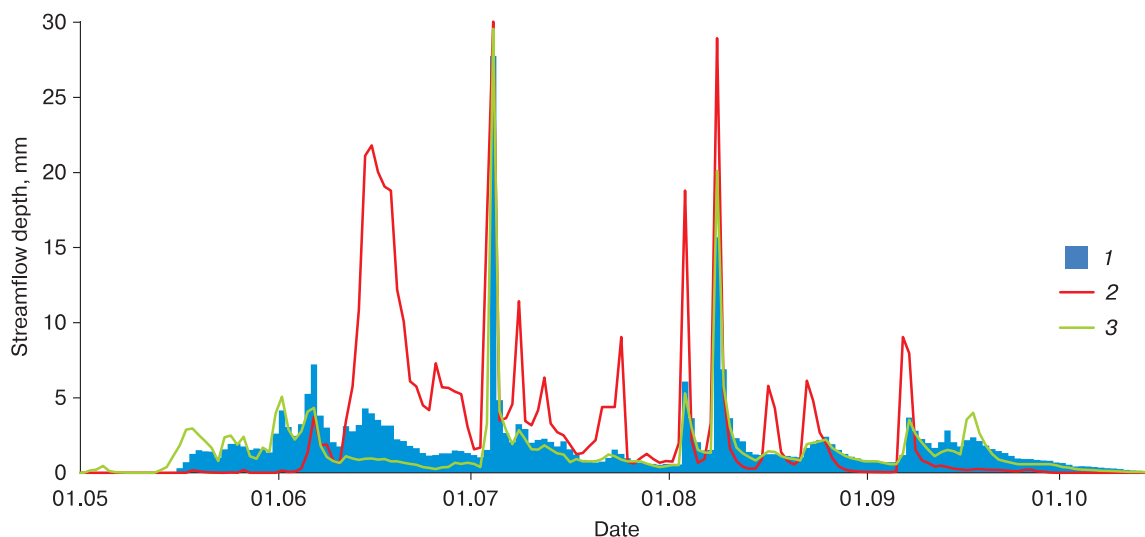


Fig. 3. Streamflow hydrographs of the creeks of the Kolyma water balance station, 1970.

1 – Kontaktovy Creek – Nizhny gauge; 2 – Morozova Creek; 3 – Severny Creek.

main highly penetrable even at negative temperatures. Thawed water or rainwater quickly penetrates the ground as far as the permafrost aquiclude and runs off along frozen subsurface ways. The depth of the active layer on the southern rocky slopes reaches 3 m by the end of the summer [Makarieva et al., 2017, 2018b].

Essential differences between hydrological regimes of the runoffs (Fig. 3) on the territory of the Kontaktovy Creek watershed necessitate the use of hydrological models able to take into account the impact of the behavior of the AL characteristics on the hydrological processes through landscape and soil-and-vegetation parameters.

THE HYDROGRAPH DETERMINISTIC MODEL OF RUNOFF FORMATION

The Hydrograph distributed deterministic hydrological model of runoff formation combines physics-based and conceptual approaches for description of the processes of the surface phase of the hydrological cycle, which allows keeping of the balance between complexity of calculations and the possibility of using limited incoming meteorological information (air temperature and water content, precipitation) [Vinogradov, Vinogradova, 2010].

In the Hydrograph model, the method of calculating the heat dynamics in the upper layer of soils was used, which allows the system of differential equations of thermal conductivity in the soil profile to be reduced to the system of linear and algebraic equations without significant loss in the calculation accuracy. In addition, methods of calculating thermal conductivity coefficients and heat exchange in the soil layers and snow cover, which are in different vari-

able states, were proposed in the model [Vinogradov et al., 2015]. The efficiency of the proposed method for the KWBS conditions is confirmed by the results of modeling the soil temperature [Vinogradov et al., 2015] and the thawing and freezing depths in different landscapes [Lebedeva et al., 2015].

As the calculation grid points, a regular hexagonal grid of representative points (RP) is used, which are the calculation elements of a unit of area, representative for a territory of a regular hexagon, in the center of which there is a RP (Fig. 1). For each RP, the following characteristics are determined: the latitude, altitude, inclination and slope aspect, the lag time from an RP to a gauging section of the river network, as well as the type of runoff formation complexes (RFC). In the system of the Hydrograph model, each RP characterizes an elementary slope, and their set is a representative sample from the entire set of elementary slopes within the modeled watershed.

RFC are the prevailing types of landscapes, characterized by conditionally homogeneous processes of runoff formation. Watershed division on RFC is conducted on the basis of descriptions and maps of landscapes, soil and vegetation cover and the AL characteristics. Unlike the RP, RFC are distributed unequally on a watershed (Fig. 1).

Meteorological input data and climatic parameters. The meteorological input data (day or hour temperatures, air moisture content and precipitation values) are interpolated in RP from the meteorological stations and precipitation observation points, and, given mountainous conditions, taking into account their altitudinal gradient.

The processes of heat exchange between the land and the atmosphere predetermine many specific de-

tails of the surface part of a hydrological cycle. However, for the vast territories of the north-east of Russia, the information required for solving the heat balance equation is inaccessible in most cases. In the Hydrograph model, as a characteristic of the energetic impact on the Earth's surface by the Sun and the atmosphere, effective air temperature is used:

$$\eta_{\text{ef}} = \eta + jS.$$

Here η is the mean daily air temperature, °C; S is the incoming solar radiation [J/m^2] with corrections for climatic parameters (albedo, orographic shadowiness, cloudiness and the other local conditions); j is the empirical coefficient, $\text{m}^2 \cdot \text{C}/\text{J}$. The value of S is calculated for each calculation interval depending on the characteristics of RP, with the necessary adjustments made [Vinogradov, Vinogradova, 2010].

The model parameters describing an RFC are divided into three groups: the parameters of the vegetation cover, those of the soil profile (calculated soil layers – CSL) and those of the slope surface.

