Article

Response of Siberian rivers discharge to disturbance of the forests caused by wildfires

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Abstract: The objective of this work was to perform a quantitative analysis of the correlation between the forest burning index and abnormal decrease in river discharge under conditions of cryolithozone of Siberia. We analyzed the long-term and seasonal variation of rivers discharge in Central Siberia (Nizhnyaya Tunguska and Podkamennaya Tunguska rivers) and in Eastern Siberia (Aldan, Vilyui rivers) together with the forest burning dynamics within the river basins. The data on rivers discharge was obtained from the archive of The Global Runoff Data Centre for 1939–2015. Relative burned area (RBA) index was calculated from wildfires database collected using satellite technique for 1996–2017. RBA was evaluated as ratio of annual burned area within the river basins to the total area of the river basin. RBA values of 2.5–6.1% per year were considered as extremely high. The analysis of available chronologies of extreme fire events in Central and Eastern Siberia showed high correlation (r > –0.55) with long-term data on the runoff minima. Abnormally low level of discharge was 68–78% of the averaged annual rate. The most significant response of river discharge to the wildfire effect was shown for summer-autumn period of season after extreme burning in mid-summer.

Keywords: Siberia, permafrost zone, river basins, discharge, wildfire, relative burned area

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1. Introduction

In Siberia, significant and long-term post-fire effects are observed in the permafrost zone [1–4]. In particular, these are changes and degradation of the near-surface layers of permafrost, short-term and long-term anomalies of the temperature and water balance [5–9]. This affects the flow regime of small and medium rivers of Siberia, the supply of which is determined by groundwater (10–25% of total) [10]. Interannual fluctuations and trends in river discharges are mainly associated with climatic processes in Siberia [11–14]. And the results of the analysis of the of wildfire impact on river flows are practically not discussed in the literature.

In this work, we determined the degree of connection between intra- and interseasonal variations in river runoff with the relative burned area (RBA) of forests in the river basins of Siberia. The following aspects of the issue were considered: (i) the correlation of long-term data on river flow anomalies and RBA; (ii) the intraseasonal variations of the river flow under post-fire conditions; (iii) features of post-fire river runoff dynamics.

The study of this issue allows us to predict the long-term response of the boreal ecosystems to the fire impact, as one of the most significant factors under current climate conditions and fire regimes [3,13].

2. Results

Data on fires and river discharges are presented in table 1.

In some seasons, we fixed the level of runoff at 68–78% of the average annual rate. When analyzing the available chronologies of extreme fire events in Central and Eastern Siberia [15–18], it was possible to compare the discharge minima with extreme fire events (Fig. 2). The frequency of extremely low runoffs, ranging from 18 to 25 years, is consistent with the reported data on the variability of the width of the tree rings in larch forests of Central Siberia [19], which is determined by the temperature and the moisture regimes of weather. Thus, the phase coincidence of the flow anomalies and extreme fire events associated with the precipitation deficit is expected.

Table 1. Long-term mean of discharge anomalies and RBA ($\gamma_{mean}\pm\sigma$, γ_{max}) for the river basin territories.

River	Area of basin[1], mln ha	Discharge, km^3	Discharge anomaly, %			γ, %	
			min	max	mean	max	σ
Lower Tunguska	45.6	108.25	–22	29	0.49	2.99	0.60
Podkamennaya Tunguska	23.8	49.87	–21	40	0.51	4.12	0.65
Vilyui	45.5	47.97	–32	36	0.76	6.13	1.15
Aldan	72.8	173.59	–28	32	0.67	5.21	0.77

[1] according to calculation in GIS.

