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Challenges of Hydrological Engineering Design in Degrading Permafrost Environment of Russia

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Abstract: The study shows that the current network of hydrometeorological observation in the permafrost zone of Russia is insufficient to provide data for the statistical approaches adopted at the state level for engineering surveys and calculations. The alternative to the financially costly and practically impossible expansion of the monitoring network is the development of hydrological research stations and the implementation of new methods for calculating streamflow characteristics based on mathematical modeling. The data of the Kolyma Water-Balance Station, the first research basin in the world in a permafrost environment (1948–1997), and the process-based hydrological model Hydrograph are applied to simulate streamflow hydrographs in remote mountainous permafrost basins. The satisfactory results confirm that mathematical modeling may substitute or replace statistical approaches in the conditions of extreme data insufficiency. The improvement of the models in a changing climate requires the renewal of historical observations at currently abandoned research stations in Russian permafrost regions. The study is important for forming the state policy in climate change adaptation and mitigation measures.

Keywords: degrading permafrost; streamflow; hydrological engineering design; deteriorating network of observations; hazards; risks; modeling; research stations

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1. Introduction

Global warming has impacted world natural and anthropogenic systems in recent decades [1], and the permafrost zone has undergone the strongest climatic changes that affect all components of the environment, including the transformation of the hydrological regime [2]. Understanding the interactions between changing hydrology and degrading permafrost is essential to reducing uncertainties in predicting the responses of water resources and aquatic ecosystems to climate change in high altitude/latitude regions [3]. Numerous studies show an increase in the total water flow of large rivers of the permafrost zone in the second half of the 20th century [4–6], a shift in the timing of floods and significant changes in the intra-annual runoff distribution [7], including the growth of maximum streamflow characteristics [8].

The increasing probability of the occurrence of natural hazards in climate change conditions is stated elsewhere in the world [9]. In the permafrost zone, dangerous phenomena are mostly associated with changes in the characteristics of frozen ground. The infrastructure is affected by the degrading of ice-rich permafrost, which may lead to the loss of mechanical strength, subsidence and foundation failure [10]. Piped systems are especially susceptible to settlement and subsequent leakage [11].

The risks caused by the changes in the functioning of the entire natural system, including the hydrological cycle, are increasing. The average annual total (direct and indirect) damage from floods in Russia is currently estimated at over RUB 40 billion (about USD 500 million) per year, and this value is constantly increasing [12]. A significant part of it is associated with the damage to transport infrastructure—the erosion of road sections, flooding, flushing of bridge constructions and destruction of hydraulic structures. Emergencies are often caused because culverts and hydraulic structures cannot cope with the release of floods of rare probability. They can be associated with improper operation and errors at the stage of engineering and hydrological surveys, design and construction, including the uncertainty of the methods used to calculate hydrological characteristics in the absence of streamflow observations.

The opening of the Nadym–Salekhard road took place in December 2020 and became a significant event for the residents of the Yamal-Nenets Autonomous region. However, the highway was closed for repairs due to the impact of high water already in the spring of 2021 [13].

The statistics on the Magadan region (north-east of Russia) show that hazard floods in this region have occurred annually over the past ten years. Thus, 74 km of roads and 15 bridges were damaged, including at the Kolyma federal highway; the damage amounted to more than RUB 600 million (USD 8.7 million) due to the flood in August 2013 [14]. The regional road "Magadan–Balagannoe–Talon" was closed, and the damage was estimated at RUB 700 million (USD 9.4 million) in 2014. The flood damage in the region reached RUB 250 million (USD 3.4 million) in August 2016. In 2019, the intensity of flood inflow to the Kolyma and Ust-Srednekan reservoirs of the Magadan region was the highest in the last 80 years [15].

Active expansion of socio-economic infrastructure has been implemented by state programs of Arctic development, allowing the extraction, processing and transportation of natural resources despite the observed changes in permafrost territory [16]. They include the large-scale overland transport construction projects in permafrost regions of Russia, such as the railway line "Severnyy shirotnyy khod", 707 km length in Yamal-Nenets Autonomous Region, connecting the Obskaya station on the left bank of the Ob River and New Urengoy through Salekhard and Nadym. In the future, it is planned to continue this railway to Norilsk through Igarka and Dudinka (connecting the Ob and Yenisei River basins by a land transport corridor) (Figure 1).

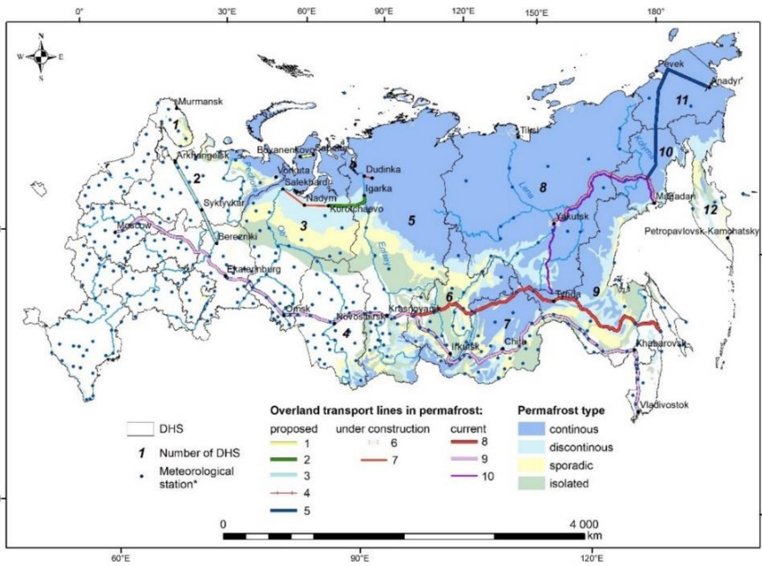

Figure 1. Distribution of permafrost type in the departments of Russian Hydrometeorological Service (DHS) located in permafrost zone (the number of DHS corresponds with Tables 1 and 2) and * the meteorological stations of Russian Hydrometeorological Service monitoring ground temperature at

