Analysis of spatial variability of river streamflow at the catchment area of the Kolyma reservoir

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Abstract. Analysis of the streamflow characteristics of fourteen streams and rivers on the catchment area of the Kolyma reservoir showed that spatial variations of the annual total streamflow agree with the variability of precipitation. The maximum daily flow and duration of the flow period depend on the catchment area. The fraction of different landscapes of the watershed is indicator of such processes as the water discharge from the talik aquifers at the river valleys and the cryogenic redistribution of streamflow that affect the variation coefficient of streamflow, the maximum flow and the duration of the flow period.

1. Introduction

The catchment area of the Kolyma reservoir is 61500 km² and it is poorly studied. There are only six hydrological gauges where river discharge is measured. 25% of the reservoir catchment area is ungauged.

Existing estimates of the streamflow changes at the Kolyma river basin are controversial. The Kolyma basin is one of the six largest Siberian Rivers analyzed by Peterson et al. [1], and this river showed no increase in yearly discharge. Majhi and Yang [2] reported moderate increases of streamflow in the upper basin and weak decreases in the mid–lower Kolyma River basin. Water inflow to the Kolyma reservoir is increasing [3] while streamflow of some rivers in the upper Kolyma river basin is decreasing [4, 5]. The spatial variability of the streamflow characteristics is explained by the permafrost properties [5], topography of the catchments [6], anthropogenic influence and tectonics [7]. Detailed hydrological studies at the Kolyma river basin was performed only at the small watersheds of the Kolyma water-balance station (KWBS): water balance estimation [8-10], investigation of the river streamflow generation in the mountainous permafrost areas [11-14], assessment of hydrological role of permafrost landscapes [15-16]. Spatial variability of the middle-sized rivers streamflow and its connection with the landscape structure has not been previously studied.

The aim of the work was to analyze the spatial variability of river streamflow characteristics and their relationship with the catchment area and land surface types at the river basins located on the catchment area of the Kolyma reservoir.
2. Materials and methods
Streamflow analysis was performed for six river basins in the catchment area of the Kolyma reservoir and eight streams within the KWBS (Table 1). Except KWBS, these are all the hydrological gauges that are currently operated in the catchment area of the Kolyma reservoir according to the Automated Information System of the State Monitoring of Water Objects (AIS GMVO, gmvo.skniivh.ru). Length of daily river discharge data series varies from 19 to 66 years.

The catchment area of studied rivers ranges from 0.27 to 42,600 km². The sources of the Kolyma River are situated in the Yano-Oimyakonsk mountain region. The headwaters of the Kolyma River and its right tributaries are located on the Kolyma mountain region where the mid-mountainous terrain predominates with average elevation of 1000-1200 m. The altitude of individual massifs reaches 2000-2500 m (the Aborigen peak is 2586 m).

The studied part of the Kolyma River basin belongs to the sub-arctic climate. The mean annual air temperature is below 9.5°C, the amount of precipitation is from 220 to 460 mm per year. 60% of precipitation falls as snow. The duration of winter is more than 7 months per year. The region is covered by continuous permafrost. The permafrost thickness on the watersheds divides is up to 600-700 m, in the river valleys – up to 180 m. The region belongs to the northern taiga landscape zone.

For each discharge data series following characteristics were calculated: 1) total annual streamflow, F, mm, 2) annual duration of the flow period, T, days, 3) highest annual daily flow, M, mm/day, 4) mean monthly streamflow for the entire observation period, mm/month, 5) mean annual total streamflow (mm/year), mean annual duration of the flow period (days), mean highest annual daily flow (mm/day), variation coefficient of the total annual streamflow (Cv F) and the variation coefficient of the highest annual daily flow (Cv M). Years with missing data were ignored. Estimated streamflow characteristics and properties of the studied river basins are shown in table 1. Relationships between streamflow characteristics, the catchment area and fractions of the land surface types were analyzed.

