

Water runoff vs modern climatic warming in mountainous cryolithic zone in North-East Russia

V E Glotov, L P Glotova

North-East Interdisciplinary Science Research Institute, Port str., 16, Magadan,
685000, Russia

Russian Academy of Sciences Far East Branch, Svetlanskaya str., 50, Vladivostok,
690990, Russia

E-mail: geoecol@neisri.ru; glotova@neisri.ru

Abstract. The article presents the results of studying the effects of current climatic warming for both surface and subsurface water runoffs in North-East Russia, where the Main Watershed of the Earth separates it into the Arctic and Pacific continental slopes. The process of climatic warming is testified by continuous weather records during 80-100 years and longer periods. Over the Arctic slope and in the northern areas of the Pacific slope, climatic warming results in a decline in a total runoff of rivers whereas the ground-water recharge becomes greater in winter low-level conditions. In the southern Pacific slope and in the Sea of Okhotsk basin, the effect of climatic warming is an overall increase in total runoff including its subsurface constituents. We believe these peculiar characters of river runoff there to be related to the cryolithic zone environments. Over the Arctic slope and the northern Pacific slope, where cryolithic zone is continuous, the total runoff has its subsurface constituent as basically resulting from discharge of ground waters hosted in seasonally thawing rocks. Warmer climatic conditions favor growth of vegetation that needs more water for the processes of evapotranspiration and evaporation from rocky surfaces in summer seasons. In the Sea of Okhotsk basin, where the cryolithic zone is discontinuous, not only ground waters in seasonally thawing layers, but also continuous taliks and subpermafrost waters participate in processes of river recharges. As a result, a greater biological productivity of vegetation cover does not have any effect on ground-water supply and river recharge processes. If a steady climate warming is provided, a continuous cryolithic zone can presumably degrade into a discontinuous and then into an island-type permafrost layer. Under such a scenario, there will be a general increase in the total runoff and its subsurface constituent. From geoecological viewpoints, a greater runoff will have quite positive effects, whereas some minor negative consequences of it can be successfully prevented.

1. Introduction

The territory of North-East Russia (NER) is geographically peculiar as it is washed by seas of the Arctic and Pacific oceans, which differ by their hydrothermal regimes (figure 1). The Arctic Ocean is a natural continuation of the Atlantic Ocean, and their drainage divide is a fragment of the Main Watershed of the Earth (MWE). Over the Arctic slope of the MWE, climatic conditions are formed at account of heat and water brought there by air masses forming over oceanic areas, the largest part of which is covered by ice even in warm seasons. As a result, the air over the land is cold and its water content is low. Climate over the Pacific slope depends on submeridional cyclones bringing heat and water from temperate warm zones of the Pacific. Such cyclones can reach high northern latitudes and



in some cases can even attack the Arctic slope raising the air temperature and increasing precipitations in the Chukotian Sea basin. Different runoff-forming factors produce their effects on the total water runoff of different oceanic slopes [1].

The study purpose is to elucidate regular relationships between changes in MWE slope runoffs and modern changes in runoff-forming climatic factors.