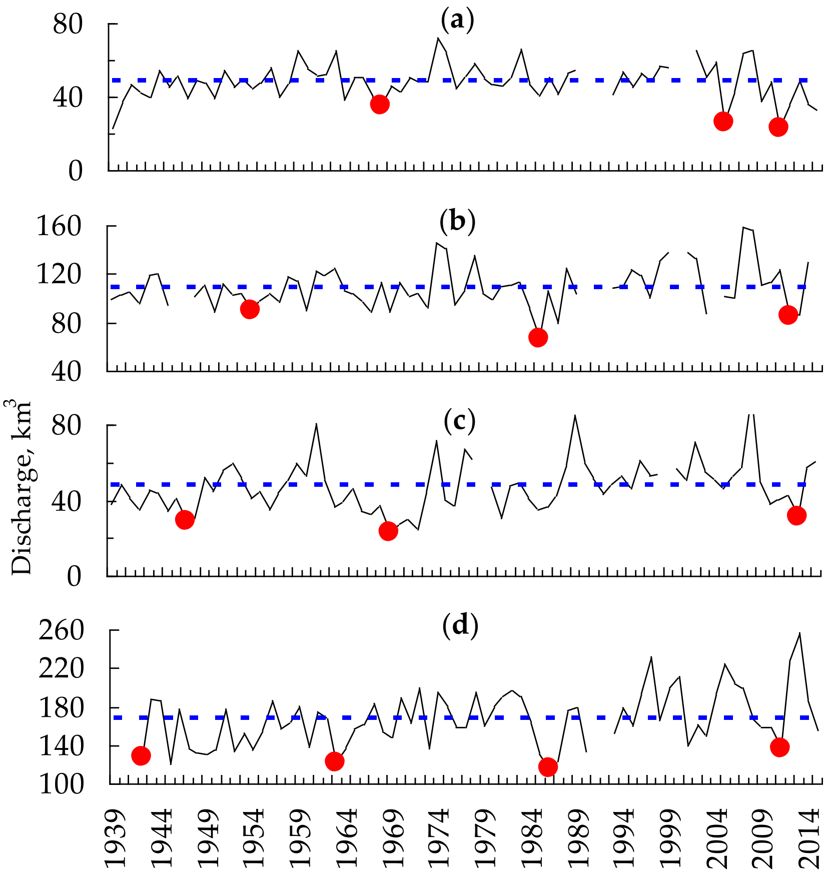

Figure 2. Long-term data on total annual runoff (km^3). The dots indicate the minima which are corresponding to the dates of extreme fire events. Dotted line – annual mean value. River basins: (a) Podkamennaya Tunguska; (b) Lower Tunguska; (c) Viluy; (d) Aldan.

Solving the problem of quantitative description of the relationship, we jointly analyzed data on the forest fire in the borders of river basins (γ,%) and runoff anomalies for the first half of the growing season (March – July) for 2002–2015 (Fig. 3). The results of the correlation analysis of the relationship between the intraseasonal dynamics of the discharge and the RBA are presented in (Table 2).

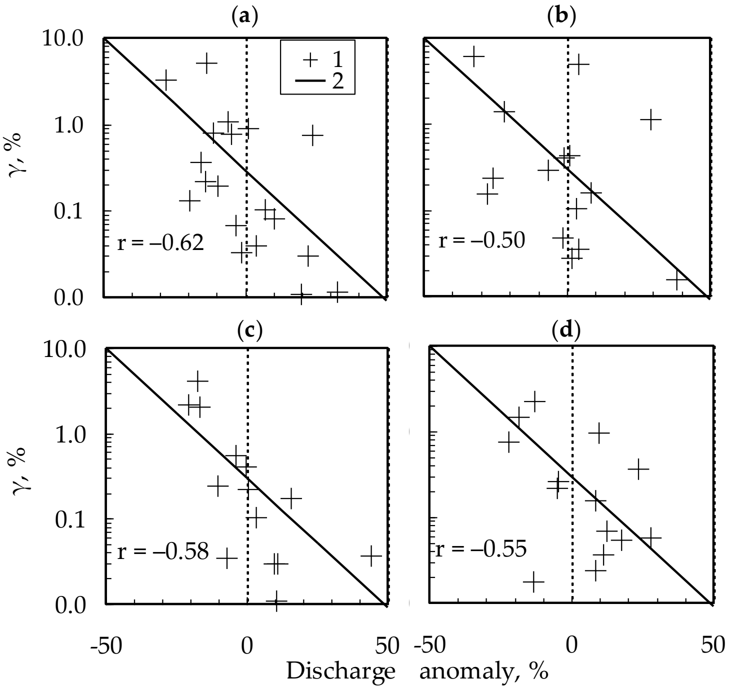

Figure 3. Correlation field for RBA within the river basins (γ,%) and discharge anomalies for the first half of the vegetation season (March – July) for the rivers of Yakutia: Aldan (a), Vilyui (b) and Central Siberia: Podkamennaya Tunguska (c), Lower Tunguska (g). 1 – experimental data, 2 – linear model.

