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Research Article

Thermal regime of water courses of different order in the basin of the Upper Kolyma River

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Abstract

Evaluation of hydrological parameters and temperature regime of watercourses of various orders comes to the fore when studying the scientific problems of hydrobiology of watercourses and solving practical problems of development of fisheries and gold exploration in the regions of the Far North. This became particularly relevant due to a significant reduction in hydrological observations since the early 1990s. This article presents a quantitative investigation into the thermal regime of water courses and their spatial pattern. The paper focuses specifically studying the temperature and basic spatial parameters of streams and rivers in the area of interest. Statistical methods helped identify a close linkage between the temperature of water courses in the basin of the Upper Kolyma River and their respective sizes. A common trend has been found proving that the water temperature in the rivers increases downstream and with the increase in water course size, also known as order. A close correlation between the average water temperature, on the one hand, and the catchment area and water course length, on the other, is indicated by the relatively high correlation coefficients of 0.61 to 0.63 and 0.71 to 0.73, respectively. Average water temperatures in the summer and warm periods have been found to escalate with the increase of water course order from low (I and II) to high (VI–VII) by 4.7°C and 5.9°C, respectively, and in the Kolyma River – in the direction from the upper section (Orotuk village) to the lower section (the Korkodon River mouth) by 1.7°C and 2.1°C, respectively, even though the lower section of the river is located almost 2° north of the upper section. Due to the presence of perennial permafrost, river taliks have a cooling effect on the thermal regime of watercourses, so coolness occurs in sections of the river where there are favorable conditions for their formation. This is, first of all, the increased thickness of the well-permeable coarse-grained alluvium of the channel facies and open fracture zones in the bedrock.

Keywords

cryolithic zone, surface waters, thermal regime, order of water courses, mean temperatures, June–August period, May–September period, and correlation

Study area

The upper reaches of the Kolyma River are located in the Upper Kolyma Highlands of the Yano-Chukotka secondary fold system. The topography of the area is typically characterised by low and medium elevation mountains. The Mesozoic sandy shale here lies in the base of the geological profile, ruptured in many places by the granitoid magmatic rock surfacing on the mountain peaks. As a result, the blanket-type bed rocks on the river valley slopes are overlapped by loose weathering products of the same rock types. These rocks are represented in the divide section by colluvial rudaceous soil and, in the lower reaches, by diluvial and diluvio-solifluctional soil. At the foot of the river valley slopes, one typically finds plumes of silty slope detrital rock. The valley bottoms are chiefly built with channel pebblestone capped by silty deposits of floodplain facies of a relatively small thickness of 2 to 3 metres (Ershov 1989, Ukhov and Pugachev 1999).

The severe climate, with an annual average air temperature below minus 8–12°C, contributes to the widespread development of permafrost. In the summer season, the soil in the area of interest thaws to a depth of 0.4 to 0.5 metres in peat and 3.0 to 3.5 metres in rudaceous rocks (Ershov 1989, Ukhov and Pugachev 1999).

The valleys of water courses on the upper reaches of the Kolyma River are characterised by elevation-dependent zonality of the terrain. For example, the areas adjacent to the water divide are typically rocky and occupied by mountain tundra; below them is a cedar shrub belt with predominance of podzolised brown soil; further below are larch tree woods with permafrost soils typical of the taiga and swamps. Thawed lenses of the permafrost develop in the bottoms of mid-sized, large and, less frequently, small water courses (Fig. 1).

Development of riverside thawed lenses in the river valleys is indicated by the presence of azonal deciduous forest stands (willows, poplar, chosenia) that grow in the near-channel belt of the water courses or by complete absence of trees. The occcurence of taliks in river valleys is favored by the presence of well-permeable coarse-grained channel alluvium and fissured bedrock, and, especially, the presence of tectonic faults under the river bed and along the river banks (Mikhailov 1993, Mikhailov and Ukhov 1999).

