Assessment of wildfire impact on hydrological extremes in eastern Siberia

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Abstract MODIS imagery was used to select two middle-scale fire-affected permafrost watersheds within the Lena River basin. A paired-watershed method and modelling approach was employed for change detection study of the watersheds to quantify effects of wildfire on the hydrological regime. Results showed that the Vitimkan River watershed with a burnt area percentage of 78% had a profound response to wildfire disturbance. It was reflected in a considerable increase of daily and monthly flow and decline of spring snowmelt runoff depth during the year after the fire. The larger Vitim River basin with a burnt area percentage 49% did not have a detectable hydrological response to fire. The results of the Hydrograph model application to the Vitimkan River watershed revealed the existence of an additional fire factor that influenced the formation of river flow during the year after the fire and was not accounted for by the model.

Key words the Hydrograph model; wildfire; paired-watershed approach; change detection

INTRODUCTION

Wildfires lead to rapid short and long-term environmental changes but have not yet been adequately incorporated into hydrological and environmental models (Hinzman *et al*., 2003). The return period for wildfire is strongly influenced by current climate changes and human activities and is supposed to be significantly decreased in future (Stocks *et al.*, 1998).

The fire regime in the permafrost environment is highly variable because of its sensitivity to vegetation, topography, climate, and human activities (Brown, 1983) and it has impacts that range from local to regional and global (Rupp *et al.*, 2001). Wildfire is one of the most important agents controlling the thickness of the organic layer in the permafrost environment, which has a profound effect on permafrost degradation or growth (Viereck, 1982). Sofronov & Vakurov (1981) consider wildfires as a factor determining forest existence in the permafrost zone.

Fires have both immediate and long-term impacts on the ecosystem due to their effects on surface energy, water balance, and underlying permafrost (Iwahana *et al.*, 2005). Seasonal thawing depth is reported to increase in fire-disturbed landscapes (Lytkina, 2005; Bolton, 2006; Isaev, 2011; Onodera & Van Stan, 2011). Burn (1998) compared hydrological and thermal regimes of soil in non-continuous permafrost zone in fire-disturbed and undisturbed spruce forest and concluded that fire provokes irreversible degradation of vegetation and permafrost. Bolton (2006) reported that the burnt organic layer may increase soil thermal conductivity by 10 times and decrease the surface albedo by up to 50% in Alaskan forests.

Fire affects the hydrological regime of a landscape in different ways. Soil moisture content increases immediately following fires due to a decrease in evapotranspiration (Moore & Keeley, 2000). Although the net surface energy balance may not change significantly after fire, the ways in which the incoming energy is partitioned does change substantially. For example, following wildfire, the surface albedo is significantly reduced. The reduced albedo means that soils can absorb more incoming shortwave radiation than before the fire, which is then converted to heat, resulting in higher ground surface temperatures (Burn, 1998) and talik formation (Bolton, 2006). Changes in depth to permafrost and active layer thickness have been observed in numerous experimental studies as the changes in the surface material and thermal properties allow for increased heat flow (Bolton, 2006; Onodera & Van Stan, 2011).

Though many studies of the effects of fire on the soil moisture, ground thermal regime and landscape characteristics driving hydrological processes in cold regions have been well documented, considerable effort is still required to advance our understanding of wildfire effect on catchment hydrology in cold environments. There are very few such studies in the world (Buttle & Metcalfe, 2000; Seibert *et al.*, 2010) and the authors are not aware of any in Siberia.

The goal of the paper is to assess forest fire effects on hydrological regime of permafrost covered watersheds within the Lena River basin in eastern Siberia using ground observation data, remote sensing products and a modelling approach.

STUDY AREA

Based on the analysis of MODIS burned area information available for 2000–2010 within the Lena River basin it was found out that the most extensive fires occurred in April, June and May 2003 in the upper Vitim River basin (Fig. 1). The Vitimkan and Vitim river basins with areas of 969 and 18 200 km^2 at Ivanovsky and Romanovka, respectively, were selected for further investigations based on availability of hydrometeorological data. Burned area percentage of selected watersheds after a fire in 2003 was 78% and 49%, respectively. The watersheds are characterized by mountain relief with elevation up to 2500 m, continuous permafrost and diverse landscapes: bare rocks, tundra, sparse larch forest and wet larch forest. There is a severe continental climate. The hydrological regime is characterized by spring snowmelt high-water period and summer floods. Annual precipitation amount is from 350 to 600 mm depending on elevation. Runoff depth varies from 140 to 300 mm per year. Daily discharge data are available for the period 1958–2004 for the Vitimkan River basin and 1958–2010 for the Vitim River basin. Meteorological data were retrieved from the only near meteorological station, Romanovka, located at an altitude of 920 m in the outlet of the Vitim River basin (approximately 150 km from the Vitimkan River basin).