For each RFC type, a vertical profile of the vegetation cover and of the upper layer of soil is developed, as well as a respective set of model parameters [Semenova et al., 2013; Lebedeva et al., 2015; Nesterova et al., 2018].

Parameters of the vegetation cover. Here belong seasonal shadowiness of the soil surface by vegetation, albedo, the layer of liquid precipitation interception by the vegetation cover, and evaporation coefficients. For each of these parameters, two values are estimated, corresponding to the minimum and maximum levels of the vegetation cover growth. The vegetation growth rate is approximated by a phenological trapezium, for which four phenological dates are set, determining the moments of the beginning of the vegetation cover growth, reaching its maximum, the beginning and the end of the period of withering [Vinogradov, Vinogradova, 2010].

The parameters of the vegetation cover include: the evaporation coefficient of RFC (k , $\text{m}/(\text{GPa}\cdot\text{s})$), which determines the depth of evaporation from soils (E , m), according to the formula

$$E = h_0 \left(1 - \exp \left[- \frac{k \Delta t d}{h_m \cos \alpha} \right] \right),$$

where d is the air moisture deficit, GPa ; Δt is the calculated period of time, s ; α – the inclination angle of the area, degrees; h_m, h_0 – the maximum water-keeping capacity of soils and the initial amount of water in them, m .

Parameters of the soil profile. The soil profile of each RFC is divided into CSL. The CSL depth may be various, but it is usually taken to be equal to 10 cm, and the total depth of the calculated soil profile should exceed the maximum AL depth, if the model is applied to the permafrost zone.

The main physical parameters of the model describing the characteristics of the CSL are the following: density, porosity, maximum water-retaining capacity (MWC) filtration coefficient under conditions of achieving the MWC, specific heat capacity and heat conductivity of the dry substance. Detailed information about the soil parameters for RFC within KWBS is provided in [Lebedeva et al., 2015].

The conceptual parameters include the parameter of the impact of ice content (n) on the filtration coefficient. The filtration coefficient of frozen soil is calculated as

$$f^* = f(1 - V)^n,$$

where f is the filtration coefficient of thawed soil, mm/min ; V – the volume of soil pores filled with ice, dimensionless; n – parameter of the impact of the ice content on the filtration coefficient. Parameter n was determined on the basis of recommendations [Vinogradov, Vinogradova, 2010] and numerical experiments. In rocky talus, the ice content does not practically influence the filtration rate, and parameter n is taken to be equal to 1; for peat horizons of the soil profile, $n = 5$, for the other types of soils composing the vertical profile of the soil layers, $n = 2$.

This set of parameters allows us to describe the heat dynamics and the vertical movement of water in the cross section of a soil column.

Parameters of the slope. Spatial heterogeneity of distribution of the snow cover on the watershed territory is described statistically: in each RP, 3 or 5 additional calculated quantile points are set, which differ only by the amount of the snow supply. They correspond to the centers of equal segments on the probability scale of the normal distribution law: 0.1, 0.3, 0.5, 0.7, 0.9. Redistribution of snow, which occurs mainly already after a snowfall, is simulated simultaneously with its fall: when interpolating solid precipitation in an RP, their values are distributed by quantile points.

Parameters of runoff elements. To describe water movement within a RFC, the concept of runoff elements is used [Vinogradov, Vinogradova, 2010]. In accordance with this concept, the watershed of a river consists of runoff elements of different levels – surface, soil and underground elements. Runoff elements are natural formations, segments of surface and underground elementary slopes and watersheds directed by their open part to the slope non-river channel or underground drainage network. Runoff elements of different types are characterized by parameters of the flow intensity (Q , m^3/s) depending on the quantity of water contained in them (W , m^3) and the time of outflow (T , s):

$$Q = \beta \left[\exp(\alpha W) - 1 \right], \quad T = \frac{1}{\alpha \beta},$$

where α [m^{-1}] and β [m/s] are the hydraulic parameters.

The hydraulic parameters of the flow of runoff elements of a CSL are determined by the method of manual selection using the observed streamflow hydrographs at small watersheds and based on the general concepts of the processes involved. For example, the time of outflow of surface runoff elements, as well as of runoff elements in the upper horizon of soils formed by moss on steep slopes of watersheds is described by minutes and hours and proceeds faster than in an icy peat layer of bogged depressions in the creek valleys.

The streamflow hydrograph formed on the area of the RP, is the sum of hydrographs of the runoff elements of different types. The runoff hydrographs of all the RPs are translated into the closing gauge of the watershed considering the lag time.

EVALUATION OF THE PARAMETERS OF THE HYDROGRAPH MODEL FOR THE KWBS CONDITIONS

Based on the results of joint analysis of the dynamic of the active layer on the KWBS landscapes, represented by the microwatersheds of the Morozova, Severny and Yuzhny Creeks [Lebedeva et al., 2015] and the conditions of runoff formation and the water balance of the KWBS creeks [Lebedeva et al., 2017], the watershed of the Kontaktovy Creek was divided into five RFC: 1) rocky talus at surface watersheds, 2) mountain tundra and Siberian dwarf pine brushwood at south-facing slopes, 3) mossy and lichenous sparse forests at north-facing slopes, 4) larch forest in river valleys, 5) larch forest in the river talik zone (Fig. 1, Table 1). It is to be noted that previously the use of the landscape-hydrological approach to the basin of the Upper Kolyma River was presented in [Korolev, 1984]. As a basis for identifying the RFC,

we used the vegetation cover map developed by Yu.B. Korolev [1984].

The indicated RFCs differ significantly by the active layer regime and the dominant hydrological processes. For each indicated RFC, schemes of the soil profiles were elaborated, and the parameters of the Hydrograph hydrological model, describing the soil and vegetation cover [Lebedeva et al., 2015], were evaluated. The accepted depth of the soil profile for all the RFC was 3 m. We divided the calculated soil profile into 30 CSL 10 cm deep, for each of which we determined the values of the soil parameters.