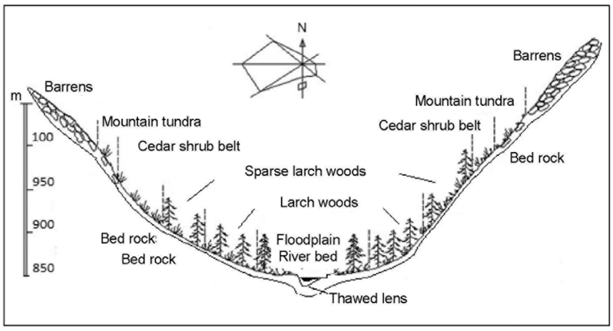

Fig. 1. Sketch of the landscape profile in the valleys of small rivers (acc. to A.A. Pugachev, with amendments)

Materials and methods

As defined by GOST Standard 19179-73, small rivers are permanent or temporary water courses that occur in uniform conditions (within the same geographic zone) and are characterised by a stream regime predicated on local factors (GOST 1973). Based on the existing rating and classification of rivers within the limits of the former USSR, the maximum length of a small river is 25 km and rivers of shorter length (up to 10 km) are rated as very small rivers (Rokhmistrov 204: 7). This classification of small rivers best suits the rivers in the basin of the Upper Kolyma River, which is characterised by mountain terrain, chiefly with medium elevation mountains.

Many researchers, starting with R.E. Horton and later A.N. Strahler, used statistical methods to establish the dependence of geomorphological and hydrological properties (e.g., yearly average discharge, number of tributaries, width of low-water bed, gradients, branching ratio, etc.) of the water courses on their order (Horton 1945, Strahler 1952, 1957). For the continental areas of the North-Eastern region, such research was carried out on the basis of statistically valid data using the example of three groups of water course with orders I through VII. The length of water courses from group one (orders I–II) is 1.0 to 2.5 km, group two (orders III–V) – 5 to 20 km, and group three (VI–VII) – 40 to 70 km, while the river bed widths are 1 to 5 m, 8 to 40 m and 30 to 210 m, respectively. The variation in the mean gradient is 0.25% to 0.01% for the first group, 0.006% to 0.042% for the second group, and 0.003% to 0.017% for the third group (The geology of alluvial deposits 1979).

The global climate changes observed in many places around the world (Vakulenko et al. 2015, Pestereva 1996) could not but impact on the pattern of hydrogeological parameters of water courses (Burn 1994), including in the permafrost region (Woo 1990). These changes occurring over the past decades, including an air temperature rise, were followed in the unique conditions of the cryolithic zone of the Kolyma River basin by an increase in river flow and a minor decrease in the water temperature in the river systems (Zasypkina et al. 2016).

The hydrological data was chiefly borrowed from digests containing the results of annual observations of the regime and resources of surface waters on land (Annual Data 1989–2015). The hydrometeorological stations whose data is used in the analysis of hydrological parameters are depicted in Kolyma-Korkodon, Kolyma-Balygychan, Elgen, Susuman-Talok, Yagodnoye, Srednekan, Orotukan, Kolyma-Sinegorye, Kolyma-Otoruk, Krivulya, Kulu Omchak, Stokovaya, Kolyma-Bokholcha, Omchuk, Magadan.

This article describes how statistical methods were used to reconfirm the size of small rivers in the basin of the upper reaches of the Kolyma River through the example of the thoroughly studied basin of the Itrikan River. The Kolymskaya water balance gauging station, the only such station in the mountainous region of Russia's cryolithic zone, is located on one of the tributaries of the Itrikan River.

The purpose of this study is to investigate the thermal regime of water courses of different orders using statistical methods. The process involved a study of the dependence of average water temperatures in the channels in the summer and warm periods on the length of water courses and their catchment area sizes.

Results

A detailed statistical analysis of the spatial properties of water courses depending on their order was carried out relying on the previously identified correlation between water course order and size through the example of the thoroughly studied hydrological aspects of the Itrikan River basin (order V, 29.6 km long). The parameters and orders of the water courses in the study are in accordance with the territorial classification (The geology of alluvial deposits 1979).

The comparison of the length of water courses in the Yano-Kolymskaya province (The geology of alluvial deposits 1979) and in the basin of the Upper Kolyma River through the example of the Itrikan River (tributary of the Kulu River) demonstrates their generally acceptable match, specifically for III – IV order water courses (Table 1).

Table 1. Qualification of small water courses in the Itrikan river basin

Parameter	Order				
	I	II	III	IV	V
Number of water courses	84	19	5	2	1
Total length, km	143.3	73.1	41.4	47.4	29.6
Mean, km	1.7	3.9	8.3	23.7	29.6
Mean error, km	0.08	0.3	0.88	1.07	–
Minimum, km	0.5	1.9	5.9	22.6	29.6
Maximum, km	3.9	6.6	10.7	24.8	29.6

This article also presents a case study of long-time water temperatures in rivers and streams along with the average temperature values in the summer months (June–August) and the warm period of May through September (Table 2).