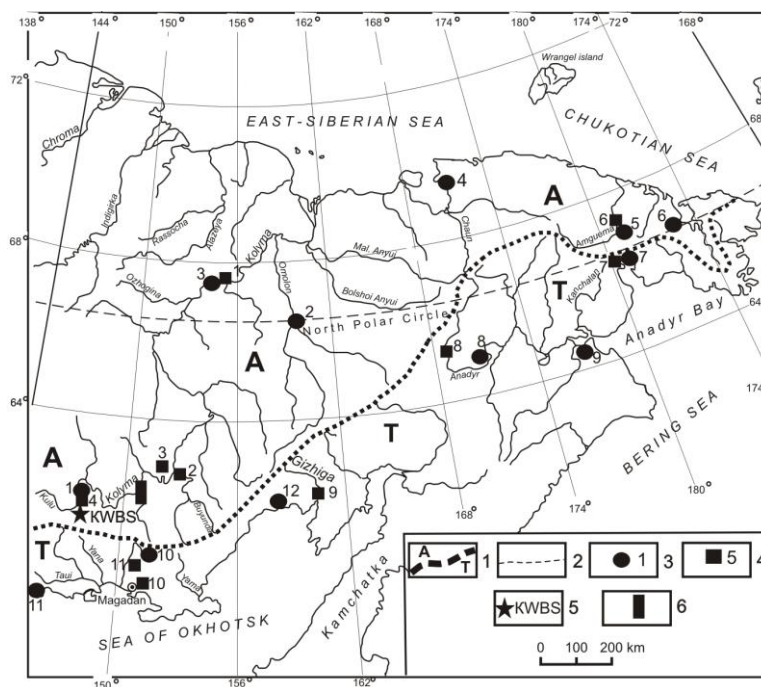


Figure 1. Schematic map of North-East Russia: **1** – the Main Watershed of the Earth (A – Arctic slope, T – Pacific slope); **2** – the Northern Polar Circle; **3** – weather monitoring stations, by their numbers in the text including: 1 – Seimchan, 2 – Omolon, 3 – Srednekolymsk, 4 – Pevek, 5 – Amguema, 6 – Uelen, 7 – Egvekinot, 8 – Markovo, 9 – Anadyr, 10 – Palatka, 11 – Okhotsk, 12 – Nayakhan; **4** – hydrologic stations, by their numbers in the text including: 1 – the Kolyma River, Srednekolymsk, 2 – the Kolyma River, Ust-Srednekan, 3 – the Taskan River, Taskan, 4 – the Kulu River, Kulu, 5 – the Detrin River, the Vakhanka River mouth, 6 – the Amguema River, bridge at 1744 km mark, 7 – the Izyskatelsky Creek, 2.5. km from its mouth, 8 – the Anadyr River, Novy Eropol, 9 – the Gizhiga River, 20 km from its mouth, 10 – the Khasyn River, Khasyn, 11 – the Dukcha River mouth; **5** – KWBS (the Kolyma Water Balance Station); **6** – water-power plant.

The study objects are runoff-forming climatic conditions, the study subjects are water runoffs over MWE slopes.

The research and actual significance of this study is presupposed by an important role of water runoff as an agent participating in fluvial denudation and deposition processes, and formation of placer deposits. Understanding the total runoff pattern and its changes is a necessary prerequisite for rational use of fresh water resources and solution of geoeological problems.

Research methods include analysis of published records of the Kolyma Water Balance Station (KWBS), which embrace periods since 1930s-1940s through the late 1980s. As a result of

sociopolitical disturbances, which followed after that period in Russia, the majority of weather monitoring stations in NE Russia ceased their activities, the observations became irregular, so observation data available with us are only till 1988, and we have just some scarce data for later period.

The subsurface constituent of the water runoff is established by virtue of genetic subdivision of runoff hydrographs in consideration of ground-water recharge pattern in the cryolithic zone. According to S.F. Fotiev [2], the basic water exchange components within the continuous cryolithic zone include water hosted in seasonally thawing rocks (STR), superpermafrost and local continuous taliks. Within discontinuous cryolithic zones, besides STR and talik ground waters, continuous band- or ribbon-shaped taliks forming beneath stream channels of the 2nd and greater orders also become important in river recharge processes. With perennally frozen rocks (PFR) having thickness less than 100-120 m, subpermafrost fractured aquifers become important components of the active water exchange zone [3].

In compliance with hydrologic budget data for mountainous cryolithic areas [4, 5] supplied by the Kolymian station for the period 1947-2002, the largest monthly average discharge in September was $550 \text{ l}\cdot\text{s}^{-1}$ at the closing range of the Kontaktovy-Nizhny Creek in 1975. It is in September, that rains and ground waters are the only recharge sources for all streams there. In order to establish the participation of ground waters, the runoff hydrograph is created (figure 2) for period of September 1-20, 1975 prior to colder season and ice forming over river banks [6].