0.8–3.2 m depth (N) in 2008. 1—"Bovanenkovo—Sabetta"; 2—railway Korotchaevo—Igarka; 3—"Belkomur" (program of the Russian Arctic); 4—railway Nizhny Bestyakh—Magadan, 5—Kolyma highway—Anadyr; 6—the bridge over the Lena river; 7—railway "Severny shirotny khod"; 8—Baikal-Amur line; 9—Transsib; 10—Kolyma highway and part of the Lena highway.

Table 1. Distribution of permafrost type (%) in the departments of Russian Hydrometeorological Service (DHS) located in a permafrost zone and the number of meteorological stations monitoring ground temperature at 0.8–3.2 m depth (N) in 2019.

DHS	Area, mln km^2	Type of Permafrost (%–mln km^2–N)				
		Continuous	Discontinuous	Sporadic	Isolated	All
1. Murmansk	0.14	0–0.00–0	1–0.00–1	16–0.02–0	8–0.01–0	26–0.04–1
2. North	1.14	15–0.17–1	2–0.02–0	4–0.05–1	4–0.05–1	26–0.30–3
3. Ob-Irtysh	1.51	21–0.32–0	20–0.30–0	18–0.27–4	14–0.21–6	73–1.10–13
4. West Siberian	0.84	2–0.02–0	3–0.03–3	5–0.04–5	9–0.08–2	19–0.16–10
5. Central Siberian	2.54	56–1.42–5	8–0.20–0	11–0.28–0	14–0.36–9	89–2.26–14
6. Irkutsk	0.77	3–0.18–2	15–0.12–3	24–0.19–7	29–0.22–7	91–0.70–19
7. Transbaikal	0.78	47–0.37–4	15–0.12–6	18–0.14–7	17–0.13–8	97–0.76–25
8. Yakutsk	3.06	93–2.84–16	5–0.15–0	1–0.03–2	1–0.03–2	100–3.06–20
9. Far East	1.18	33–0.39–1	20–0.24–2	13–0.15–2	14–0.17–6	81–0.95–11
10. Kolyma	0.46	87–0.40–1	11–0.05–1	1–0.00–0	1–0.00–0	100–0.46–2
11. Chukotka	0.71	100–0.71–3	0–0.00–0	0–0.00–0	0–0.00–0	100–0.71–3
12. Kamchatka	0.46	30–0.14–0	19–0.09–0	9–0.04–0	11–0.05–1	69–0.32–1
Total km^2 per station	14.3	51–6.96–33 210,000	10–1.31–16 69,000	9–1.21–28 43,000	10–1.31–42 30,000	80–10.8–122 87,000

Table 2. The number of hydrological gauges where streamflow discharge is measured, classified by basin area.

DHS	<200			200–2000			2000–10,000			>10,000			All		
	1980	2008	2019	1980	2008	2019	1980	2008	2019	1980	2008	2019	1980	2008	2019
1. Murmansk	21	8	5	39	18	15	16	11	10	9	1	1	85	38	31
2. North	18	9	9	91	70	71	63	51	49	34	30	31	206	160	160
3. Ob-Irtysh	7	0	0	35	18	19	36	21	24	54	35	42	132	74	85
4. West Siberian	12	5	4	82	65	64	68	53	55	47	46	41	209	169	164
5. Central Siberian	15	14	14	50	47	45	36	33	34	52	42	38	153	136	131

Table 2. *Cont.*

DHS	<200			200–2000			2000–10,000			>10,000			All		
	1980	2008	2019	1980	2008	2019	1980	2008	2019	1980	2008	2019	1980	2008	2019
6. Irkutsk	14	7	7	43	30	31	45	31	30	27	26	27	129	94	95
7. Transbaikal	24	10	8	93	49	41	57	53	44	37	39	34	211	151	127
8. Yakutsk	38	20	16	28	13	12	25	17	13	60	57	55	151	107	96
9. Far East	20	16	15	33	24	28	23	22	19	20	16	17	96	78	79
10. Kolyma	36	12	7	17	5	5	13	2	2	8	3	3	74	22	17
11. Chukotka	7	0	0	6	1	0	4	0	0	12	2	2	29	3	2
12. Kamchatka	37	21	19	38	24	24	17	5	6	10	8	7	102	58	56
Total	249	122	104	555	364	355	403	299	286	370	305	298	1577	1090	1043

The Kolyma–Omsukchan–Omolon–Anadyr highway construction began in 2012. Its planned length is about 2300 km (Figure 1). This road would unite three regions of the Far East—Chukotka, Magadan Region and Yakutia, including the federal highway "Kolyma". It is also planned to build a new railway line Nizhny Bestyakh–Magadan [17]. The engineering studies and design for the bridge's construction over the Lena River in Yakutsk have begun. The construction cost will be about RUB 83 billion (USD 1.1 billion). It was planned to put the bridge into operation in 2026. The Lena bridge will connect three federal and five regional highways, the Amur–Yakutsk railway, a river port and an international airport [18].