3. Results
The mean F in the Kolyma reservoir watershed varies from 177 (Talok - mouth, 65 km²) to 454 mm/year (Morozova-Vodopadny, 0.63 km²) and does not depend on the catchment area (Figure 1B). The minimum F is equal to 63 mm/year (Talok, 1983), the maximum - 810 mm/year (Omchak - Omchak, 2013; data for 2013 may be of lower accuracy due to high flooding). Among the analyzed rivers Morozova stream has the lowest Cv F (0.16). The middle-sized catchments of the Talok, Omchak and Omchuk rivers with areas ranging from 65 to 583 km² have the largest values of Cv F (> 0.4). Cv F goes down both with decreasing and increasing the catchment area (figure 1D).

The mean M varies from 6.5 (Kolyma - Orotuk, 42,600 km²) to 29.6 (Morozova - Vodopadny, 0.63 km²) mm/day and is characterized by Cv M from 0.29 (Morozova - Vodopadny, 0.63 km²) to 0.64 (Omchak - Omchak, 151 km²). The mean M increases with decreasing catchment area (figure 1C). Outliers from this relation are Talok River towards lower value and Morozova stream towards higher M. The highest values of Cv M (> 0.5) have both medium-sized (65-583 km²) and small (<0.4 km²) catchments (figure 1D).

All the studied streams and rivers flow every year. On annually freezing-up rivers, the mean T varies from 116 (Morozova creek, 0.63 km²) to 203 (Omchuk - Ust-Omchug, 583 km²) days and increases with the catchment area (figure 1B). Detrin River with a catchment area of 3,490 km² freezes up occasionally. Larger rivers do not freeze up and flow year-round.

The largest part of the flow of the Dozhdemerny, the Vstrecha creeks, the Detrin and the Kulu Rivers occurs during the spring flood in May and June. At the Yuzhny, Severny creeks, the Talok and Omchak rivers flash floods in July and August dominate over spring freshet. The streamflow of the Kontaktovy creek, the Omchuk and Kolyma Rivers is distributed evenly between periods of spring freshet and summer floods with a slight predominance of the first one.


| Code  | River - gauge          | A, km² | H, m  | Y, years | F, mm  | Cv F | T, days | M, mm  | Cv M |
|-------|------------------------|--------|-------|----------|--------|------|---------|--------|------|
| 1104  | Yuzhny- mouth          | 0.27   | 850-1100 | 53      | 203    | 0.29 | 150     | 17.5   | 0.53 |
| 1107  | Severny - flume        | 0.38   | 880-1300 | 55      | 250    | 0.36 | 159     | 16.9   | 0.53 |
| 1103  | Morozova- Vodopadny   | 0.63   | 1100-1700 | 29      | 454    | 0.16 | 116     | 29.6   | 0.29 |
| 1106  | Dozhdemerny- mouth     | 1.43   | 850-1300 | 24      | 209    | 0.26 | 161     | 12.7   | 0.25 |
| 1105  | Vstrecha – upstream Ugroza mouth | 5.35 | 830-1300 | 65      | 266    | 0.34 | 162     | 15.5   | 0.50 |
| 1625  | Vstrecha- Ugroza mouth| 6.57   | 800-1200 | 26      | 322    | 0.24 | 165     | 18.5   | 0.38 |
| 1101  | Kontaktovy- Sredny     | 14.2   | 840-1700 | 64      | 324    | 0.34 | 165     | 17.0   | 0.43 |
| 1102  | Kontaktovy- Nizhny     | 21.3   | 800-1700 | 66      | 322    | 0.29 | 179     | 16.4   | 0.41 |
| 1081  | Tanok - mouth          | 65     | 600-1900 | 45      | 177    | 0.56 | 169     | 8.0    | 0.58 |
| 1127  | Omchak - Omchak        | 151    | 800-1500 | 41      | 312    | 0.41 | 169     | 14.6   | 0.64 |
| 1619  | Omchuk–Ust’-Omchug    | 583    | 500-1600 | 54      | 227    | 0.42 | 203     | 13.2   | 0.51 |
| 1151  | Detrin - Omchuk mouth | 3490   | 500-1800 | 59      | 325    | 0.30 | 364     | 10.5   | 0.38 |
| 1095  | Kulu - Kulu            | 10300  | 600-2000 | 52      | 294    | 0.22 | 365     | 8.5    | 0.33 |
| 1001  | Kolyma - Orotuk       | 42600  | 500-2200 | 19      | 230    | 0.26 | 365     | 6.8    | 0.37 |