The presence or absence of a talik in the RFC was set in modeling by the parameters of the lower boundary condition to calculate the heat dynamic in soils. In RFC 1–4 (without a talik), the mean annual course of the monthly ground temperature at the depth of 3.2 m at the Nizhny weather station was taken as the lower boundary condition. In the period of observations of 1974–1980, the mean annual temperature of the ground at the Nizhny weather station was -3.5°C , and its average monthly values rose to -1.2°C in October and dropped to -6.7°C in April. In RFC 5 (with a talik), the positive temperature of the ground below the seasonal freezing layer ($+2^{\circ}\text{C}$) was set as the boundary condition, on condition that the talik contained fresh water.

In [Lebedeva et al., 2015], the results of using the Hydrograph model in calculating the thawing-freezing depths are shown for seven characteristic areas within the limits of the KWBS, where the depths of the active layer were measured. Deviations between the mean annual maximum measured and calculated thawing depths varied in the range from -0.04 to 0.13 m (i.e., not more than 12 % of the recorded val-

Table 1. Runoff-forming complexes and their hydrological role

No.	RFC, vegetation type	Soil and ground type	Specific features of runoff formation, maximum thawing depth
1	Rock talus, stone glider in watersheds, without vegetation	Fragments of clay slate of different sizes	The process of fast and deep thawing (up to 3 m), free filtration of thawed and rain water to the frozen as far as the permafrost aquiclude. Formation of internal soil ice in snow melting and its further melting in the warm period of the year [Bantsekina, 2003]. During snow melting and rainfall, fast suprapermafrost runoff is formed
2	Mountain tundra, dwarf Siberian pinewood on southern slopes, fragmentary moss and lichen cover	Fragments of clay slate of different sizes	Maximum thawing depth (up to 1.5 m) is less compared to clastic rocks. During snow melting and rainfall, suprapermafrost runoff is formed
3	Mossy-lichenous sparse larch forest on northern slopes	Fragmentary material of clay slate under peated horizon	During snow melting, both surface and suprapermafrost runoff is formed in the frozen ground (along preferred filtration channels). The thawing depth is 0.6 m and less
4	Wet larch forest in river valleys	Fragmentary material of clay slate under peated horizon	During snow melting and severe rainfall surface, runoff is formed. In other time, the groundwater level is observed to be close to the ground surface. The thawing depth is 0.5 m and less
5	Wet larch forest in river valleys in the zone of suprapermafrost taliks	Fragmentary material of clay slate; suprapermafrost talik 5–9 m thick [Glotova, Glotov, 2012; Mikhailov, 2013]	Seasonal freezing of the ground in the winter period. Underground runoff proceeds during the greater part of the year

Table 2. **Hydraulic parameters α (m^{-1}) and β (m/s) of the ground surface and soil runoff elements for small watersheds and the corresponding RFC**

RFC number	Ground surface			Soil			Underground cavities		
	α	β	T	α	β	T	α	β	T
1, 2	1000	10^{-6}	~17 min	100	$2.5 \cdot 10^{-5}$	~8 h	–	–	–
3, 4	100	10^{-6}	~3 h	10	10^{-6}	~1 day	–	–	–
5	100	10^{-6}	~3 h	10	10^{-6}	~1 day	1	10^{-6}	~12 days

Note. T – the characteristic time of discharge for ground surface and soil runoff elements.

ues). The mean absolute deviation of the daily values of the thawing depth for the same objects did not exceed 0.16 m. Thus, agreement between the calculated and observed values may be considered satisfactory. This allows us to assume that the developed scheme of the soil profiles and the set of the model parameters describing their properties may be used to calculate the behavior of the characteristics of the active layer for different conditions of the KWBS.

In modeling streamflow formation, the microwatersheds of the Morozova, Severny and Yuzhny Creeks were assumed to be conditionally homogeneous and were referred to one of the indicated RFC. Such an approach seems to be sensible, as the territory of each of them has the dominant type of the landscape and is characterized by the pronounced runoff regime [Boyarintsev, 1988]. Thus, the watershed of the Morozova Creeks was referred to RFC 1 (rocky talus), the Severny Creek – RFC 2 (mountain tundra and the Siberian dwarf pine brushwood), the Yuzhny Creek – RFC 3 (sparse mossy and lichenous larch forest). The watershed of the Kontaktovy Creek is a combination of all the five RFCs.

The parameters of the Hydrograph model describing the properties of the soil-and-vegetation cover, evaluated in [Lebedeva et al., 2015] at the stage of modeling the heat dynamic in the soil and adjusted in accordance with the reference book [Agrohydrological properties..., 1974], remained unchanged as the runoff formation was calculated. Additionally in modeling the runoff formation, the parameters were estimated, responsible for the spatial heterogeneity of the snow cover, formation of the surface, soil and underground runoff and evaporation.

Based on the summarized data of the snow measurements on different landscapes of the KWBS [Makariev et al., 2018b], the variation coefficient of the snow water equivalent in the snow cover was taken to be 0.85 for the rock talus zone, 0.70 for the mountain tundra and Siberian dwarf pine brushwood, 0.50 for sparse larch forest and 0.40 for larch forest. In general, these values are close to the evaluations made by S.E. McCartney [McCartney et al., 2006] for the watershed Granger Creek and J.B. Pomeroy [Pomeroy et al., 2004] for the basin Wolf Creek in the mountainous conditions of the upper reaches of the Yukon River (Canada).

Parameters of evaporation were estimated on the basis of the KWBS data in different landscapes: the observations made with GGI-500-30 evaporators [Lebedeva et al., 2017], as well as with the experimental instruments designed by E.L. Boyarintsev [Sushchansky, 2002]. The values of the evaporation coefficients (k , $10^8 \text{ m}/(\text{GPa}\cdot\text{s})$) for the areas in the rocky talus zone were 0.09, for Siberian dwarf pine brushwood – 0.11, for the sparse moss-lichenous forest and for the larch forest – 0.22 and 0.25 in the period of maximum development of the vegetation cover, respectively. The adopted values agree with the data provided by E.L. Boyarintsev et al. [2006] testifying that evaporation from the talus accounts for about 30 % of the amount of evaporation from the peaty and loamy soils.

