Dynamics of Hydrological Regime in Permafrost Zone of Central Siberia

Tamara Burenina 1+, Alexander Onuchin 1, Georg Guggenberger 2, Anastasia Musokhranova 1 and Dmitri Prisov 1

1 V. N. Sukachev Institute of Forest, Siberian Branch of the Russian, Academy of Sciences, Krasnoyarsk, Russia
2 Leibniz University, Hannover, Germany

Abstract. It was analyzed the runoff for northern rivers to find that it varies both spatially and temporally. Its spatial variability is determined by the locations of the rivers of interest, which relationship is clearly manifested in the seasonal dynamics of the hydrological regimes of the rivers. The more to the north the river, the more pronounced the snowmelt flood and rain-caused stream rise peaks. The flow of the river having small basins may increase many times after even small rains. The study of river flow in permafrost zone showed that trends of river flow dynamics are differ during 1950-2000 and 2001-2012 years. In 2001-2012, winter low water was increasing considerably. Correlation of the annual flow with precipitation and air temperature of the particular years was obtained. The role of precipitation, as a factor in the flow formation is enhanced from the boreal forest to tundra zone, and the role of summer temperatures on the contrary weakens.

Keywords: Hydrology, Central Siberia, dynamics of river flow, climate change, permafrost zone

1. Introduction

Almost half of the territory of Russia (60%) is the region with prevalent permafrost. It covers the north of European Russia and western Siberia, and spread over the Yenisei River from the Arctic Ocean to the southern borders of the country. The study of the hydrological regime of rivers in the permafrost regions becomes especially important due to Global Warming. The noticeable climate warming has been revealed in Siberia for the last several decades. These are inducing by air temperature increase, and to a lesser extent of atmospheric precipitation. It is expected the thawing of permafrost will cause significant changes in the hydrological regime of the territory. In this connection, the assessment of water resources in Siberia under the effect of unstable climate is actual. The study of space-time characteristics of the river flow formation makes it possible to analyze change of hydrological regime in the northern regions of central Siberia in connection with global climate change. The task of our research was the determine the patterns of river flow formation in permafrost zone of Central Siberia on the basis of the analysis of spatial-temporal dynamics of runoff and meteorological characteristics (air temperature and precipitations).

2. Literature Review

Hydrology of rivers in permafrost zone is one of the most difficult scientific fields of hydrology land. Under this discipline, we understand the doctrine on irregularities of the formation of water resources and the hydrological regime of rivers in the territory with permafrost. As the scientific field, the river hydrology of permafrost zone was formed in the 80s of XX century in the result of the expansion of hydrological research within the cryolithozone. One of the founders of river hydrology of permafrost zone in Russia was V.E.
Vodogreetsky. In the 50s, he first summarized the observations of river flow regime at the Northeast of the USSR and developed methods for the calculation of annual, maximum, minimum river flow and seasonal distribution of it [1].

Further development and improvement of methods for calculating the of the river flow characteristics is represented in publications [2]-[6]. The demand for more in-depth study of regularities of river flow formation in permafrost zone was due to the intensive mastering of arctic and subarctic regions of the northern hemisphere in the second half of the 20th century [7]-[14]. The study of regional peculiarities of the hydrological regime in permafrost zone and the mapping streamflow characteristics had a great importance for development of theoretical aspects of river hydrology in permafrost zone [15]-[19].

In the last two decades due to global warming the accent in hydrology of permafrost zone is on the study of patterns of change in the river flow under influence of different factors as meteorological so anthropogenic [20]-[24]. Despite the fact that by now there are many publications, summarizing a study on river runoff in the cryolithozone, however, the problem of estimation of the impact of permafrost on hydrological cycle remains to be solved. We hope that the results of our local and regional studies of hydrological regime in Central Siberia will contribute to the general understanding of Climate Change impact on river hydrology of permafrost zone.

3. Materials and Study Areas

In the Central Siberia, the nine river basins located within three landscape zones: tundra, northern and southern taiga were selected as test sites (Fig. 1). The long-term observations of the flow on nine hydrological stations and precipitation at weather stations in the region under study were involved to create database. Series of observations on the hydrological and weather stations is from 10 to 60 years [25]. Created database was used to develop models of the annual river flow formation in the study region depending on climatic factors and to analyze the spatial and temporal characteristics of the formation of river flow in the permafrost zone of Central Siberia.