The planned development program requires scientifically based methods for calculating the characteristics of river streamflow, forecasting and assessing flood risk for the projected, industrial and social infrastructure given the high cost of construction projects. The Russian government draws special attention to the compilation of methodological recommendations for assessing climate risks and corporate plans according to the approved national action plan for adapting the economy and the population to climate change [19].

This study aims to show that the current network of hydrometeorological observation in the permafrost zone of Russia is insufficient to provide data for the statistical approaches adopted at the state level for engineering surveys and calculations. The alternative to the financially costly and practically impossible expansion of the hydrometeorological network is the development of a hydrological research network and the implementation of new methods for calculating flow characteristics based on mathematical modeling.

2. Study Area and Permafrost Data Availability

Permafrost is distributed mainly in the northern hemisphere of the earth and occupies 65% of the territory of Russia. The permafrost type varies from continuous (thickness up to 1500 m or more) to isolated (10–20 m thick) at the southern border of the permafrost distribution (Figure 1) [20]. The forecast and assessment of changes in permafrost conditions and hydrological regime and flow characteristics in Russia are complicated by the rapid reduction in the observation network. It is still the least provided with data of standard hydrometeorological measurements, despite the growing interest in the development of the permafrost zone in Russia. This study analyzes the distribution of ground temperature stations and hydrological gauges where streamflow discharge is measured along the Russian permafrost zone. We investigate the dynamic of those gauges sorted by basin area and DHS in the last several decades.

2.1. Soil Temperature Observation in Permafrost Zone of Russia

Table 1 shows the list of twelve territorial departments of the Russian Hydrometeorological Service (DHS) where permafrost occupies more than 20% of the territory. The total area of those DHS constitutes 13.6 mln km^2 with 10.8 mln km^2 (80%) covered by permafrost of different types. Continuous permafrost is present in more than half of the area (51%); other types are distributed evenly (each about 10%). Three departments are located entirely in the permafrost zone (Chukotka, Yakutsk and Kolyma with 100, 93 and 87% of continuous type, respectively). Permafrost covers more than 80% in Transbaikal, Irkutsk, Central Siberian and Far Eastern departments, here the proportion of continuous permafrost type ranges from 23 to 56%. The discontinuous permafrost zone varies from 1 to 20%, sporadic and isolated from 1 to 29% in presented DHS. Table 1 contains the data regarding the number of meteorological stations with the data on the ground temperature at any depth in the range of 0.8–3.2 m available online at the official website of the Russian Hydrometeorological Service [21] up to 2008.

At an area of 10.8 mln km^2, there are 123 stations monitoring ground temperature. Though the stations are unevenly concentrated close to industrial centers and city agglomerations, on average, one station covers about 87,000 km^2; for continuous permafrost, this value increases by three times and reaches 210,000 km^2 (for example, together at Chukotka and Kolyma DHS, the north-east of Russia, with a total area 1.17 mln km^2 there are only five stations of standard observational network with ground temperature data). As well as the severe lack of stations, they may also present data of uncertain quality (for example, [22]); often, the data contains many gaps and presents a minimum number of ground depths.

2.2. Reduction in Hydrological Observation Network in Permafrost Zone of Russia

Streamflow discharge is the main hydrological engineering characteristic. The historical and current hydrological gauges with streamflow measurements were compiled from [23–26], respectively.

The number of hydrological gauges with streamflow discharge measurements in the permafrost zone constituted 1577 in 1980 and dropped to 1043 in 2019. The network density has decreased by about 1.5 times over the past 40 years. The situation is even more acute with tiny rivers (catchment area <200 km^2)—the number of observation gauges has decreased more than two-fold, and for gauges with a catchment area of 200–2000 km^2—1.3-fold (Table 3, Figure 2). One may note that the strongest drop in the number of hydrological gauges occurred between 1980 and 2008. However, the tendency of further decrease is well seen at most DHS. In total, the number of gauges has decreased by 47 (about 5 %) over the past ten years (by six gauges for each DHS on average, ranging from 0 to 11 gauges). The most critical situation is observed in the Kolyma DHS. In 2008–2019, the total number of discharge gauges had dropped from 22 to 17 (23% decrease), the losses (5 gauges) are characteristic for the most crucial data—small rivers with basin areas less than 200 km^2. In the Chukchi peninsula, the number of gauges dropped from 3 to 2; considering the area of this DHS (>700 thousand km^2), the situation in the north-east of Russia is critical. The main reason for hydrometeorological network reduction is the significant depopulation of northern territories and the limited funding of the service due to the decline of the Russian economy after the collapse of the Soviet Union.