Table 2. Correlation between discharge anomalies and RBA during the season.

River	Correlation during the season			
	November–February	March–April	May–July	August–October
Lower Tunguska	–0.43	–0.25	–0.83	–0.77
Podkamennaya Tunguska	–0.20	–0.24	–0.66	–0.57
Vilyui	–0.22	–0.16	–0.42	–0.42
Aldan	–0.21	–0.10	–0.47	–0.22

All figures and tables should be cited in the main text as Figure 1, Table 1, *etc.*

3. Discussion

In [14], it was shown that the data on the moisture content in the soil are an effective indicator of the prediction of forest burning in the permafrost zone of Siberia. At the same time, it is noted that the moisture reserves in the soil in the current season determine the degree of fire danger of this and subsequent season. To use these results in fire monitoring practice requires a wide network of data collection points. It is not always possible to implement in remote areas of Central and Eastern Siberia. An alternative solution is the development of methods for remote monitoring of water mass dynamics according to gravimetric survey data [1,20]. In our work, a qualitatively similar result was obtained, while the data on anomalies of river discharge are a more effective criterion for predicting the fire regime within the river basins.

Also the response to the fire impact was recorded in the territories of the considered basins of the rivers of Central Siberia, expressed in an abnormal low discharge in the post-fire summer-autumn period (r > –0.55). At the same time, the level of relation is lower for the basins of rivers in Eastern Siberia/Yakutia (r < –0.45).

The revealed differences can be a consequence of the post-fire condition of permafrost soils, which determines the share of groundwater in the formation of the total river flow. Post-fire transformation of vegetation and on-ground cover can be the cause of heat and water balance anomalies [17,21], changes in the depth of seasonally thawed layer of soils, changes in water permeability of soil horizons [22,23]. Thus, if we do not take into account seasonal variations in the precipitation regime, the features of the post-fire discharge anomalies are determined by condition of system "fire effect" – "ground cover and vegetation" – "soil". The influence of wildfires is significant only for the seasonally thawed layer that is active in the summer-autumn period.

A more detailed study of post-fire effects on river discharge anomalies is important for predicting the response of boreal ecosystems to the fires effects, which currently tends to increase [1,4,24].

4. Materials and Methods

The area of interest is the territory of Siberia within the boundaries of 57–67 N, 85–110 E. The total area is more than 110 million hectares. The studies were performed for four river basins of Central Siberia and Yakutia (Fig. 1), such as Lower Tunguska, Podkamennaya Tunguska (Basin District of Yenisei River), and Aldan, Viluy (Basin District of Lena River).