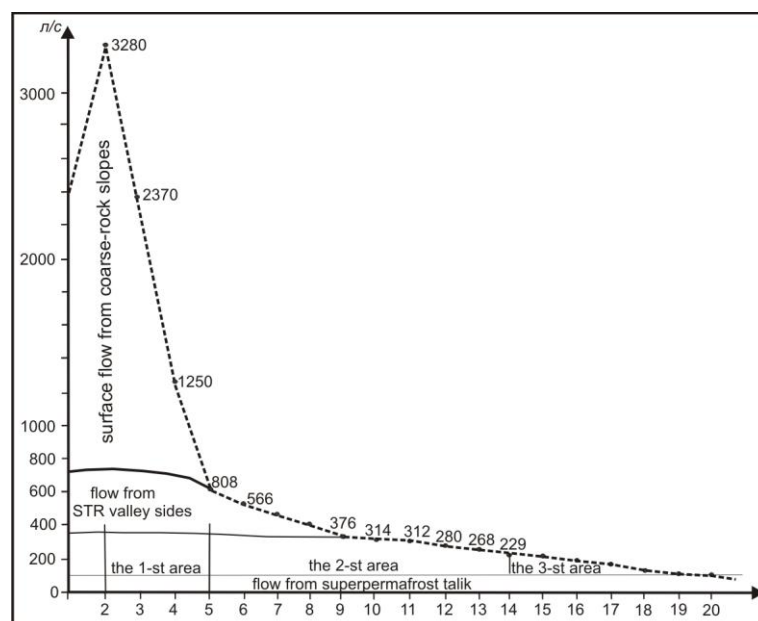


Figure 2. The Kontaktovy-Nizhny Cr. runoff hydrograph, September 1-20, 1975, the catchment area 21.2 km^2 .

The hydrograph shows the peak runoff of $3280 \text{ l}\cdot\text{s}^{-1}$ on September 2, and till September 5, the following daily average runoff is represented as an almost straight declining graph. During three days, the discharge amount became 75% less of its daily average maximum. In the next 5 days, the discharge lessened to $314 \text{ l}\cdot\text{s}^{-1}$ that made about 10% of the peak value. We believe that such a drastic decrease in water discharge intensity is due both to ceasing water flow from coarse STR characterized by complete water yield and also to commencing drainage of less-yielding rock debris with small- and fine-grained infilling. Such a runoff type can be undoubtedly identified as a subsurface one. In that case, on September 5, the river was replenished at account of ground waters with daily average discharge of $808 \text{ l}\cdot\text{s}^{-1}$, which was much higher than the average monthly value. Proceeding from these

data, we can conclude that throughout NE Russia in September the monthly average runoff is provided by subsurface recharge sources dominated by water flows from STR. In November, when STR layer is frozen, subsurface recharge is mainly provided by superpermafrost subchannel taliks. According to the Kolyma Water Station data, the ground-water table in mid-December comes down to depth about 5 m in superpermafrost talik [7]. Over the Arctic slope of MWE since January through April, and over the Pacific slope since January through March, the runoff is supplied by water flows from superpermafrost and continuous taliks, and there is also subpermafrost water over the Pacific slope [8 9].

The study objects description. The most representative climatic data reported during as long observation periods as 60 years and more are summarized in table 1, which represents the basic runoff-forming climatic factors including the annual average air temperatures and precipitations over NE Russia. Since climatic warming has been reported during the last 50-60 years [10], the table is distinguished into two observation periods: before 1960 and later on.

Table 1. The annual average air temperatures and precipitations (according to the Kolymian Hydrometeorologic Department).