![Fig. 1: A map of study area](image)

4. Results and Discussion
4.1. Spatial and temporal characteristics of river flow in the study area

Changing the annual and minimum discharge of rivers in permafrost areas varying degrees reflects the dynamics of thawing frozen ground and shows the importance of this process in the formation of the water resources under present climatic conditions and predictable climate change. Calculation of many years’ runoff characteristics was used to analyze the dynamics of annual and low flow under different variations of climatic conditions. For selected hydrological stations, graphic models of mean annual and low water runoff and the histograms of the deviation mean annual and low water runoff from the average of their values during the observation period were developed. We suggest considering winter runoff from November to April as low water runoff.

All river basins, except Podkamennay Tunguska River, are in the forest-tundra and northern taiga zone. Podkamennay Tunguska basin belongs to the zone of middle taiga. A considerable extent of the area from north to south and the associated differences of climatic parameters (temperature of air and precipitation) determine the features of the hydrological regime of the studied rivers. However, it should be noted general features to the seasonal dynamics of the water regime of these rivers. This is high spring flood, summer-autumn low water, interrupted by rain floods, and winter low water.

The analysis of the hydrological regime of the studied rivers showed that 90-95% of the annual river runoff come to in the warm season, but winter low water does not exceed 10%. For some rivers, such as Tembenchi River mean annual winter runoff does not exceed 3% of the annual. This is due to the fact that the most of studied rivers except Turuhan and Podkamennay Tunguska have not ground-water flow, i.e., runoff of these rivers is formed by melt water and rain. The analysis of seasonal dynamics of runoff in the hydrological stations of studied rivers showed that the flood, which continues from May to July, is about 60-70% of annual runoff. The dynamics of flow reflect the changes in both precipitation and air temperature. In this case, the important point is not only the magnitude of these changes, but also seasons (months) of their revealing. For some rivers, such as Taimura, Erachimo, flood peak occurs in May, for PodkamennayTunguska-in May or June, and for other rivers - in June – July.

![Fig. 2: Inter annual variability of low flow (in %) of the annual runoff](image-url)
The duration of the spring-summer flood for rivers Turuhan and Podkamennaya Tunguska is significantly greater than in rivers with smaller catchment areas. In the time scale, duration of the flood is primarily determined by the dynamics of daily temperatures and precipitation during this period of year. During the summer-autumn drought period there is a gradual decline of water level, which extends over the summer-autumn season and fall down to the freezing of rivers. This reduction of flow is interrupted only by rain floods. On the rivers with small catchment area, water level is rising the several times even after momentary rains. Comparison of the annual hydrographs for studied rivers showed that up to 2001 significant changes seasonal flow dynamics were not observed.

All the rivers, without exception, characterized by a significant flow variability from year to year. The average deviation from the mean annual flow ranged from 27 to 57%, for the river Taimura the deviation from the mean annual runoff in some years reached 80%. This was the case in 1964, 1974 and 1975.

Analysis of data on low flows for the period from November to March showed a significant interannual variability of this magnitude in both absolute and relative terms (the percentage the winter low flow from annual). In some years, the part of low flow (percentage of annual) increases five-seven times over the years, which are characterized by minimum value winter low water (Fig. 2). The average deviation of the maximum and minimum values of low flows from average many years’ data reaches 77-88%. Analysis of long-term dynamics of hydrological characteristics of the studied rivers showed that for the majority of the rivers low flow values correlate with the annual runoff. For the rivers Gobichin, Erachimo and Tembenchi correlation between these values is absent.

Starting from the 40s years changes in winter low flow of the seven out of nine studied rivers have a trend to increase runoff of 0.1 to 1.3 mm/year. Accordingly, the attitude of the annual and winter flow is changing; there is a trend of increasing of percentage of winter flow. The trend of percentage increasing of winter flow is more significant for the river Erachimo (Fig. 3). For the rivers, Taimura and Tukalanda trends in low flow are not observed, and for the river Gobichin a negative trend of winter low water, both in absolute and relative terms was observed from 1981 to 2000 year.