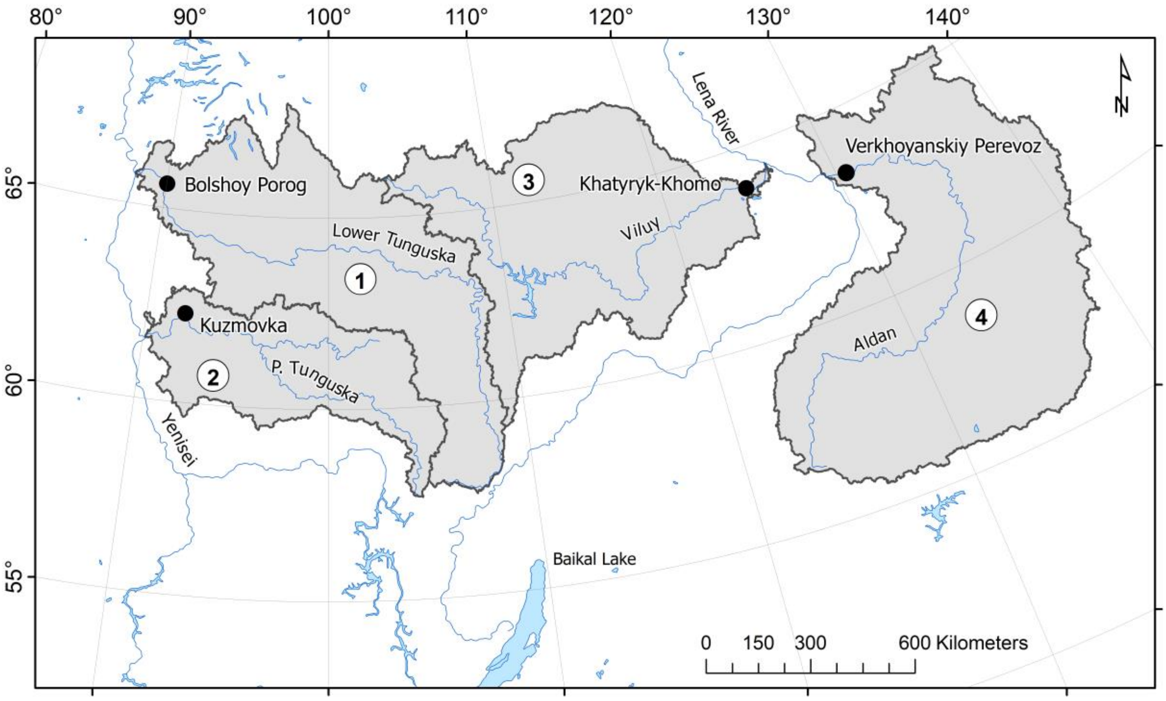

Figure 1. Area of interest. River basins and hydrological points for data collection. River basins are: 1 – Lower Tunguska, 2 - Podkamennaya Tunguska, 3 - Viluy, 4 - Aldan.

The long-term data on the flow rate (m^3/s) and river discharge (km^3) were compiled from the open database R-ArcticNET 4.0 (http://www.R-ArcticNET.sr.unh.edu), an integrated monitoring system Arctic-RIMS (Rapid Integrated Monitoring System) (http://rims.unh.edu/index.shtml), The Global Runoff Data Center (http://www.bafg.de), Composite Runoff Field V 1.0 (http: //www.compositerunoff.sr.unh.edu/) [25–27]. We analyzed the monthly average water runoff for 1936–2015 at the following hydrological posts: Bolshoy Porog (basin of Lower Tunguska), Kuzmovka (basin of Podkamennaya Tunguska), Khatyryk-Khomo (basin of Vilyui River), Verkhoyanskiy Perevoz (basin of Aldan River).

We determined the average annual value of the discharge ($\overline{RD_i}$) and analyzed deviations (RD_i^*) from the average statistical norm (discharge anomalies) for the each month (*i*) as

$$RD_i^* = \frac{(RD_i - \overline{RD_i})}{\overline{RD_i}} \times 100\% . \quad (1)$$

We determined the relative burned area (RBA) of forests within the river basins on the basis of satellite fire monitoring data of the Sukachev Institute of Forest (Federal Research Center KSC SB RAS, Krasnoyarsk, Russia). The data were presented in the format of a geoinformation (GIS) wildfire database for 1996–2015 [28]. RBA (γ) was defined for each month, as the ratio of the total area of fires (S_{burned}) to the total area of the river basin (S):

$$\gamma = \frac{\sum S_{burned}}{S} \times 100\% . \quad (2)$$

Data processing was performed using geospatial pre-processing of vector data layers using GIS tools, correlation and statistical analysis, and method for optimization of regression coefficients.

5. Conclusions

For the current river basins the scale of wildfire impact is up to 2.5–6.1% of the total area per year. It is effects strong on forest ecosystems of the permafrost zone. Within the river basins of Central Siberia, the response to pyrogenic (post-fire) impact is expressed in anomalies of discharge in the post-fire summer-autumn period (r >–0.52). For river basins in Eastern Siberia, the correlation is lower. The level of significance is determined highly likely by the state and post-fire changes in the permafrost soil conditions.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RBA: Relative burned area
RIMS: Rapid Integrated Monitoring System
RD: river discharge
KSC SB RAS: Krasnoyarsk Science Center of Siberian Branch of Russian Academy of Sciences
GIS: Geographic Information System

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