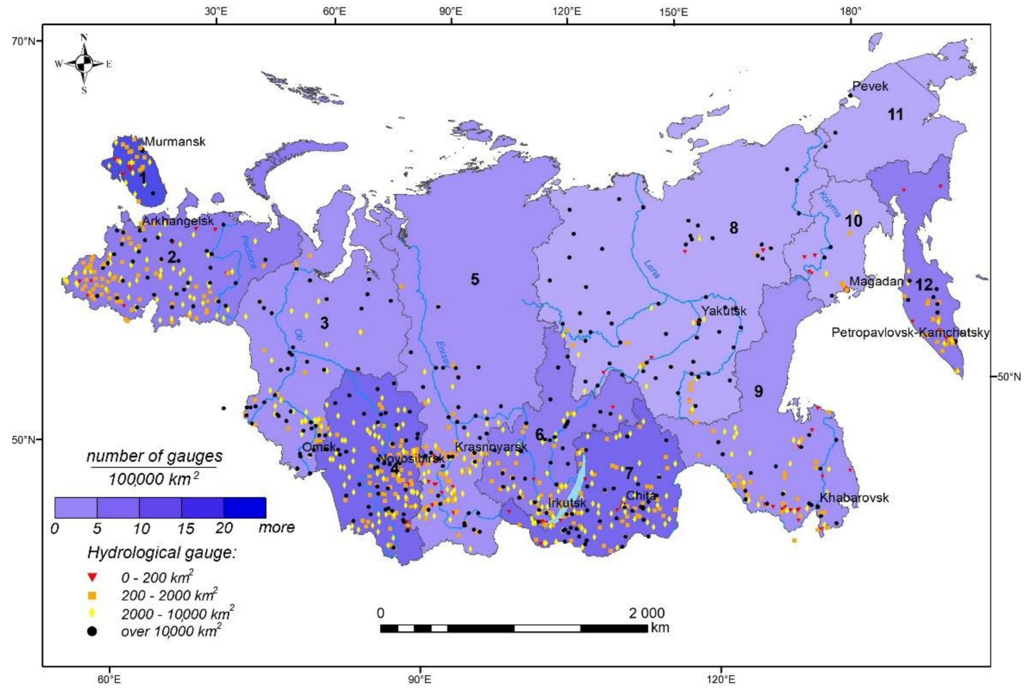

Figure 2. Total density (number of gauges per 100,000 km^2) and location of hydrological network with streamflow observations in the departments of Russian Hydrometeorological Service of permafrost zone (DHS, the numbers correlate to Tables 1 and 2) by 2019.

Figure 2 shows the density of hydrological gauges of all area categories in permafrost DHS. By density, we mean the number of any hydrological gauges with discharge measurements per 100,000 km^2. Figure 2 also depicts the location of hydrological gauges with different basin areas. Figure 3 gives a more exact idea about the density of gauges in each DHS. Additionally, the percentage of the DHS area covered by the permafrost of any type is shown.

Most territory in east Siberia and the north-east (DHS 8, 10, 11 with 100% permafrost) is characterized by the density of fewer than five gauges per 100,000 km^2 (Figure 2). In the Republic of Yakutia (DHS 8), those values are $\leq$ 0.5 for basin areas less than 10,000 km^2 and 1.8 for larger basins. In the Magadan region (DHS 10), the density varies from 0.4 to 1.5 with a total (all gauges) average of 4.0. In Chukotka, there are no gauges in the category less than 10,000 km^2. The density is 0.3 for the gauges of basin areas more than 10,000 km^2. In DHS 3 and 4 (the Ob' River basin), most gauges are located beyond the permafrost zone in the south of the regions. The same situation is characteristic for DHS 5, 6 and 9, where the gauges' density is representative of the non-permafrost zone. In DHS 1 and 2, permafrost is distributed in the north-eastern edges of the regions exactly where no gauges are situated. A relatively acceptable situation with the network density may be considered in DHS 6 and 7 (Irkutsk and Transbaikal regions), where permafrost covers more than 90 % of the territory and the density of gauges with basin areas > 200 km^2 reaches 3.5–5.6.