Hydraulic parameters (α , β) and the characteristic discharge time (T) of surface and soil runoff elements, adjusted for all the five RFCs, are shown in Table 2. For RFC 5, one underground aquifer was introduced (Table 2).

The daily values of the air temperature and moisture content, as well as of the amount of precipitation recorded at the Nizhnaya weather station (Fig. 1), considering their altitudinal gradients at interpolation into RP, were used as meteorological input data.

The standard value of the empirical coefficient $j = 0.08$ in the formula of calculating the effective air temperature [Vinogradov et al., 2011] was taken for the watershed of the Severny Creek and all the RP situated on the southern slopes of the KWBS. For the Yuzhny and Morozova Creeks and for the slopes of the northern aspect of the Kontaktovy Creek $j = 0.04$.

THE RESULTS OF MODELING RUNOFF FORMATION PROCESSES

The complex program of the Hydrograph distributed hydrological model [Certificate of state registration..., 2018] was used for the calculations.

Continuous modeling of the river runoff with the calculated daily interval was carried out for the microwatersheds of the Severny and Yuzhny Creeks for the period of 1960–1997, for those of the Morozova Creeks – 1969–1996 and in the basin of the Kontaktovy Creek – Nizhny gauge for the period of 1951–1997. Table 3 presents the calculated and observed

Table 3. Calculated and observed values of the annual water balance and the mean and median Nash–Sutcliffe coefficient value for the KWBS watersheds

Parameter	Yuzhny (1960–1997)	Severny (1959–1997)	Morozova (1969–1996)	Kontaktovy – Nizhny (1951–1997)
Calculated runoff layer, mm	218	250	454	302
Observed runoff layer, mm	195	259	448	280
Calculated cprecipitation layer, mm	356	401	523	420
Calculated evaporation layer, mm	143	153	69	121
Evaporation layer estimate, by observations*, mm	132	120	73	114
Nash–Sutcliffe model efficiency coefficient	0.28/0.38	0.50/0.62	0.52/0.52	0.66/0.69

* According to [Lebedeva et al., 2017].

values of the water balance elements and of the Nash–Sutcliffe model efficiency coefficient (NS) [Nash, Sutcliffe, 1970].

Morozova, Severny and Yuzhny Creeks

Figs. 4, A and B are the examples of the diagrams of observed and calculated daily values reflecting the variable states and streamflow hydrographs of the Yuzhny Creek in 1972 and of the Morozova Creek in 1980, respectively.

Before the beginning of soil thawing in the sparse larch forest (Yuzhny Creek), the runoff prevails, which is formed on the ground surface and in the upper layer of the soil cover. Further, during the summer season, the surface runoff is observed only in intense rainfall. The major amount of water coming to the soil surface penetrates the ground to form supra-permafrost soil runoff. In the given RFC, soil thaws only to the depth of 0.6 m during four warm months

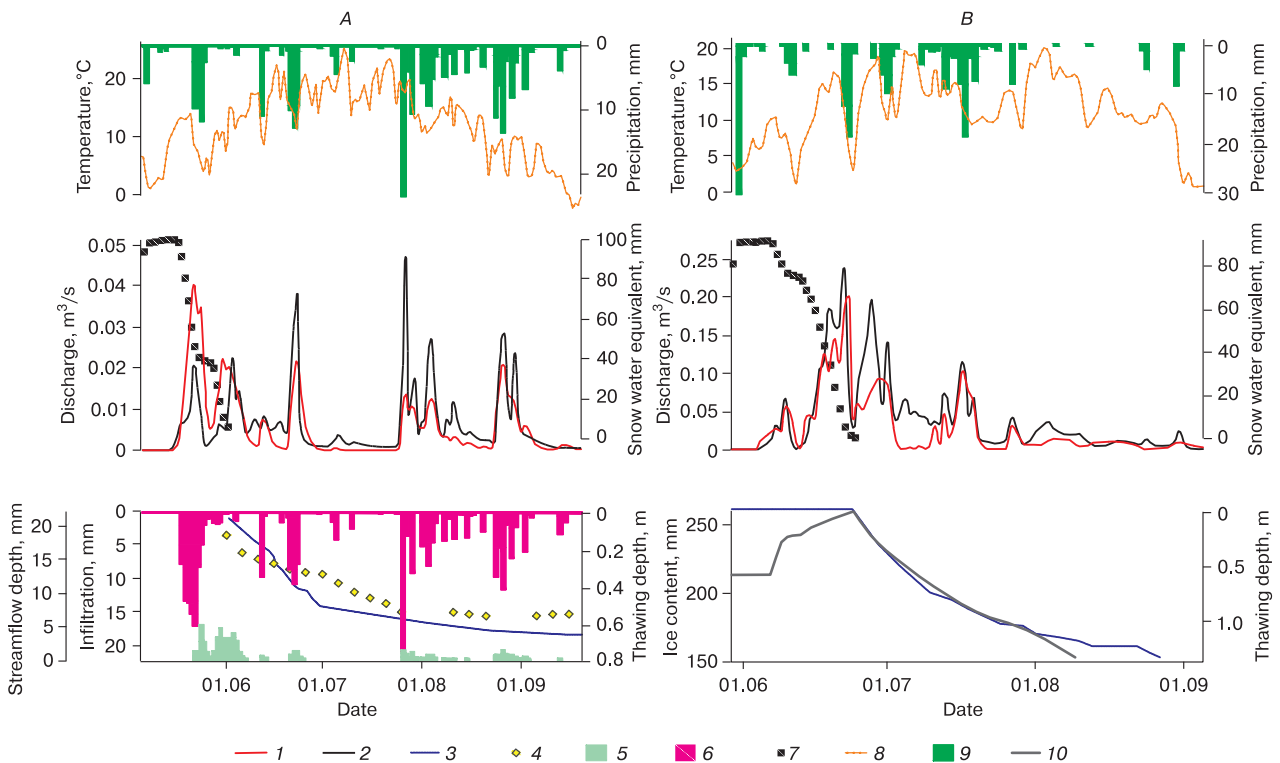


Fig. 4. Combined graphs of the calculated and observed variable states of the water and thermal regimes in the sparse larch forest (A – Yuzhny Creek, 1972) and in the rocky talus zone (B – Morozova Creek, 1980) [Makarieva et al., 2017, 2018b]:

1 – the calculated streamflow hydrograph, m^3/s ; 2 – the observed streamflow hydrograph, m^3/s ; 3 – the calculated thawing depth, m; 4 – the observed thawing depth, m; 5 – the calculated depth of the surface runoff, mm; 6 – the calculated depth of water which infiltrated into the ground, mm; 7 – snow water equivalent, mm; 8 – the calculated effective air temperature (considering the incoming direct solar radiation), $^{\circ}\text{C}$; 9 – liquid precipitation reaching the soil surface, mm; 10 – the calculated ice content of the upper two-meter soil column, mm.

(June–September), and the AL is waterlogged for the major part of the time.

In the talus (Morozova Creek), thawed water freely penetrates the ground and gets partly frozen on rocks, forming the talus ice. The growth of the ice content in the upper 2 meters of the ground as the snow melts is considered in modeling (Fig. 4, B). According to the results of field observations made by T.V. Bantsekina [2003], in 1997–2001, a layer from 40 to 60 mm of ice was formed every spring in the AL of the talus; according to the modeling results for the period of 1969–1997, a layer from 21 to 48 mm is formed. Ice melts during the entire warm season; therefore, in the dry periods dependence of the runoff on the air temperature can be seen.

The calculated and observed mean annual streamflow depth over the period considered was 454 and 448 mm in the talus and 218 and 195 mm in the sparse larch forest.

Shown in Fig. 5 are the examples of comparing the calculated and observed runoff hydrographs for the watershed of the Severny Creek (RFC 2) for three selected years with good, satisfactory and unsatisfactory quality of calculation. The calculated and observed values of the mean annual streamflow depth for the Severny Creek for the entire period of time were 250 and 259 mm.

The mean and median values of the NS model efficiency coefficient are 0.50/0.62 and 0.52/0.52 for the Severny and Morozova Creeks, and for the Yuzhny Creek, these values are much lower – 0.28/0.38. In the same way, the residual (closure error) of the mean annual streamflow depth is the fol-

lowing: +(1–3) % for the Morozova and Severny Creeks, +12 % for the Yuzhny Creek.

The calculated values of the mean annual evaporation are higher by 6, 8 and 28 % in the Yuzhny, Morozova and Severny Creeks compared to the observation data [Lebedeva et al., 2017]. However, considering significant uncertainty of the evaporation estimates according to the evaporator data noted in [Gusev, Nasonova, 2004], the obtained modeling results may be considered acceptable.

The greatest differences between the calculated and measured streamflow values for all the microwatersheds occur in the periods of spring floods, when the calculated streamflow usually exceeds the measured streamflow. We can suggest that in the Severny and Morozova Creeks, this occurs due to undervaluation of the parameters of the model simulating the water filtration process and frozen soils. For the watershed of the Yuzhny Creek, more correct evaluation of the moisture behavior in the mossy cover and in the upper organic layer of soil and of its impact on runoff formation is required.

L.P. Glotova and V.E. Glotov [2012] note that in the KWBS creeks, the first portions of water do not enter the river channel network during snow melting but fill up dry alluvial deposits, which sets back (by several days, up to a week) the beginning of the spring flood. Small mountain streams may, even at the beginning of the warm season, have not a fast-flowing runoff along the surface of the frozen ground but subsurface cavities which ensure less intense but more prolonged discharge. Hence, melted water may continue to come to the river channel also after the end

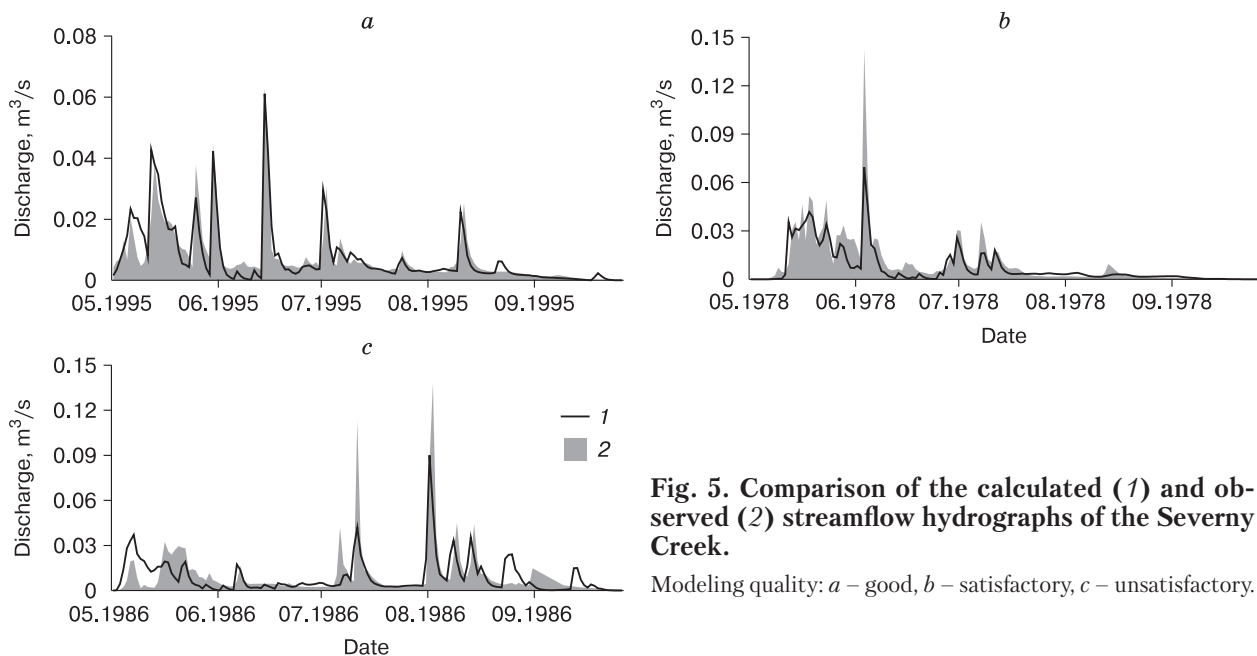


Fig. 5. Comparison of the calculated (1) and observed (2) streamflow hydrographs of the Severny Creek.