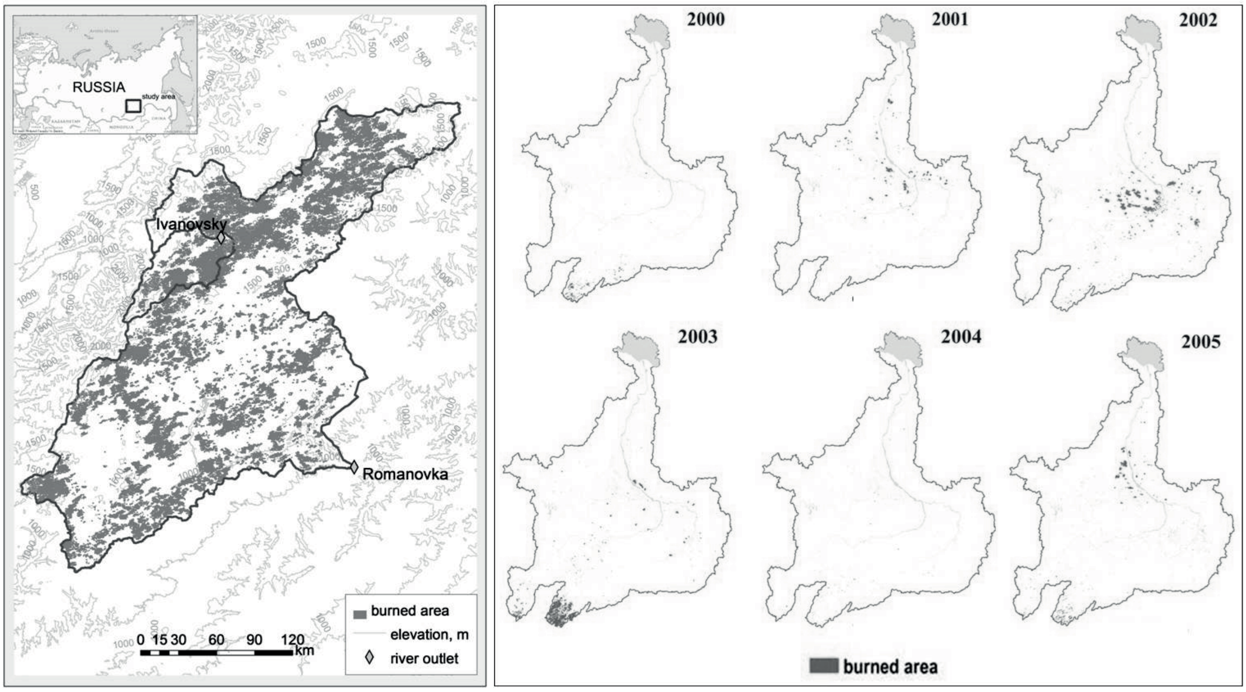

Fig. 1 Left, the location of the Vitimkan and Vitim river basins; right, the examples of MODIS burned area data for the Lena River basin.

METHODOLOGY

Paired-watershed approach

The paired-watershed approach (Bosch & Hewlett, 1982) was used for preliminary detection of fire-induced changes of hydrological regime. Annual, seasonal, monthly and daily peak flow of the Vitim and Vitimkan river basins were compared to assess possible changes in the hydrological regime after wildfire disturbance. Daily discharges (cubic metres per second) were converted to daily runoff depth (millimetres per day) and plotted on graphs.

Process-based hydrological modelling

The process-based hydrological model Hydrograph with physically observable parameters (Vinogradov *et al.*, 2011; Semenova *et al.*, 2013) was applied in the study. It is a distributed model of runoff generation processes describing all essential components of the land hydrological cycle including precipitation interception; thermo-dynamic modelling of snow accumulation and melt; sublimation, representation of soil and vegetation cover and evapotranspiration; surface flow and infiltration; soil water dynamics; heat dynamics and phase change in soil layers; subsurface flow, hillslope and channel flow and routing.

The hydrograph model combines a physical-process basis with certain strategic conceptual simplifications, which allow it to be applied successfully in remote, sparsely-gauged permafrost regions. The model has an important ability – it can use many parameters that can be observed in the field or estimated according to remote sensing products. The model concepts and approaches were verified at numerous permafrost basins in eastern Siberia and Canada (Pomeroy *et al.*, 2010; Vinogradov *et al.*, 2011; Lebedeva & Semenova, 2012; Semenova *et al.*, 2013).