№	Weather station; absolute elevation, m; co-ordinates	Observation periods	Annual average values during the observation periods	
			Air temperature, °C	Precipitations, mm
Arctic Slope				
The East Siberian Sea runoff basin				
1	Seimchan, 205 m; 62°55' N 152°25'' E	1934-1959	-11.9	286
		1934-2010	-10.3	307
2	Omolon, 260; 65°44' N 160°32' E	1944-1959	-13.2	256
		1944-2010	-11.6	264
3	Srednekolym'sk, 29; 67°27' N 158°43' E	1887-1959	-12.6	195
		1887-2010	-11.2	234
4	Pevek, the sea shore, 8; 69°42' N 150°56' E	1940-1959	-10.4	136
		1940-2010	-9.5	190
The Chukotian Sea runoff basin				
5	Amguema, 62; 64°47' N 177°34' E	1948-1959	11.9	422
		1948-1987	11.5	494
6	Uelen, 5; 66°10' N 169°50' W	1928-1959	8.2	386
		1928-2010	7.1	432
Pacific Slope				
The Bering Sea runoff basin				
7	Egvekinot, 29; 66°15' N 179°09' E	1946-1959	7.1	432
		1946-2010	6.9	557
8	Markovo, 28; 64°41' N 170°25' E	1895-1959	9.1	334
		1895-2010	7.2	432
9	Anadyr, 62; 64°47' N 170°25' E	1898-1959	7.7	312
		1898-2010	6.9	382
The Okhotian Sea runoff basin				
10	Palatka, 341; 60°06' N 150°56' E	1940-1959	-6.6	383
		1940-2010	-5.7	411
11	Okhotsk, 12; 59°22' N 147°12' E	1844-1959	4.8	322.5
		1844-2010	-3.8	499
12	Nayakhan, 23; 61°55' N 158°59' E	1914-1959	-4.9	411
		1914-2010	-4.5	463

As this table shows, the processes of climatic warming have manifested themselves over the entire territory under consideration and are the most obvious over the Arctic slope of MWE and on the Pacific coasts. This warming phenomenon is everywhere associated with greater precipitations, the increase in which ranges from 3 % to 55 % with respect to preceding periods. Precipitations increased to the largest extent over the Pacific slope, and over the Arctic slope the increase makes up 3-7 % in intermountain areas and is as high as 20-40% in cyclone-accessible areas as Pevek, Srednekolymysk, Amguema.

2. The Study Results

In order to establish the relationships between the water runoff parameters and climatic factors, the data available on streams with all-year-round runoff regimes were examined with reference to atmospheric changes reported during long-term periods of observations, with just few exclusions of lacking data. It should be noted here, that due to socioeconomic disturbances in Russia at the end of 1980s, the majority of weather stations in NER were abandoned and hydrometric studies were interrupted. It was during that very decade that the Kolymian Hydro came into its full capacity operation, the result of which was a significant alteration of both subsurface and surface runoffs in the Kolyma River valley [11]. The runoff calculations for representative rivers are given in table 2.

Table 2. The representative runoff data for NER [12 - 16].

№	Rivers, closing range; catchment area, km ²	Observation periods	Annual average discharge, m ³ ·s ⁻¹	Winter low-level subsurface runoff, month, m ³ ·s ⁻¹			
				IX	XI	I	IV (III)*
Arctic Slope							
1	Kolyma R., Srednekolymsk; 361 000	1927-1960	2234.1	3076	280.5	111.9	59.1
		1961-1980	2156	3256	254.4	111.3	58.1
		1981-1999	2030	-	-	-	-
2	Kolyma R., Ust- Srednekan; 99 400	1933-1960	724	960	76.8	17.4	6.02
		1961-1980	720.9	961.5	69.7	17.9	6.1
3	Taskan R., Taskan; 9 970	1938-1960	73.8	80.4	6.12	3.67	2.94
		1961-1999	71.6	86.1	6	3.24	2.5
4	Kulu R., Kulu; 10 300	1942-1960	92	132	12.1	2.78	1.02
		1961-1988	95.2	136.2	13	2.83	1.3
5	Detrin R., Vakhanka R. mouth; 5 630	1938-1960	52.3	89.9	7.17	0.82	0.21
		1961-1988	51.1	80.4	6.25	0.92	0.26
6	Amguema R., 1744 km; 26 700	1944-1960	280	280	18.9	0.28	0.006
		1961-1988	271	283	7.6	0.25	0.005
Pacific Slope							
7	Izyskatelsky Cr., 1.5 km from the mouth; 13.2	1947-1960	0.36	0.28	0	0	0
		1961-1980	0.31	0.38	0	0	0
8	Anadyr R., Novy Eropol; 43 300	1958-1970	502	443	50.4	16.3	10.7
		1971-1988	431.4	499	50.9	17.5	12.3
9	Gizhiga R., 20 km up the mouth; 11 700	1951-1960	148	132	24.5	10.1	7.27
		1961-1988	156	161	27.1	11.2	7.98
10	Khasyn R., Khasyn; 682	1941-1960	9.04	15.6	1.73	0.33	0.09
		1961-1999	9.19	13.9	1.72	0.02	0.01
11	Dukcha R., the mouth; 330	1961-1970	5.27	7.08	2.69	1.2	0.7
		1971-1988	5.66	7.28	2.78	1.25	0.8