Modeling quality: a – good, b – satisfactory, c – unsatisfactory.

of the spring flood. During the remaining warm period, alluvial deposits are in a state of water saturation [Mikhaylov, 2013], which is likely to influence formation of maximum water outflows during rain floods, which are not always satisfactorily reproduced by the hydrological model. These processes were not considered in modeling.

In general, the calculated runoff of the Morozova and Severny Creeks demonstrates good convergence with the observation data, and the Hydrograph model satisfactorily describes the water and thermal regime of the talus and of the mountain tundra. The calculated runoff characteristics of the Yuzhny Creek have worse coincidence with the observed values, indicating the necessity of further development of the algorithms of the Hydrograph model for describing the processes of runoff formation in the waterlogged landscapes of KWBS.

Kontaktovy Creek

For the purpose of modeling, the entire watershed of the Kontaktovy Creek (Nizhny gauge, the area 21.3 km²) was assumed to consist of 28 representative points, each of which referring to one type of the RFC (the talus accounted for 32 % of the entire watershed area, tundra with Siberian dwarf pine brushwood – 29 %, sparse larch forests – 21 % and wet larch forest – 18 %). For each RFC, sets of parameters were used, previously obtained in modeling microwatersheds. One calculation point, referred by the soil and vegetation parameters to larch forest, was “devoid of permafrost” and simulated the zone of suprapermafrost taliks by setting initial conditions on the soil temperature at the depth of 4 m.

Shown in Fig. 6 are the examples of comparing the observed and calculated streamflow hydrographs of the Kontaktovy Creek for a period of three years with good, satisfactory and unsatisfactory quality of calculation. The calculated and observed streamflow depth for the period of 1951–1997 was 302 and 280 mm, and their residual was 7 %. The mean and median values of the NS criterion for the daily water outflows are equal to 0.66 and 0.69. In accordance with the modeling results, AL waters are the main source of water supply for the Kontaktovy Creek. The amount of the underground runoff (due to taliks) was evaluated on average to be 1.3 mm (<1 %). The surface runoff according to modeling was 9 mm (3 %).

Fig. 7 demonstrates a comparison of the curves of exceedance probability for the calculated and observed maximum outflows of water. One may note certain underestimation in the calculated maximum outflows of water within the probability range of 5–60 %. It is related not only to the necessity of inclusion into the hydrological model of certain processes taking place in the watersheds considered above but also to insufficient regard for the irregularity of rainfall in the territory of the KWBS and of its daily intensity.

Despite the revealed imperfections, the calculations made confirm the principal possibility of using the method of sequential estimation of parameters in conditionally similar landscapes, its application in the “soil column – microwatershed – small watershed” framework. In [Vinogradov *et al.*, 2011; Lebedeva, 2018; Makarieva *et al.*, 2019a,b], the same approach was used for the basins of larger rivers and rivers having more complex structure.

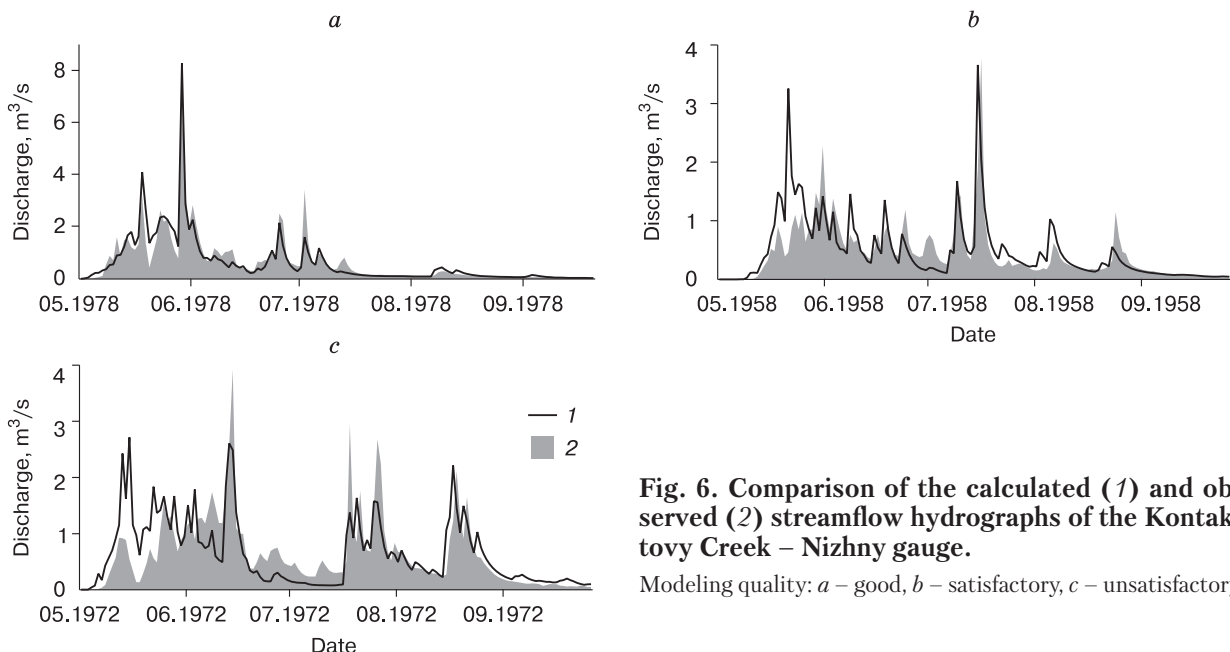


Fig. 6. Comparison of the calculated (1) and observed (2) streamflow hydrographs of the Kontaktovy Creek – Nizhny gauge.