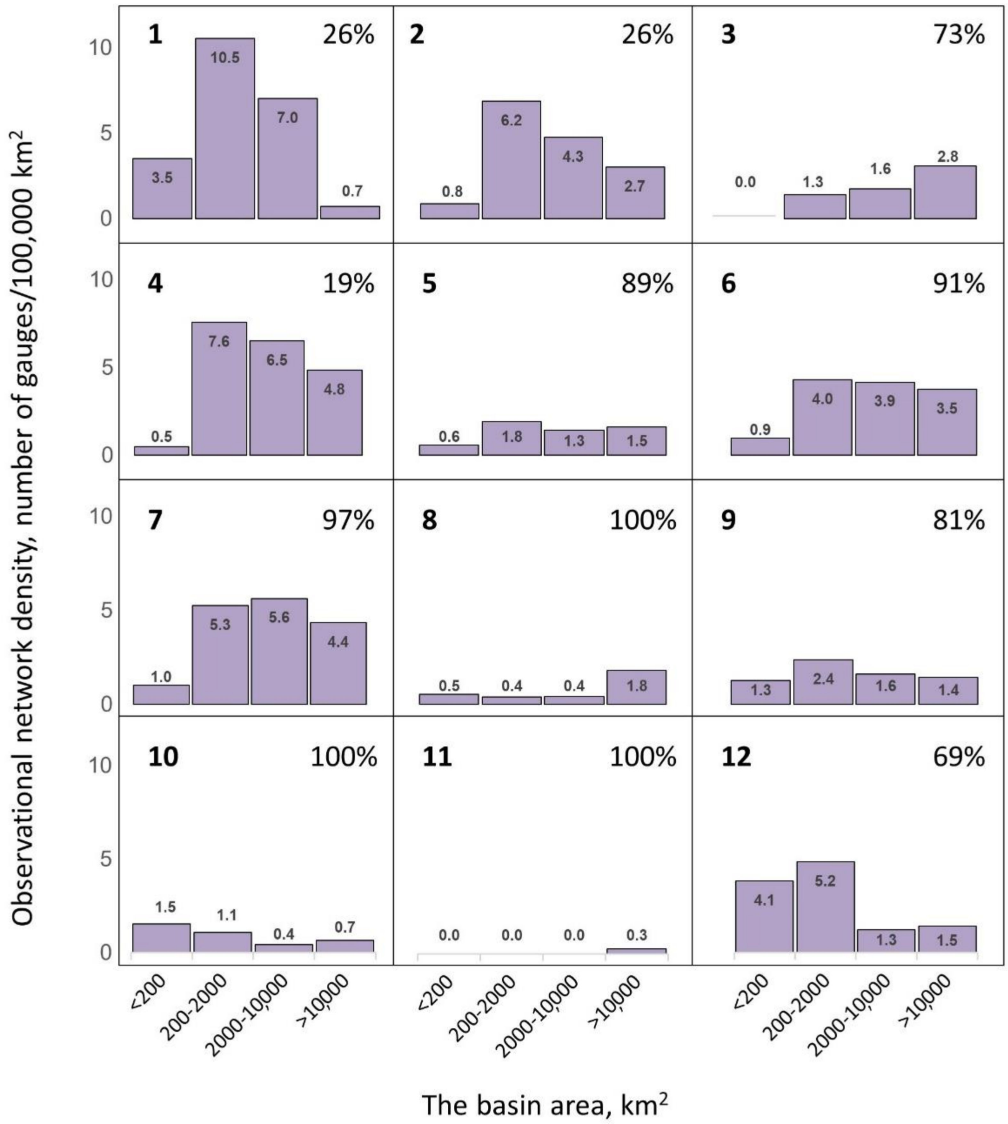

Figure 3. The density of hydrological gauges with streamflow discharge observations is classified by basin area in different DHS (see Tables 1 and 2) with indicated permafrost (%) for DHS territory.

3. Methods

3.1. Modern Methods for Calculating the Hydrological Engineering Characteristics

Any construction projects require engineering field studies and design. Most countries use statistical estimation methods in civil hydrological engineering. Their base is various distribution functions that describe observed streamflow data and estimate hydrological characteristics of low probabilities [27].

Developing cost-effective and sustainable plans requires the assessment of flood risk. In the United States, that computation is done following guidelines in Bulletin 17C [28]. It is recommended that the flow discharge be determined by the method of the probable maximum flood. The probable maximum flood (PMF) calculation is carried out during the construction design of hydraulic engineering facilities for particularly critical structures [29–31].

In Europe, most studies are based on statistical methods applied to individual time series of extreme precipitation or extreme streamflow; moreover, many assessments are carried out based on the regional principle. In [32], various approaches for producing climate projections of extreme precipitation and flood frequency, methods for statistical downscaling and bias correction, and alternative hydrological models are presented.

In Canada, flood management is primarily the responsibility of the provinces and territories. Therefore, most flood management activities are executed at the 'local' rather than provincial, territorial or federal levels [33]. The statistical frequency analysis is performed on high river flows to obtain a set of design flow values corresponding to selected frequencies of occurrence, commonly interpreted in terms of return periods or annual exceedance probabilities [34]. The statistical approach is used to develop precipitation intensity-duration-frequency estimates, then integrated with urban hydrological models to produce the desired design flow values. The estimated design flows are then used in hydraulic models to generate flood extents and levels to develop flood inundation, flood hazard and other flood-related maps and products [34].

In Russia, the Calculation Set of Rules 33-101-2003 (SR) [35], based on applying statistical processing methods of long-term series of streamflow observations, is currently demanded. The SR is an updated version of the document SNiP 2.01.14-83 [36], issued in 1983, and fundamentally does not differ from its predecessor in terms of methods for calculating runoff characteristics. The previous edition assumed that hydrological processes are statistically stationary, and consequently, retrospective observations can be considered representative. The SR methods recognize climate change and require the use of current hydrometeorological information when making calculations and clarifying the parameters of calculation equations based on the generalization of current hydrological data. However, such recommendations do not offer clearly described methods to consider the influence of climate on streamflow characteristics [37–39].

In [40], the calculations of maximum streamflow characteristics for several rivers in the permafrost zone of Russia based on the recommendations of SR were conducted. The calculation was carried out for four very small (up to 200 km^2) and two small (up to 2000 km^2) river basins located in eastern Siberia and the north-east with different hydrological regimes, provided by long series of streamflow data. Analyzed river basins were treated as ungauged. The data of other hydrological gauges (following the recommendation of SR) was used as the analog for conducting the calculations. Calculated characteristics of maximum discharge of different probabilities were compared with observed values. The results of the study have shown that the choice of analog rivers provided with recent observational data (including last 20–25 years) is limited to 2–3 options of watersheds that have no alternative for the area of up to several hundred thousand km^2 and the requirements for the selection of analog rivers are largely wide, leading to large uncertainty of calculation results.