* The minimum winter runoff is observed in April over the Arctic slope and in March over the Pacific slope.

As this table shows, the general climatic trend optimizing, the total annual runoff of the majority of rivers over the Arctic slope of MWE becomes lower. Due to effects of warmer climatic conditions, rivers become to a greater extent recharged with ground waters hosted in STR, superpermafrost and continuous taliks. The exclusions are just some streams (the Kulu River), the runoff of which becomes greater including the subsurface constituent under warmer climate, which is due to different tectonic and neotectonic settings [17].

Over the Pacific slope, the similar trend of total runoff's decrease associated with its growing subsurface constituent is reported from the Anadyr Bay of the Bering Sea. Since 1960, all rivers within the Sea of Okhotsk basin have increased their runoffs. This increase dynamics is exemplified by the Dukcha River with its total runoff having increased as high as $0.35 \text{ m}^3 \cdot \text{s}^{-1}$ during 17 years (since 1971) relative to period of 1961-1971. The ground-water share of the river recharge in winter low-level period has obviously increased.

3. Discussing the Results

In current warmer climate conditions, different formational trends of water runoffs over the oceanic slopes are explained as due to cryolithic zone characteristics [18]. A continuous cryolithic zone having thickness greater than hypergenous fracturing depth (100-150 m) is distributed over the Arctic slope of MWE and in the northern areas of the Pacific slope. In our opinion, a decrease in the total water runoff under such geocryological settings has been the result of a whole set of natural and industrial factors.

Natural effects caused by climatic warming include higher annual average temperatures of STR, their greater thickness and a longer duration of the warm season. The results are the growing biological productivity of herbaceous vegetation, shrubby and arboreal plants, and formation of mountain-tundra soils of mountain-pine belt at divides with elevations about 1300-1400 m [19]. Losses of water used for evapotranspiration and photosynthesis become greater. An increase in air temperature in warm seasons enhances water evaporation losses over rocky slopes and mountain tundra of any type.

Besides natural impacts, industrial factors as well negatively affect the total runoff of rivers over the Arctic slope of MWE and are the most significant in mountain valleys of minor and medium rivers having catchment areas about 5000 – 6000 km^2 , where gold placers are mined by opencut methods. Thus, the bottoms of valleys of the Taskan, Detrin, Bererlyok and other river tributaries, and the lower portions of mountain slopes there are totally reworked by opencut activities from rivers headwaters down to mouth areas. Vegetation cover was destroyed and removed with gravel and pebble rocks outside the placer area. Alluvial deposits are washed off silt and clay and disposed in dumps. River channels were repeatedly displaced and superpermafrost taliks destroyed, and many artificial ponds were made with their surface water evaporation exceeding the amount of precipitations in warm seasons [20]. Industrial activities were accompanied by slope landslide processes destroying STR layers. These industrial activity effects combined with long-term natural alterations result in decrease tendencies of annual average water discharge and subsurface recharge of rivers in winter low-level period. The examples of such industrially altered rivers, as the Taskan and Detrin rivers, are presented in table 2.