Modeling quality: *a* – good, *b* – satisfactory, *c* – unsatisfactory.

In [Gusev, Nasonova, 2004; Gusev et al., 2006], the results of modeling the variable runoff states and of the processes of runoff formations at the KWBS objects on the basis of the physical and mathematical model of heat and water exchange between soil and the atmosphere of SWAP (Soil Water – Atmosphere – Plants) are presented. In general, the quality of modeling the soil temperature, the thawing and freezing depths and the streamflow hydrographs at the KWBS on the basis of the SWAP and Hydrograph models is comparable. However, the parameterization methods, namely, automatic calibration of the parameters of the SWAP model on the basis of observation data [Gusev, Nasonova, 2004; Gusev et al., 2006], differ dramatically from the approaches we used. In this study, the authors develop the concepts of Yu.B. Vinogradov and T.A. Vinogradova [2010] and follow the *a priori* evaluation of the parameters of the hydrological models. Under conditions of climate changes and reduction of the weather observation network, the methods of the *a priori* evaluation of parameters are largely preferable [Makarieva et al., 2018a].

CONCLUSION

Based on analysis of the active layer regime and of the conditions of runoff formation at the microwatersheds of the KWBS, five types of runoff formation complexes have been identified, which are representative for the mountainous territories of the north-east of Russia: rocky talus; mountain tundra and Siberian dwarf pine brushwood; mossy and lichenous sparse larch forest; larch forest; larch forest under conditions of a suprapermafrost talik.

For each type of a RFC, the schemes of the soil and vegetation cover have been developed. Based on the field study data without using calibration methods, the parameters of the Hydrograph hydrological model have been determined and a database of their values has been compiled.

Modeling of water balance elements and of streamflow hydrographs for the watershed of the Kontaktovy Creek (Nizhny gauge) and three microwatersheds (Morozova, Severny and Yuzhny Creeks), presenting individual types of the RFC has been conducted. The calculation was carried out with the daily time interval for the continuous period of 1951–1997. Comparison of the calculated values and of the observation data has allowed us to evaluate the results of computer simulation as satisfactory.

The novelty of the study consists in implementation of the approach of *a priori* parametrization of a hydrological model, allowing the use of uniform sets of parameters in different scales from a single soil column to whole watersheds. Such an approach is perspective for analysis of the future changes in the processes of runoff formation and of the evolution of fro-

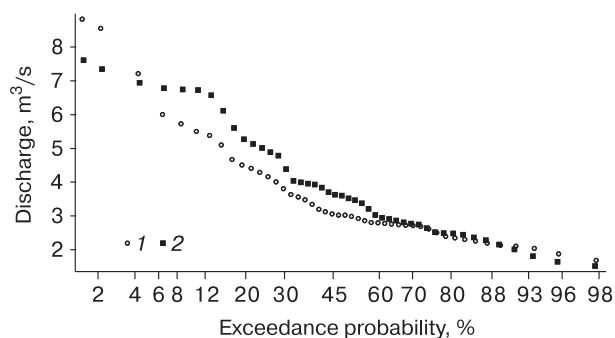


Fig. 7. Curves of exceedance probability for the calculated (1) and observed (2) maximum discharge in the Kontaktovy Creek – Nizhny gauge, 1951–1997.

zen soils under conditions of climate change. The results of the study conducted also confirm the extreme necessity of reviving and developing the network of monitoring stations in small watersheds in the permafrost zone of Russia.

The authors are thankful to reviewer V.M. Mikhailov and to the editors of the journal N.V. Arutyunyan and V.E. Tumskoy for their comments and recommendations.

The study was carried out with the support of the St. Petersburg State University (project # 38376534).

References

- Agrohydrological properties of the soil. Catalog, 1974. Chukotka National District and Magadan Region. Magadan, 74 pp. (in Russian).
- Bantsekina, T.V., 2003. Peculiarities of hydrothermal regime of seasonal thawing layer in coarsely clastic rocks during the spring-summer period (with an example of Upper Kolyma highland). PhD Thesis. Yakutsk, 20 pp. (in Russian).
- Boyarintsev, E.L., 1988. Azonal factors of rainfall runoff formation in the territory of Kolyma WBS. In: Proceedings DVNIGMI, Far-East Institute of Hydrometeorology, Vladivostok, vol. 135, pp. 67–93 (in Russian).
- Boyarintsev, E.L., Serbov, N.G., Popova N.I., 2006. Formation of the spring high-water balance in small catchments of the Upper Kolyma River mountainous areas (by the Kolyma water-balance station records). Bulletin SVNC DVO RAN, No. 4, 12–19.
- Bring, A., Fedorova, I., Dibike, Y., et al., 2016. Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. J. Geophys. Research: Biogeosciences 121 (3), 621–649.
- Certificate of state registration of computer program No. 2018619084 “Comprehensive program of the distributed hydrological model “Hydrograph”. Right holder Makarieva O.M.; the date of registration 30.07.2018 (in Russian).
- Fedorov, A.N., Konstantinov, P.Y., 2009. Response of permafrost landscapes of Central Yakutia to current changes of climate and anthropogenic impacts. Geography and Natural Resources, No. 2, 146–150.