3.2. The Mathematical Modeling Methods and Special Monitoring of Runoff Formation Processes in the Permafrost Zone

Hydrological calculations and forecasts in the conditions of vast and remote permafrost territories, where the network of hydrometeorological observations is either very rare or absent, are related to the use of mathematical models. The permafrost zone imposes increased requirements on hydrological models [2]. Among the hydrological models that describe the processes of heat and moisture transfer in frozen soil and have been tested in cold regions of the earth are the TopoFlow model [41], Cold Region Hydrological Model (CHRM) [42], Variable Infiltration Capacity (VIC) model [43], cryospheric basin hydrological model (CBHM) [44], GEOTop model [45], SoilWater—Atmosphere—Plants model (SWAP) [46], Ecological model for Applied Geophysics (ECOMAG) [47], the Hydrograph model [48,49] and others.

The complexity of runoff formation processes in permafrost regions requires understanding the physical mechanisms of heat and moisture exchange processes to improve and apply mathematical modeling methods. One of the most important obstacles for such studies is obtaining full-scale data of special and experimental observations. Stationary observations at small research catchments are the main source of information about the physical mechanisms of runoff formation and ongoing hydrological cycle changes. Therefore, the low density of the standard observation network may be compensated by the development of a network of research catchments. Canada and the USA, where the area of permafrost territories and their inaccessibility are commensurate with the permafrost zone of Russia, are leading in those studies [50–54]. Watershed research is accompanied by the development and application of mathematical modeling methods.

Russia has lagged significantly behind other Arctic countries in instrumental studies of the hydrological cycle processes over the past 30 years. However, it had the world's first system of integrated scientific hydrological stations organized in various climatic conditions in the USSR. M. Velikanov was the first to propose the organization of special hydrological stations in various physical and geographical conditions in 1925, and D. Sokolovsky compiled the plan for the placement of 45 field laboratories on the territory of the USSR in 1933. There were already 11 stations from 1928 to 1940. However, most of them were closed entirely during World War II. In 1954, the monography with the first results of the studies at hydrological research stations, called runoff stations, was published [55]. The runoff stations made comprehensive observations of all elements of the water balance and the factors causing their changes. The objects of the study were small catchments and runoff sites characteristic of the region. By 1981, there were 16 water balance stations (WBS) at natural catchments (not subject to reclamation) and nine marsh stations on the territory of the USSR.

The Kolyma Water Balance Station (KWBS) was the only comprehensive research station in the permafrost zone with long-term observation. The location of the KWBS (upper reaches of the Kolyma River, Magadan region) was representative of the vast mountainous territories of the permafrost zone of eastern Siberia, the north-east and the Far East of Russia. Detailed observations of the runoff formation and the seasonal thawing and freezing of soils were carried out at the KWBS from 1947 to 1997 [56]. The processes of formation of water balance [57], hydrogeological structure and talik zone [58], runoff in various landscapes (the distribution of precipitation, evaporation and water runoff in permafrost rocks and mountain relief were studied based on the analysis of observational data [59,60]. Another example is the Mogot research station of the Baikal-Amur expedition of the Russian State Hydrological Institute (1976-1985). The Mogot station was created to provide design and construction solutions for hydrological calculations in the permafrost zone of economic development of the Baikal-Amur mainline [61–64].

Historically, the observations at WBS have contributed significantly to the development of both applied and fundamental hydrology. Nowadays, there is no permanent state hydrological research station in the permafrost zone of Russia.

In this study we have used one of the available hydrological models which has shown the significant potential to be applied in remote permafrost regions. The parameters of the Hydrograph model were previously elaborated at the base of KWBS data for typical permafrost landscapes [49,56,57,59,60] to simulate the runoff formation processes in hard-to reach river basins of the north-east of Russia. The results are aimed to show that the data of research basins and appropriate process-based models allowing for regionalization of their parameters could become a decent alternative to statistical approaches in the poorly gauged permafrost basins.

3.3. Hydrograph Model

The Hydrograph, a distributed process-based model of runoff formation processes is applied in the study. The model has proven to be an effective tool for research and projection of hydrological processes in the permafrost and on poorly gauged river basins [48,49,65,66]. The model algorithms combine physically based and conceptual approaches in describing the processes of the terrestrial hydrological cycle, which allows a balance to be maintained between the complexity of the design schemes and orientation to limited input information. Precipitation and interception of rainfall water, compaction and ablation of snow cover, moisture and heat flux in the snow cover and in soils, including freezing and thawing, are described in an explicit way in the model. Underground water, slope and channel flow transformation, snow redistribution by wind and evaporation are calculated by conceptual methods that have shown their effectiveness in various conditions of cold regions [49,66]. Using a limited list of meteorological variables (air temperature and humidity, precipitation) as the input information allows the model to be applied at remote, poorly gauged basins. The model parameters are related to runoff formation complexes—landscapes with similar characteristics of soil and vegetation. The sets of parameters refined on the studied catchments (analogous watersheds) can be transferred to ungauged basins with similar surface types. The Hydrograph model is used on watersheds of different sizes from the soil column to the Lena River basin without changing its structure and algorithms [48]. The results of the studies [49,59,65] have shown that the Hydrograph model performs satisfactorily in terms of active layer dynamic and soil temperature simulations. The description of the procedures of basin schematization and model parametrization are presented in detail in the studies [48,49,59,60,66] and therefore is omitted here.

The processes of groundwater and surface flow interactions are complicated in the permafrost zone; therefore, the main limitations of the Hydrograph model are related to the representation of those processes. They include the formation and development of taliks, the formation of giant groundwater aufeis which are widely distributed in the study region, and other geocryological processes. Those processes and phenomena should be studied at research watersheds for the improvement of model algorithms and their parametrization.