Over the Pacific slope of MWE, within the Sea of Okhotsk basin, cryolithic zone becomes intermittent and continuous band-shaped taliks occur beneath channels of rivers of the 3rd and 2nd orders with catchment areas of 5 – 10 km^2 . Taliks are frequent over mountain slopes and in divide areas beneath bottoms of lakes of glacial or tectonic origins. All these factors contribute to both the reduction of the PFR layer's thickness to 100-150 m and formation of subpermafrost water-bearing fractured rocks. The result is that the river recharge in winter low-level period is here many times greater than over the Arctic slope. A growth of total runoff amounts is reported here from everywhere even for rivers with industrially impacted valleys, such as the Dukcha and Khasyn rivers, due to a rise in subsurface replenishment, the share of which can be as high as 70% of the total recharge. From here it follows, that in discontinuous cryolithic zone conditions, precipitations to a great extent replenish

the ground-water reserves within the active water-exchange zone, at account of which the surface streams with small catchment areas are recharged and have their runoffs all year round.

Current forecasts and predictions for expected climatic changes and possible responses of the cryolithic zone and hydrogeosphere are diverse and contradictory. The majority of researchers suggest a continuous rise in air temperature and precipitations amount. Presumably, the climate will become as warm as in the late Pleistocene, when the annual average temperature of air in NER territory was 4 – 4.5 °C higher than at present. So, over the coasts of the Anadyr Bay of the Bering Sea and at the Chukotian Sea the air temperatures will be 4-3 °C below zero and over the coasts of the East Siberian Sea temperatures will be 7-5 °C below zero. Within the Sea of Okhotsk basin, it can range from 2-3 °C below zero in continental areas to 0 °C over the coasts. In such temperature conditions, a continuous cryolithic zone becomes intermittent and then it transforms into the island-like or spot type. Over the Arctic slope of MWE, in compliance with the current situation described in this paper, a growing discontinuity of the cryolithic zone will be associated with its thickness reduction to 100-150 m in divide areas and even less over river valley slopes. A region-wide subpermafrost zone of hypergenous fracturing can form with its aquifer capacities generated by ice freezing and melting processes in fractures; such zone can be reasonable defined as the “cryohypergenous fracturing zone”. In climatic conditions, which will be similar to those existing now in mountain-taiga areas of the northern Amur River basin, atmospheric precipitations will be almost completely absorbed by soils [21]. Thus, the climatic conditions incessantly becoming warmer, the total river runoff is expected to increase both over the Arctic and Pacific slopes of MWE within the NER territory. Such an increase will be provided by active water-exchange zones developing everywhere at account of greater areas of thawing rocks, smaller cryolithic thicknesses, and formation of subpermafrost aquifer zone of regional cryohypergenous fracturing. On the whole, this prediction is geocologically favorable as it raises the industrial attractiveness of this region including its agricultural sector. However, the negative consequences are as well possible due to intense denudational and thermoerosional processes. In order to control this situation, long-term monitoring stations shall be established as soon as possible in areas of crucial climate-monitoring significance.

4. Conclusion

The results obtained from conducted studies serve for us as a basis to make the following conclusions:

- Long-term meteorological observations, as long as 160 – 50 years periods, over the NER territory, indicate unambiguously a progressive warming of climate that has become even more intense since the 1960s;
- Warmer climates and greater precipitations in areas of continuous cryolithic zone having thicknesses more than 150-180 m over the Arctic slope of MWE and in the northern part of the Pacific slope, that is the drainage area of rivers flowing into the Anadyr Bay of the Bering Sea, result in a decrease of the total runoff there, whereas the share of subsurface replenishment of streams is increased to a greater extent at account of STR water, and to a lesser extent – of subchannel taliks;
- Modern climatic changes over the Pacific slope of MWE, within the Sea of Okhotsk basin, where cryolithic zone is discontinuous, are associated both with an increase in total runoff of rivers and a considerable share of their subsurface recharge including subpermafrost aquifer zone of regional cryohypergenous fracturing and long subchannel continuous taliks;
- The runoff balance responses to modern climatic changes are influenced by their different ground-water recharge regimes in continuous and discontinuous cryolithic zone conditions;
- In the first case, the STR layer is the basic constituent of the active water exchange zone; it has a small thickness and its ground waters are placed close to the day surface, so the STR water is mainly used to provide the processes of evapotranspiration and plants photosynthesis, and evaporation of summer precipitations from rocky slopes; the losses of water become naturally greater due to higher air temperatures and also as a result of such industrial activities as opencut mining of gold placers in river valleys;