- Glotov, V.E., Glotova, L.P., 2018. Peculiarities of modern changes of the total and underground runoff in North-East Russia. *Bulletin of the North-East Science Center*, No. 1, 39–48.
- Glotova, L.P., Glotov, V.E., 2012. The role of underground waters in total streamflow of small mountain rivers in the Kolyma River basin. *Bulletin of the Samara Science Center of Russian Academy of Sciences* 14, No. 1 (9), 2321–2324.
- Gusev, E.M., Nasonova, O.N., 2004. Simulation of heat and water exchange at the land–atmosphere interface on a local scale for permafrost territories. *Eurasia Soil Science*, No. 9, 1077–1092.
- Gusev, E.M., Nasonova, O.N., Dzhozhan, L.Ya., 2006. The simulation of runoff from small catchments in the permafrost zone by the SWAP model. *Water Resources* 33 (2), 115–126.
- Korolev, Yu.B., 1984. Mapping of vegetation in connection with assessment of its hydrological role (by the example of the Upper Kolyma region). PhD Thesis. Magadan, 231 pp. (in Russian).
- Lebedeva, L.S., 2018. Runoff formation in the permafrost zone of Eastern Siberia. PhD Thesis. Yakutsk, 24 pp. (in Russian).
- Lebedeva, L.S., Semenova, O.M., Vinogradova, T.A., 2015. Hydrological modeling: Seasonal thaw depths in different landscapes of the Kolyma water balance station (Part 2). *Earth's Cryosphere* XIX (2), 32–39.
- Lebedeva, L.S., Makarieva, O.M., Vinogradova, T.A., 2017. Peculiarities of water balance formation in mountain catchments of Northeastern Russia (a case study for the Kolyma water balance station). *Meteorology and Hydrology*, No. 4, 90–101.
- Makarieva, O., Nesterova, N., Lebedeva, L., Sushansky, S., 2017. Water-balance and hydrology database for a mountainous permafrost watershed in the up-streams of the Kolyma River, Russia – the Kolyma Water-Balance Station, 1948–1997. 3PANGAEA, <https://doi.org/10.1594/PANGAEA.881731>.
- Makarieva, O.M., Nesterova, N.V., Beldiman, I.N., Lebedeva, L.S., 2018a. Actual problems of hydrological assessments in the Arctic zone of Russian Federation and adjacent permafrost territories. *Arctic and Antarctic Research* 64 (1), 101–118.
- Makarieva, O., Nesterova, N., Lebedeva, L., Sushansky, S., 2018b. Water balance and hydrology research in a mountainous permafrost watershed in upland streams of the Kolyma River, Russia: a database from the Kolyma Water-Balance Station, 1948–1997. *Earth Syst. Sci. Data* 10, 689–710.
- Makarieva, O.M., Nesterova, N.V., Lebedeva, L.S., Vinogradova, T.A., 2019a. Modelling runoff formation processes in the high mountain permafrost zone of Eastern Siberia (a case study of Suntar-Khayata range). *Geography and Natural Resources*, No. 1, 178–186.
- Makarieva, O.M., Nesterova, N.V., Yamolsky, G.P., et al., 2019b. Assessment of maximum instant discharge of various frequency at ungauged mountainous river Khemchik (Tuva Republic) based on mathematical modeling. *Engineering Survey* 2 (13), 36–51.
- Makarieva, O., Nesterova, N., Post, D.A., et al., 2019c. Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost. *The Cryosphere* 13, 1635–1659.
- McCartney, S.E., Carey, S.K., Pomeroy, J.W., 2006. Intra-basin variability of snowmelt water balance calculations in a subarctic catchment. *Hydrol. Processes* 20 (4), 1001–1016.
- Mikhaylov, V.M., 2013. Floodplain taliks of the North-East of Russia. Geo Publishing House, Novosibirsk, 176 pp. (in Russian).
- Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I – A discussion of principles. *J. Hydrology* 10 (3), 282–290.
- Nasybulin, P.S., 1976. The representativity of runoff characteristics at the Kolyma water-balance station for the upper Kolyma area. In: *Natural resources of the USSR North-East*. Vladivostok, AN DVIS IBPS, pp. 32–41 (in Russian).
- Nesterova, N.V., Makarieva, O.M., Vinogradova, T.A., Lebedeva, L.S., 2018. Modelling runoff formation processes at the BAM zone based on the data of the Mogot research site. *Water Sector of Russia: problems, technologies, management*, vol. 1, pp. 18–36.
- Pomeroy, J.W., Essery, R.H., Toth, B., 2004. Implications of spatial distributions of snow mass and melt rate for snow-cover depletion: observations in a subarctic mountain catchment. *Ann. Glaciol.*, No. 38, 195–201.
- Pomeroy, J., Gray, D., Brown, T., et al., 2007. The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence. *Hydrol. Processes* 21, 2650–2667.
- Quinton, W.L., Hayashi, M., Chasmer, L.E., 2011. Permafrost-thaw-induced land-cover change in the Canadian subarctic: Implications for water resources. *Hydrol. Processes* 25 (1), 152–158.
- Semenova, O., Lebedeva, L., Vinogradov, Yu., 2013. Simulation of subsurface heat and water dynamics, and runoff generation in mountainous permafrost conditions, in the Upper Kolyma River basin, Russia. *Hydrogeol. J.* 21 (1), 107–119.
- Sushchansky, S.I., 2002. History of creation, methods, objects and some results of studies in the Kolyma water balance station. In: V. Glotov, N. Ukhov (Eds.). *Factors affecting the formation of a general drainage system of minor mountain rivers in sub-arctic areas*. Magadan, SVKNII DVO RAN, pp. 18–35 (in Russian).
- Tananaev, N.I., Makarieva, O.M., Lebedeva, L.S., 2016. Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. *Geophys. Res. Lett.* 43, 10,764–10,772.
- Vinogradov, Yu.B., Semenova, O.M., Vinogradova, T.A., 2011. An approach to the scaling problem in hydrological modelling: the deterministic modelling hydrological system. *Hydrol. Processes* 25, 1055–1073.
- Vinogradov, Yu.B., Semenova, O.M., Vinogradova, T.A., 2015. Hydrological modelling: heat dynamics in a soil profile (Part 1). *Earth's Cryosphere* XIX (1), 11–19.
- Vinogradov, Yu.B., Vinogradova, T.A., 2010. *Mathematical Modelling in Hydrology*. Academia, Moscow, 366 pp. (in Russian).
- Walvoord, M.A., Kurylyk, B.L., 2016. Hydrologic impacts of thawing permafrost – a review. *Vadose Zone J.*, vol. 15, 20 pp., doi.org/10.2136/vzj2016.01.0010.

Received March 2, 2017

Revised version received October 4, 2019

Accepted October 24, 2019