Starting from the 40s years changes in winter low flow of the seven out of nine studied rivers have a trend to increase runoff of 0.1 to 1.3 mm/year. Accordingly, the attitude of the annual and winter flow is changing; there is a trend of increasing of percentage of winter flow. The trend of percentage increasing of winter flow is more significant for the river Erachimo (Fig. 3). For the rivers, Taimura and Tukalanda trends in low flow are not observed, and for the river Gobichin a negative trend of winter low water, both in absolute and relative terms was observed from 1981 to 2000 year.

Of great interest is the analysis of the dynamics of river runoff in permafrost of Siberia after 2000, because according to many researchers in those years the process of melting permafrost is the most active [23], [24], [26]. The results of the analysis of the dynamics of the river flow for 2001-2012 years show that the low winter flow is increasing, but annual runoff is decreasing (Fig. 4a-d). Reduction in annual runoff is likely due to a decrease of the total precipitation in studied region, which is confirmed by the dynamics of the maximum water content in the snowpack at the meteorological station of Norilsk. It is noteworthy that while reducing water content in the snow over the past decade a trend of the establishment of maximum snowpack in earlier dates revealed. In the beginning of the observation period, the maximum snowpack was
observed in early May, in the end of the observation period the date of the snowpack maximum was altered. It is observe in February - midle-April.

Thus, analysis of river flow dynamics in region study showed that spatial variability is determined by the locations of the rivers of interest, which relationship is clearly manifested in the seasonal dynamics of the hydrological regimes of the rivers. The more to the north the river, the more pronounced the snowmelt flood and rain-caused stream rise peaks. The flow of the river having small basins may increase many times after even small rains. According to our results, the river flow formation in permafrost zone of Central Siberia revealed that an increase in the winter low flow indirectly indicates the activation of hydrological processes due to thawing permafrost in the warm season of the year.

![Fig. 4: Trends of river flow Podkamennay Tunguska (A) Turuhan (B) Soviet River (C) Erachimo (D)](image)

**4.2. The influence of climatic factors on the annual river flow**

In the result of the data processing, the equations reflecting the dependence of the annual runoff from the complex hydro-climatic parameters were obtained for each of the watersheds. The dependences obtained are shown in Table 1.

where: Y - annual flow of the river, mm; X_j - the annual amount of liquid precipitation, mm; X_i - the annual amount of solid atmospheric precipitation, mm; X_{8,9} - the average monthly rainfall in August and September; Y_p - flow of the river of the previous year; T_{5,6,7} - average air temperature respectively in May, June and July, °C; t_9 - average air temperature in September, °C; R^2 - coefficient of multiple determination; G - the standard error of the equation; F - Fisher criterion.

Analysis of hydrological models shows that the annual flow of the rivers is significantly dependent on complex of hydro-climatic parameters (Fig. 5a-5d). For all rivers, the increasing of runoff is correlated with a rising of total precipitation, especially snowfall. It was revealed an ambiguous relationship of the annual river flow with temperatures in the warm season. The increase in the average temperature in July and September causes the rising of the annual flow, which is indirect evidence that moisture of periodically
thawing frozen soils is involved to runoff formation of studied rivers. Reduction of annual runoff of Turuhan, Erachimo and Podkamennay Tunguska due to raising of the average temperature in May could be correlated with more high intensity of physical evaporation from the snow surface according to increasing of day length.