4. Results

Four watersheds with an area from 84 to 8290 km^2 located in the mountainous regions of such river basins as Yana, Indigirka and Kolyma were chosen as the study objects (Table 3). The following data were used in the modeling process: daily meteorological and hydrological information from standard hydrometeorological networks, previously developed model parameters for main permafrost landscapes [49,59,60]. The assignment of typical landscapes within the watersheds was conducted using a SRTM digital elevation model and Landsat-8 images using previously developed schemes of landscape distribution in the mountainous basins of the Kolyma [60] and Indigirka [66].

Table 3. The characteristics of the simulated watersheds and modelling results.

Large River Basin	River	S *	H	Pr	Yo	Ys	P	E	Qo	Qs	NS (av)	NS (max)
Indigirka	Sakharynia	84.4	833	1966–2012	93	113	294	181	14	12	0.32	0.76
	Artyk-Yuryah	644	591	1966–1991	82	81.8	274	189	90.3	149	0.14	0.72
Yana	Charky	8290	274	1966–2007	216	223	361	120	1424	1490	0.34	0.70
Kolyma	Anmangynda	400	668	1966–1987	273	237	375	125	161	81.1	0.43	0.71

* here, S—watershed area, km^2; H—average watershed elevation, m; Pr—period of simulation, years; Yo, Ys—observed and simulated annual streamflow, mm; P and E—simulated annual precipitation and evaporation, mm; Qo, Qs—observed and simulated maximum discharge (m^3/s); NS (av) and NS (max)—average and maximum Nash–Sutcliffe criteria.

The model was run in continuous mode for the period from 22 to 47 years with daily time step. The results of modeling compared to the observed values are presented in Table 3, including the distribution of annual water balance, the Nash–Sutcliffe (NS) criteria for daily streamflow hydrographs and maximum discharges. It is important to mention that all meteorological stations to which data was applied are located beyond the watershed's borders. In mountainous conditions, it plays a significant role in flood modeling results.

Simulated values of annual precipitation and evapotranspiration vary in the ranges 274–375 and 120–189 mm, respectively. The bias between simulated and observed annual values of streamflow reaches the numbers between 0 to 22%, increasing with the decrease in watershed size. The difference between simulated and observed maximum discharges is proportional to the distance of the meteorological station to the watershed which confirms the limitation of modeling results by input data. One may see observed and simulated hydrographs with good, average and poor convergence which mainly depends on the representativity of the input meteorological data (Figures 4 and 5). The average Nash–Sutcliffe (NS) criteria is not very high varying from 0.14 to 0.43, but in some years, it reaches up to 0.76.

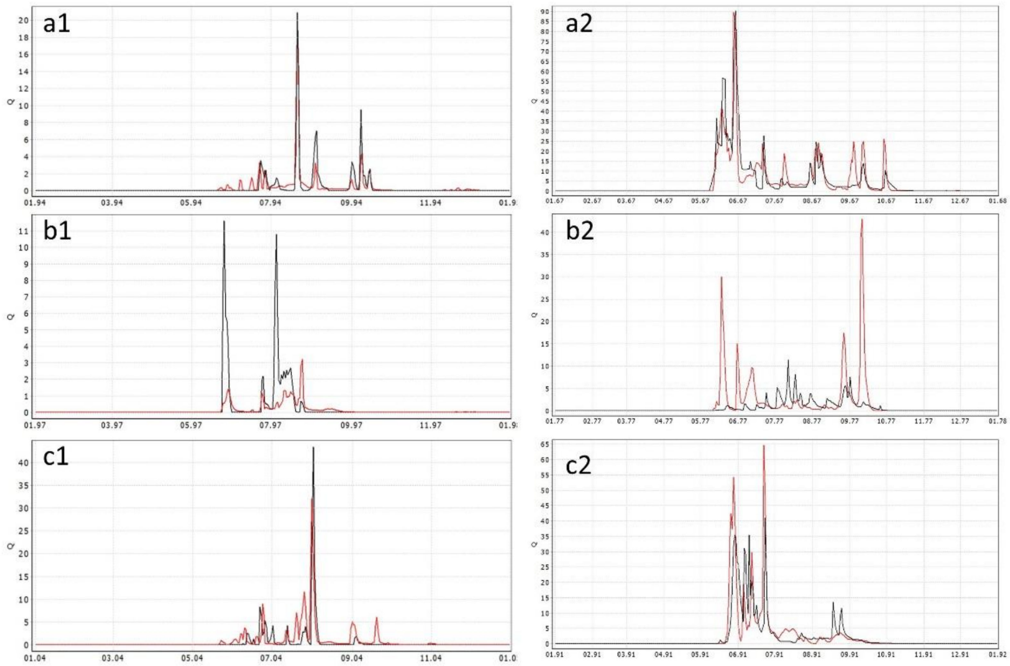

Figure 4. Observed (black) and simulated (red) streamflow hydrographs; **1**—Sakharynia, **2**—Artyk-Yuryah; (**a**–**c**)—high, low and average NS criteria.