- In discontinuous cryolithic zone conditions, meteoric water is absorbed not only by STR layer, but also, via continuous taliks, by subpermafrost aquifer zone of cryohypergenous fracturing; therefore, warmer climate conditions favor both infiltration processes of atmospheric water and its participation in rivers recharges;

- The expected warming shall cause transformation of continuous cryolithic zone into discontinuous type over the Arctic slope of MWE and in the northern areas of the Pacific slope, and its subsequent transformation into the island-shaped and spot types within the Sea of Okhotsk basin of the Pacific slope; such transformations of the cryolithic zone shall favor an increase in the total runoff everywhere, including to the largest extent an increase in its subsurface constituent; from geoecological viewpoints, the expected warming and presumed responses to it of the cryolithic zone and hydrogeosphere shall have positive effects for people, however, a strict monitoring of these processes is obligatory.

References

- [1] Glotov V E 2002 *The factors forming total runoff of small mountain rivers in the Subarctic* (Magadan: SVKNII DVO RAN) 182-201
- [2] Fotiev S M 2013 *Earth's Cryosphere* **17** (2) 41-59
- [3] Glotov V E and Glotova L P 2011 *Russ. J. of Pacific Geology* **30** (5) 93-104
- [4] Bojcov Ju A, and Kuznecov A S 1979 *Kolyma* **10** 28-30
- [5] Slaughter C, Glotov V E and Michailov W M 1995 *Water Air and Soil Pollution* 351-361
- [6] 1977 *Observational data of Kolyma podnebesova station in 1975* (Magadan: KUGMS) **16** 155
- [7] Glotov V E 2002 *The factors forming total runoff of small mountain rivers in the Subarctic* (Magadan: SVKNII DVO RAN) 102-141
- [8] Glotov V E 2016 *Bulletin of the North-East Scientific Center, Russia Academy of Sciences Far East Branch* **3** 36-46
- [9] Glotov V E and Glotova L P 2012 *Earth's Cryosphere* **16** 57-66
- [10] Gavrilova M K 2003 *Review of the status and trends in the climate of Yakutia* (Jakutsk: JaF SO RAN) 12-18
- [11] Glotov V E, Glotova L P and Ushakov M V 2014 *Environmental geoscience* **1** 20-27
- [12] 1988 *Annual data on the regime and resources of surface land waters* **1100**
- [13] 1985 *Annual data on the regime and resources of surface land waters* **1** 430
- [14] 1966 *The main hydrological characteristics. North-East of the USSR* (L.: Gidrometeoizdat) **19** 379
- [15] 1974 *The main hydrological characteristics. North-East of the USSR* (L.: Gidrometeoizdat) **19** 230
- [16] 1978 *The main hydrological characteristics. North-East of the USSR* (L.: Gidrometeoizdat) **19** 226
- [17] Glotov V E and Glotova L P 2010 *Bulletin of the North-East Scientific Center, Russia Academy of Sciences Far East Branch* **1** 89-98
- [18] Woo M-K 1990 *Northern Hydrology: Canadian Perspectives* ed. Prowse T D **1** 63-76
- [19] Pugachev A A 2002 *The factors forming total runoff of small mountain rivers in the Subarctic* (Magadan: SVKNII DVO RAN) 141-166
- [20] Sushhanskij S I 2002 *The factors forming total runoff of small mountain rivers in the Subarctic* (Magadan: SVKNII DVO RAN) 18-35
- [21] Kirjuhin V P 1981 *Zonality of underground waters of platform and homoscedastic areas* (L.: GO SSSR) 12-25