Table 1: Regression hydrological models

<table>
<thead>
<tr>
<th>River</th>
<th>Models</th>
<th>Criteria of model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorbachin</td>
<td>$Y = -517.5 + 0.69X_p + 2.93X_t + 45.7T_7$</td>
<td>$R^2 = 0.84; G = 46.3; F = 28.1$</td>
</tr>
<tr>
<td>Taimura</td>
<td>$Y = -250.5 + 0.50X_p + 10.6T_7 + 0.57X_6$</td>
<td>$R^2 = 0.73; G = 27.7; F = 13.7$</td>
</tr>
<tr>
<td>Turuhan</td>
<td>$Y = 115.3 + 0.39X_p + 0.53X_t + 17.2T_{(5+6)}$</td>
<td>$R^2 = 0.45; G = 44.0; F = 10.9$</td>
</tr>
<tr>
<td>Soviet River</td>
<td>$Y = 157.9 + 0.26X_p + 0.41X_t - 10.1T_5$</td>
<td>$R^2 = 0.30; G = 46.6; F = 4.9$</td>
</tr>
<tr>
<td>Tembenchi</td>
<td>$Y = -447.7 + 1.5X_p + 1.75X_t + 1.7X_5$</td>
<td>$R^2 = 0.57; G = 55.5; F = 10.6$</td>
</tr>
<tr>
<td>Graviyka</td>
<td>$Y = 62.7 + 0.50X_p + 1.1X_t - 12.2T_5$</td>
<td>$R^2 = 0.46; G = 76.7; F = 14.3$</td>
</tr>
<tr>
<td>Erachimo</td>
<td>$Y = 154.5 + 0.37Y_p + 0.58X_t - 10.1T_5$</td>
<td>$R^2 = 0.46; G = 57.5; F = 11.4$</td>
</tr>
<tr>
<td>Kureika</td>
<td>$Y = 6.3 + 0.9X_p + 3.4T_5 + 0.00108(X_p^2X_t)$</td>
<td>$R^2 = 0.63; G = 60.4; F = 15.1$</td>
</tr>
<tr>
<td>Podkamennay Tunguska</td>
<td>$Y = 51.3 + 0.15X_p + 0.41X_t - 3.2T_5$</td>
<td>$R^2 = 0.70; G = 19.4; F = 20.3$</td>
</tr>
</tbody>
</table>

Analyzing the general climatic patterns of river flow formation in permafrost of Siberia it should be noted the following trends. The role of liquid and solid precipitation, as a factor in the flow formation is enhanced from the boreal forest to tundra zone, but the role of summer temperatures on the contrary becomes weaker. In the north region with a short and cool summer, heat is mainly spent on the melting of snow, warming and thawing of the upper soil horizons. Probably, in these conditions, the heat energy is not enough to provide high evaporative capacity and significantly, to re-distribute water balance components to increasing of total evaporation. The portion of runoff in any of the observed values of meteorological parameters is significantly higher than the proportion attributable to evaporation.

Analysis of the results of snow measurements over a long period in permafrost zone of Siberia showed the suitability of their using for the development of adequate models of the spatial distribution of solid precipitation. The models reflect the relationship of maximum background values of snow pack with the amount of solid precipitation at key weather stations and characterize the features of the distribution of snow cover in the study area taking into consideration geographical coordinates, altitude terrain and topography parameters that determine the barrier-shadow effects.

5. Conclusions

Analysis of river flow dynamics in permafrost zone of Central Siberia showed that annual runoff decreases, but winter low water has trend to increase. Reduction of annual runoff is likely due to a decrease of the total moisture of the territory. The increase in the winter low flow indirectly indicates activation of hydrological processes in the winter due to thawing of permafrost in the warmer seasons.

Analysis of hydrological models suggests that the annual flow of the rivers significantly associated with a complex of hydro-climatic parameters. For all study rivers, increasing of runoff is correlated with higher amounts of precipitation, especially winter. An ambiguous relationship of magnitude of the annual river flow with the air temperature was detected. The increase of temperature in July and September, accompanied by an increase in annual runoff, which indirectly indicates that the moisture of periodically permafrost thawing is partly involved in formation of rivers flow. Analyzing the general climatic patterns in river flow formation of permafrost zone of Siberia it should be noted the following regularities: the role of liquid and solid precipitation, as a factor in the flow formation, is enhanced from the boreal forest to tundra zone, and the role of summer temperatures on the contrary weakens.
Fig. 5: Dependence of the annual flow of Gorbiachin (A), Soviet River (B), Erachimo (C), Kureyka (D)

6. Acknowledgements

The study was supported by the Government of the Russian Federation Grant 14.B25.31.0031. The authors would like to thank Elena Fedotova and Sergey Im for their helpful comments. Thanks are also given to anonymous reviewers for their constructive remarks.

7. References


http://meteo.krasnoyarsk.ru/.