A – catchment area, km²; H – minimum and maximum catchment elevation, m; Y – length of river discharge data series, years; F – mean, minimum and maximum total annual streamflow, mm; Cv F – variation coefficient of total annual streamflow; T – mean, minimum and maximum duration of the flow period, days; M - mean, minimum and maximum highest annual daily flow, mm; Cv M– variation coefficient of highest annual daily flow.
Figure 1. A – relation between variation coefficient and mean annual streamflow, B – relation between mean annual streamflow, duration of flow period and catchment area, C – relation between maximum daily flow and catchment area, D – relation between variation coefficient of mean annual streamflow, variation coefficient of maximum daily flow and catchment area, E – relation between variation coefficient of mean annual streamflow and fraction of rocky talus, F – relation between maximum daily flow and fraction of rocky talus and larch forest.

A scheme of the land surface type distribution for the Kolyma reservoir catchment area was developed based on the historical landscapes studies at the KWBS [16]. The areas above 1,100 m were attributed to rocky talus, territory below 900 m – to larch forest. The south-facing slopes within
elevation range of 900-1100 m were attributed to the dwarf cedar and alder shrubs, north-facing – to the larch sparse woodland with moss-lichen cover. The more detailed information about development of land cover distribution scheme could be found in [17, 18].

Relationship between streamflow characteristics and fraction of land cover types showed that the mean $F$ does not depend on land cover. Fig. 1E shows that the larger area of the rocky talus, the lower the $Cv F$. The higher fraction of rocky talus and the lower fraction of larch forest, the greater mean $M$ (figure 1F). For freezing-up rivers, it was found that the higher fraction of larch forest, the longer the duration of the flow period.

4. Discussion
The Morozova stream and the Talok River outlie at the scatter plot of $F$ and $Cv F$ (figure 1A). The streamflow of the remaining rivers and streams varies within relatively narrow limits — from 203 to 325 mm/year, which is comparable to the spatial variability of precipitation in the region — from 220 to 460 mm/year. Talok River catchment is located in a narrow elongated valley, closed from the east, north and west sidesby mountain ranges. Presumably, due to the specific topography, this catchment receives less precipitation than the surrounding area, and has reduced streamflow. The average elevation of the Morozova watershed is 1370 m – the largest among all studied river basins. It is located on the windward slope of the ridge, receives more precipitation and produces higher streamflow. According to Mikhailov (2014) the spatial variability of maximum discharge in the Kolyma river basin is lower than in the Yana and Indigirka rivers basins and associated with the topography of the watersheds that is consistent with our findings.

Low $Cv F$ at the Morozova stream, in addition to its high absolute value, could be explained by cryogenic flow redistribution due to the partial freezing of the melt and rain water in the rocky talus. Ice in the rocky talus melts during the warm season and feed stream even in dry periods [9, 13, 18, 19]. The same process explains the decrease in the $Cv F$ with an increase of rocky talus fraction of the catchment. An increase in $M$ with an increase of rocky talus fraction and a decrease of larch forest fraction may be associated with precipitation and slope incline increase with elevation in the mountains. The $T$ increase with an increase of larch forest fraction can be explained by the water discharge from the talik aquifers at the river valleys longer in autumn and winter. According to Mikhailov [20] two thirds of the total length of the river network is occupied by taliks in the Kulu river basin. In the Upper Kolyma basin, floodplain taliks occupy about 90% of the river valleys.

Monthly distribution of streamflow and other hydrological characteristics of Kontaktovy - Nizhny and Kolyma - Orotuk are very close, that confirms that KWBS is still representative for the upper part of the Kolyma river basin even in changing climate that was firstly shown by Nasybulin [21].

5. Conclusion
Spatial variations of the streamflow agree with the variability of precipitation in the catchment area of the Kolyma reservoir. The maximum flow and duration of the flow period depend on the catchment area and dominant land surface types. The land surface types indicate such processes as water discharge from the talik aquifers at the river valleys and the cryogenic redistribution of streamflow. Topography could explain outliers from the found relations between streamflow characteristics and catchment area.