The Hydrograph model was applied to simulate runoff formation in pre- and post-fire periods to detect changes in hydrological regime of disturbed basins.

RESULTS

The analysis of fire impact on flow regime of selected watersheds was carried out using available daily flow and precipitation time series. Correlations of mean annual, seasonal, monthly, daily maximum flow of watersheds were studied using the paired-watershed approach.

The analysis of flow and meteorological data in fire-affected watersheds revealed that in August 2003 precipitation with an exceedance probability of 52.1% formed discharge with an exceedance probability of 6.2% in the Vitimkan River basin. Plotted annual peak floods of the Vitimkan and Vitim river basins for 1958–2004 showed that the 2003 peak flood in the Vitimkan River basin is 20–50% higher compared to the Vitim River basin (Fig. 2, left). The July and August monthly runoff depth in Vitimkan River basin in 2003 is 1.5–3 times larger compared to the Vitim River watershed (Fig. 2, right). 2003 and 2004 spring flood depths in the Vitimkan River basin is three times lower compared to the Vitim River basin (Fig. 3). The values of the difference were assessed using linear approximation of respective relationships between peak, monthly and seasonal runoff depths of the two basins for the period 1958–2002. The results showed that the Vitimkan River basin had quick and profound hydrological response to wildfire in 2003 whereas the larger Vitim River basin showed no significant changes. It agrees with the higher proportion of burned area in the Vitimkan River basin. Considerable change of flow regime of the Vitimkan River basin could be ascribed to its smaller size and sparse larch forest on steep slopes as a dominant landscape. This issue requires further and more detailed investigation.

The model detection method was applied to the Vitimkan River watershed. Precipitation from Romanovka meteorological station was adjusted using an elevation correction factor. For the Hydrograph model application the basin was represented by three conditionally uniform landscapes: bare rocks on tops of the mountains, sparse larch forest on mountain slopes and wet larch forest in river valleys. The model parameters were estimated according to land cover maps and literature review. The results of the Hydrograph model application were obtained for historic (1966–2003) and disturbed (2003–2004) periods (Fig. 4). Runoff generation simulations for the Vitimkan River watersheds showed that the Hydrograph model satisfactorily represents flow formation in the mountainous watershed with lack of input meteorological information in the pre-fire period. The Nash-Sutcliffe criteria for daily discharges amounted to 0.55 in dry year (1979), 0.59 in a wet year (1967), 0.79 in an average year (1991) and only 0.13 in a fire-affected year (2003).

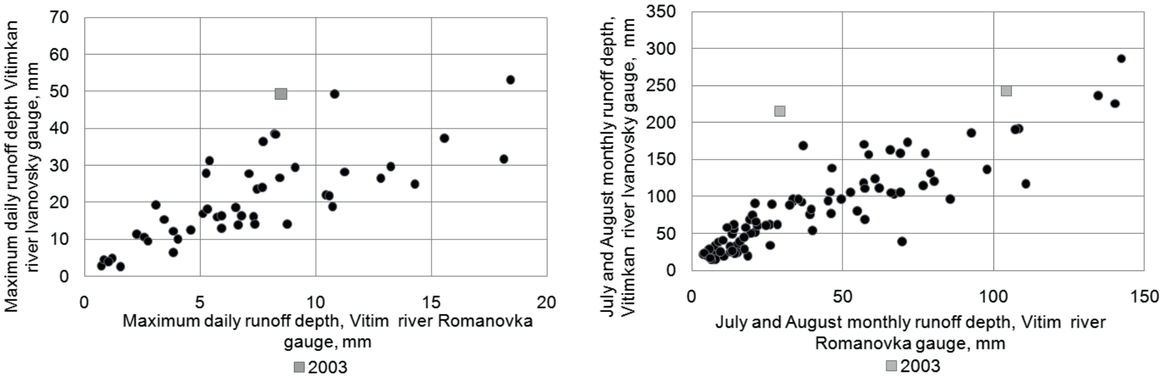

Fig. 2 Left, correlation between annual peak flood in the Vitimkan and Vitim river basins; right, correlation between July and August monthly runoff depths in the Vitimkan and Vitim river basins.