Note that gauging stations of the Kolyma Hydrometeorological Department where the water temperature is measured in the river channels are located on water courses of different orders. Some of them are set up on small, first order water courses, such as the Yuzhny Stream, with a catchment area of 0.27 km^2, and others on bigger rivers, for example, the main channel of the Kolyma River (ninth order water course).

Table 2. consolidated, average, long-time water temperatures in the water courses of the upper Kolyma River basin in June–August and May–September

Station	Observation period	Spatial parameters of water courses		Average water temperature, °C, in the periods	
		Length, km	Catchment area, km²	May–September	June–August
Orotuk, Kolyma River	1989–2014	360	42600	7.6	10.6
Sinegorye, Kolyma River	1989–1992, 1994–2014	585	61500	6.6	7.5
Srednekan, Kolyma River	1989–2014	806	99400	7.9	11.0
Balygychan, Kolyma River	1989–2014	1063	140000	9.0	12.1
Korkodon, Weather Station, Kolyma River	1989–1991, 1993–1997, 1999–2014	1203	231000	9.3	12.7
Susuman, Berelekh River	1989–1993, 1995–2014	172	7140	5.9	8.7
Mouth of Bokhapcha River	1989–2014	206.6	13600	7.4	10.4
Mouth of Talok River	1989–2014	24	65.2	4.4	6.7
Kulu, Kulu River	1989–1994, 1996–2014	217	10300	6.7	9.3
Omchak, Omchak River	1989–2014	46	151	6.2	6.5
Mouth of Omchuk River, Detrin River	1989–2014	126	3490	6.2	8.1
Ust-Omchug, Omchuk River	1989–2014	94.5	583	6.1	8.2
Mouth of Yagodny Stream	1989–2014	15.6	100	3.5	4.9
Orotukan, Orotukan River	1989–1992, 1994–1999, 1997–2007, 2009–2014	47	740	7.0	9.9
Elgen, Taskan River	1996–2014	219	9970	6.9	9.7
Kontaktovy Stream, middle	2000–2013	6.2	14.2	2.4	3.3
Kontaktovy Stream, low	1999–2014	7.1	21.2	2.6	3.1
Mouth of Yuzhny Stream	2000–2012	0.51	0.27	0.7	1.1
Mouth of Vstrecha Stream	2000–2013	3.6	6.42	2.1	2.8
Mouth of Krivulya Stream	1989–1994	6.1	8.52	2.7	3.7

The catchment area of big rivers may be as much as dozens to hundreds of thousands of square kilometres. The gauging stations whose temperature measurement results were analysed in this paper are distributed as follows: seven on low-order, four on medium-order and nine on high-order water courses.

The data on average water temperatures in sections of water courses of different lengths and catchment areas are presented in Table 2. Consolidated quantitative spatial data (total number and mean length) and average temperatures in the water courses of different orders in the area of interest are also provided in Table 2.

Statistically processed data on average water temperatures in water courses of different length indicates a generally consistent trend of temperature growth as the size of water courses increases (Fig. 2).

Discussion

The correlation coefficients between the average temperatures in the periods of June–August and May–September in the water courses and their catchment area at the location of gauging stations are 0.61 and 0.63, respectively, and between the temperatures and the length of water courses – 0.71 and 0.73, respectively, this proving a close correlation.

Let us look into the reasons for deviation by the correlation coefficient amid the general trend of rising average temperatures with the increase in water course size from small to large. The break points on the graph of average water temperatures are indicative of the features of heat exchange between the water course and the rock in the near-channel belts (Fig. 2). Let us consistently analyse the key elements that influence the thermal regime of the

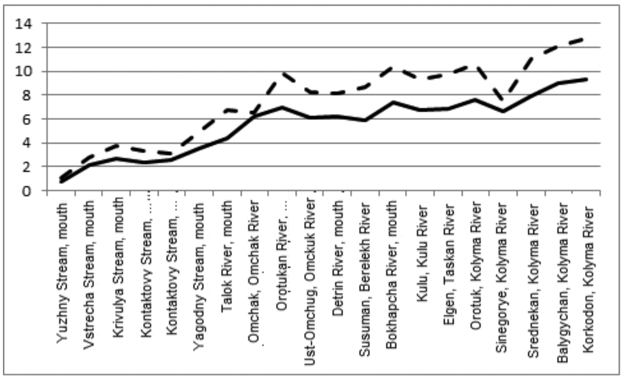

Fig. 2. Correlation between average temperature of water courses in the periods of June – August (dotted line) and May – September (solid line) and their length

water courses depending on their size (length and catchment area).