References
[1] Peterson B, Holmes R, McClelland J, Vorosmarty C, Lammers R, Shiklomanov A, Shiklomanov I and Rahmstorf S 2002 Increasing river discharge to the Arctic Ocean. Science 298 2171–2173
[2] Majhi I and Yang D 2008 Streamflow characteristics and changes in Kolyma Basin in Siberia. J. Hydrometro 9 267–279
[3] Ushakov M, Lebedeva L 2016 Climate change regime of formation of water inflow in the Kolyma reservoir Scientific bulletins of the Belgorod State University Series: Natural Sciences 25(246) 37 120-127 (in Russian)

[4] Glotov V and Glotova L 2011 Changes of fresh natural waters resources in mountain areas of cryolithozone at global climate warming (on the example of northeast of Russia) Izvestia of Samara Scientific Center of the RAS 13 1(6) (in Russian)

[5] Glotov V and Glotova L 2018 Peculiarities of modern changes of the total and underground runoff in North-East Russia Vestnik NESC FEB RAS 1 39-48 (in Russian)

[6] Mikhaylov V 2014 Variation and estimation of mean maximum water discharges in the rivers of the North-East Russia Vestnik NESC FEB RAS 2 21-26 (in Russian)

[7] Glotov V, Glotova L and Ushakov M 2011 Anomalous changes of Kolyma-river runoff condition in winter period Earth’s Cryosphere J. 15 1(1) 52-60 (in Russian)

[8] Zhuravin S 2004 Features of water balance for small mountainous basins in East Siberia: Kolyma Water Balance Station case study IAHS Publ 290 28–40

[9] Lebedeva L, Makarieva O and Vinogradova T 2017 Spatial variability of the water balance elements in mountain catchments in the North-East Russia (case study of the Kolyma Water Balance Station) Meteorology Hydrometeorology J. 4 90–101 (in Russian)

[10] Makarieva O, Nesterova N, Lebedeva L and Sushansky S 2018 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

[11] Boyarintsev E and Gopchenko E 1992 Summer period water balance of small mountain catchments of the permafrost and its calculation Meteorology Climatol Hidrometeorology J. 27 105–16 (in Russian)

[12] Sushansky S 1990 Peculiarities of water balance elements in the Morozova Creek catchment, Kolyma J. 1 33–40 (in Russian)

[13] Bantsekina T 2002 Temperature regime and dynamics of icing of coarse-grained slope deposits without filling during spring-summer period (case study of the Kontaktovy creek) Kolyma J. 4 1–9 (in Russian)

[14] Bolgov M, Boyarintsev Y and Filimonova M 2018 Simulating of the flood runoff in case of heavy rains in the zone of many-year frozen earths Water sector of Russia: problems, technologies, management 1 6-17 (in Russian)

[15] Korolev Y 1984 Mapping of the vegetation cover in connection with an assessment of its hydrological role (by the example of the Upper Kolyma) PhD Magadan University Yakutia, 231 (in Russian)

[16] Pugachev A 2002 Top soil in the territory of the Kolyma Water Balance Station Subarctic Small Mountain Rivers: Runoff Controls (from Data of Kolyma Water Balance Station). SVKNIIDVO RAN Magadan 141–166 (in Russian)

[17] Lebedeva L, Makarieva O and Vinogradova T 2015 Hydrological modeling: seasonal thaw depths in different landscapes of the Kolyma Water Balance Station (Part 2) Earth’s Cryosphere J. 2 35–44 (in Russian)

[18] Lebedeva L 2018 Formation of river streamflow in permafrost zone of Eastern Siberia PhD thesis Melnikov Permafrost Institute Yakutsk 125 (in Russian)

[19] Semenova O, Lebedeva L and Vinogradov Y 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

[20] Mikhaylov V 2010 Assessment of floodplain taliks in the upper reaches of the Kolyma River basin Geokolologiya 1 52–61 (in Russian)

[21] Nasybulin P 1976 The representativity of runoff characteristics at the Kolyma Water Balance Station for the upper Kolyma area Natural resources of the USSR North-East, Vladivostok, AN DVISIBPS 32–41 (in Russian)