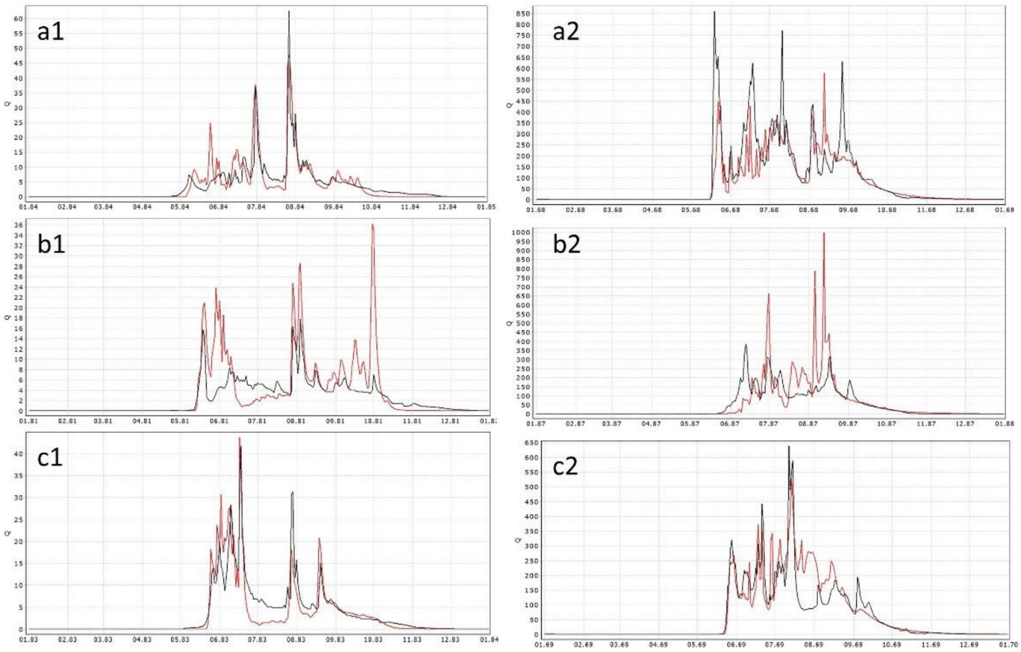

Figure 5. Observed (black) and simulated (red) streamflow hydrographs; **1**—Anmangynda, **2**—Charky; (**a**–**c**)—high, low and average NS criteria.

The results confirm that the data of special research basins can be used for model parameter estimation in remote permafrost basins. The quality of simulations is satisfactory. The modeling results may substitute or replace statistical approaches in the conditions of extreme data insufficiency. The improvement of the models in current climate conditions require the renewal of historical observation in currently abandoned research stations.

5. Conclusions

Most of the territory of Russia can be classified as unexplored hydrological territories. Currently, calculations of flow characteristics in the permafrost zone are based on regional statistical parameters. Their refinement was conducted more than 40 years ago, when the hydrological data from all over the country were summarized fully, using unified methods developed in the Russian State Hydrological Institute. One could argue there are serious scientific and practical problems related to the extreme limitations and poor quality of observational data, as well as the lack of funding and human resources to restore a wide hydrological observation network in the permafrost regions of Russia. The main problems related to hazards and water resources are the following: (1) estimating streamflow characteristics in the tasks of engineering and survey design; (2) forecasting the magnitude and frequency of catastrophic floods; (3) predicting the inflow of water into reservoirs and river systems for the needs of hydropower and water transport.

The annual hazard damages in a permafrost region of Russia are comparable with the costs of building a modern research station. For example, the cost of the Samoylov Island Arctic permafrost research site built in the Lena River delta in 2012 was RUB 500 million (about USD 17 million). This station is located in a remote hard-to-reach place and requires complicated logistics for its provision due to the need for self-efficiency [67,68]. Building a station in a less remote place with access to roads, energy and communication networks would significantly reduce the costs while providing important data for coping with the stated problems.

The solution of the tasks set can be achieved only at the state level and should be carried out in three directions:

1. The development of a state program to organize a network of representative catchments in various climatic zones of permafrost regions for the comprehensive monitoring of main components of water balance and hydrological processes using modern equipment with a high time resolution and new research methods. It is also necessary to consider the feasibility of restoring historical stations with a long series of observations, such as the Kolyma water balance station [56]. The development of such a program should be based on the results of a detailed inventory of historical data of standard and specialized information on the characteristics of the natural environment (climate, permafrost, hydrology, hazardous phenomena, landscapes, etc.). The research stations should be equipped for year-round living and may serve educational purposes for student field practice and experience in the future.

Nowadays, limited in scope and duration, some hydrological research is carried out in a permafrost environment by individual research teams on a non-permanent basis of grant funding and without uniform methods [69–71]. Obviously, it is impossible to solve the discussed tasks solely by the research teams in terms of capital infrastructure. This is due to the lack of resources for construction works, purchase of transport, maintenance of property, etc. State and business input are required to support such initiatives.

2. State order for the development of approaches for the estimation of the main hydrological characteristics in engineering and survey design tasks based on mathematical modeling methods.
3. Improvement (in particular, expansion) of the standard hydrological observation network, based on modern modeling and remote sensing methods and accounting for historical experience, and social and economic development programs [72]. The improvement of the measurements' quality would require the renewal and expansion of hydrometeorological education which has been in deep decline for the last 30 years. Implementing these three tasks would require us to solve many problems. Among them are an acute shortage of qualified specialists in hydrometeorology (from observers to researchers), the loss of experience in organizing and conducting complex

hydrological research, a lag in the development of modern hydrometeorological devices' domestic production, financing of the industry on a residual basis, and others.

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