Since the basin of the Upper Kolyma River is located in the mountains, the sizes of the water courses (effective cross-section, length, catchment area) increase chiefly thanks to the width. Turbulent water flow, specifically in high-order water courses, results in almost uniform temperatures in a given water course. This causes a higher intake of heat from the atmosphere and a rise in the water temperature in the channel with the increase in the order of the water course and, therefore, its length, catchment area and channel width. The graph in Fig. 2 shows that the water temperature in Kontaktovy Stream rise as the length of water courses increases in the section between Yuzhny Stream and Krivulya Stream.

Table 3. Average spatial parameters and temepratures of water courses of different orders

Order		Water course parameters		Average water temperature, °C, in the periods	
Groups	Valleys	Number	Mean length	May – September	June – August
Low	I	36 350	1	2.9	4.0
	II	7 830	3.4		
Medium	III	1880	8.3	5.3	7.0
	IV	450	17.5		
	V	110	36.9		
High	VI	26	76.9	7.2	9.9
	VII	7	175		

Many sections of water courses, even small ones, with a relatively thick and highly permeable layer of pebblestone deposit in the river valleys offer suitable environments for development of under-channel and, less frequently, alluvial thawed lenses in permafrost. These are the most favourable areas for multiple “discharge” of warmer river waters into cold frozen ground and their subsequent recharge back into the river channel. Thermal energy of talik water is spent heating and thawing frozen, mainly coarse alluvium. Such deviations from the general trend of increasing surface temperature in watercourses depending on their size (length) indicate the degree of intensity of the development of taliks. (Table 2, Fig. 2). For example, a minor and less frequently inverse trend of temperature growth is typical of water courses with lateral thawed lenses, such as Kontaktovy Stream and rivers Omchug, Detrin and Berelekh, and a higher trend – in the sections of rivers Orotukan and Bokhapcha. In the latter case, we must note the small thickness and low permeability of the lateral alluvial rock, which impedes development of thawed lenses. Significant anomalies in the temperature trend are most likely a result of human impact, i.e., construction of the Kolyma hydropower system.

In the main channel of the Kolyma River, water temperature rises from the springhead to the mouth of the river. For example, in the section of the valley from Orotuk village to the Korkodon weather station, average water temperature in the summer and warm periods has been observed to rise by 1.7°C to 2.1°C, even though the weather station is located almost 2 degrees to the north.

Statistical processing of the basic hydrological properties of rivers in the basin of the upper reaches of the Kolyma River helped determine the average number and length of water courses of order I – VII (Table 3). Moreover, average water temperatures over the summer and in the warm period have been determined for the same water courses.

The data provided in the table indicate there is a close correlation between the thermal regime of the water and the order of water courses, and average temperatures in such water courses increase from low order (I and II) to high order (VI – VII) both in the summer period (4.7°C) and in the warm period (5.9°C).

Conclusion

This study presents research intended to establish a statistically valid correlation between certain hydrological parameters of water courses in the basin of the Upper Kolyma River.

The research helped determine the mean length and number of water courses depending on their order, as well as their thermal regime in the summer period (June–August) and warm period (May–September).

The high correlation coefficient between the average temperatures in the summer period (June – August) and warm period (May – September) and the length of the water courses proves a close tie between these parameters. It is worth mentioning that, if factors other than the size of water course did not impact on the water temperature, the above correlations would verge toward functional correlations and the correlation coefficient value would be close to unity.

There is a consistent trend of water temperature rise in the channel of water courses not only with the increase in the water course order but also in any given water course in the direction from the springhead toward the mouth, for instance, in the Kolyma River.

There is also a common pattern of rising average water temperature in the channels as the water course order increases, despite the changes in both "external" heat exchange (with the atmosphere) and "internal" exchange (with the rock).

Owing to the exchange of heat with the rock, the high rate of appearance of thawed lenses in the near channel becomes the major cause of deviation from the general trend of rising average water temperatures with the increase in length or catchment area of the water courses. Consequently, average temperatures of water courses of certain orders in the basin of the upper reaches of the Kolyma River in the summer and warm periods might indicate development of thawed lenses and, by implication, provide qualitative evidence of the thickness and permeability of near-channel rocks in river valleys. Quantitative resolution of these problems will require further detailed investigations.

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