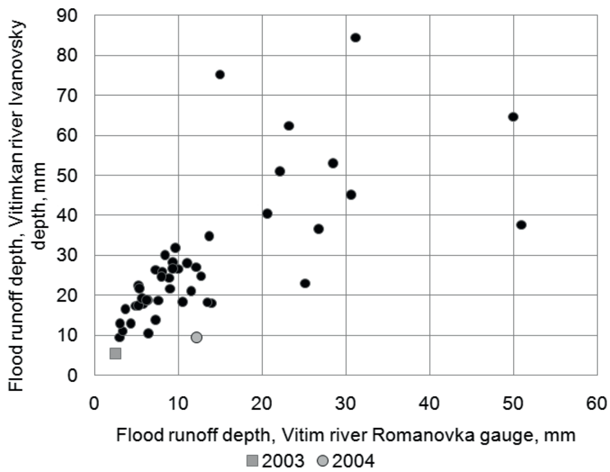

Fig. 3 Correlation between spring flood runoff depth in the Vitimkan and Vitim river basins.

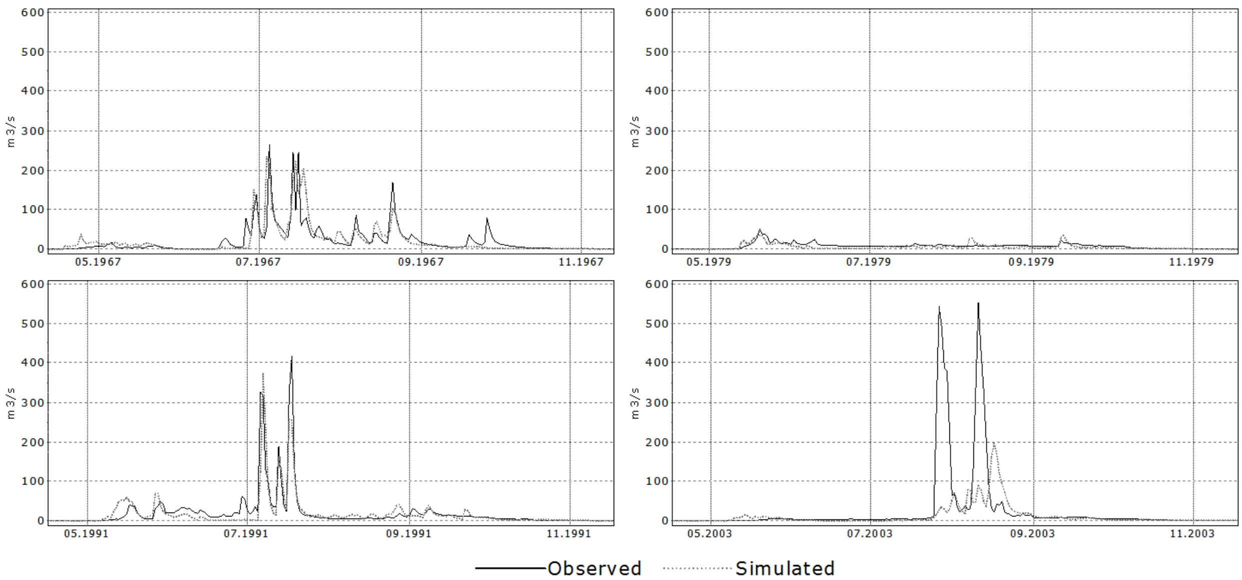

Fig. 4 Simulated and observed hydrographs for short-, high- and average-water years 1979, 1967, 1991 respectively, and fire-affected year 2003.

The use of a fixed set of model parameters for the simulations in pre- and post-fire periods showed that the agreement of calculated and observed hydrographs in fire-affected 2003 is the lowest within the whole modelling period 1966–2004. It suggests the existence of an additional fire factor that influenced the formation of river flow in 2003 and was not accounted for by the model.

CONCLUSION

The goal of the paper was to assess forest fire effects on the hydrological regime of river basins in eastern Siberia using a paired-watershed approach and model detection method. Two fire-disturbed basins in the upper Vitim River were chosen based on analysis of MODIS burned area information and available hydrometeorological data.

The paired-watershed approach showed considerable increase of daily and monthly flow in the smaller and more disturbed Vitimkan River watershed after fire in 2003. Spring flood depths in 2003 and 2004 in the Vitimkan River basin were significantly lower than in the Vitim River basin. The larger and less disturbed Vitim River basin did not show a detectable hydrological response to fire.

The model detection method was applied to the Vitimkan River watershed. The Hydrograph model satisfactorily simulates flow formation in a mountainous watershed with lack of input of meteorological information in the pre-fire period. Exceptionally poor agreement of observed and modelled discharges in 2003 allows a conclusion about the existence of an additional fire factor that influenced runoff formation processes in 2003 that was not accounted for by the model.

The next stage of research will be the development and verification of the model dynamic parameters describing change of landscape properties in a post-fire period. Possibly, the dynamic set of parameters would allow simulation of the historic period and assessment of future possible changes of hydrological regime and permafrost characteristics in different landscapes due to wildfires.

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