Hydrological process change with air temperature over the Lena Basin in Siberia

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Abstract We use long-term monthly discharge and sub-basin air temperature data in the Lena River to examine the relationship between hydrological processes and permafrost change. The ratio of the maximum to minimum monthly discharge (Qmax/Qmin) decreased, while the recession coefficient in the cold season (Qapr/Qdec, discharge in April *vs* discharge in November) increased over the upper Lena and Aldan sub-basin during 1936 to 2000. The annual basin air temperature (AT) has increased from 1940 to 2000. There is a significant relationship between Qmax/Qmin, Qapr/Qdec and AT. The positive relationship between Qapr/Qdec and AT, and the negative relationship between Qmax/Qmin and AT became significant from a single year to 7-year running average. These results suggest that the Qmax/Qmin and Qapr/Qdec changes may be related to the basin warming and perhaps permafrost degradation.

Key words hydrology; permafrost; temperature; Siberia

INTRODUCTION

In cold regions, the hydrological regime is closely related to permafrost conditions, such as permafrost extent and thermal characteristics. Permafrost has a very low permeability and commonly acts as a barrier to infiltration or as a confining layer to aquifers. Because it is a barrier to infiltration, permafrost increases the surface runoff and reduces subsurface flow. Permafrost extent over a region plays a key role in the distribution of surface–subsurface interaction (Carey & Woo, 2001; Lemieux *et al.*, 2008; Woo *et al.*, 2008). Permafrost and non-permafrost rivers have very different hydrological regimes. Relative to non-permafrost basins, permafrost watersheds have higher peak flow and lower base flow (Woo, 1986; Kane, 1997). In the permafrost regions, watersheds with higher permafrost coverage have lower subsurface storage capacity and thus a lower winter runoff and a higher summer peak flow (Woo, 1986; Kane, 1997; Yang *et al.*, 2003). There exists a significant positive relationship between the ratio of maximum to minimum monthly discharge (Qmax/Qmin) and basin permafrost coverage over the Lena River. This relationship indicates that permafrost condition does not significantly affect streamflow regime over the low permafrost (less than 40%) regions, but strongly affects the discharge regime for regions with high permafrost (greater than 60%) (Ye *et al.*, 2009).

The ratio of Qmax/Qmin decreased during 1937–2000 for the Lena River. The recession coefficient (RC, ratio of April to December discharge) during the cold season increased from 1937 to 2000 in the main branches of the Lena River without reservoir regulation (Ye *et al.*, 2009). These changes may be related to permafrost degradation. This study analyses the relationship between the Qmax/Qmin, RC, and basin air temperature. It is difficult to accurately determine changes in permafrost distribution. We therefore use the basin air temperature to reflect permafrost condition changes. The objective of this study is to explore the effect of the permafrost degradation on hydrological processes and their changes.

BASIN DESCRIPTION, DATA SETS AND METHOD OF ANALYSIS

The Lena River originates from the Baikal Mountains in the south central Siberian Plateau and flows northeast and north into the Arctic Ocean (Fig. 1). Relative to other large rivers, this basin

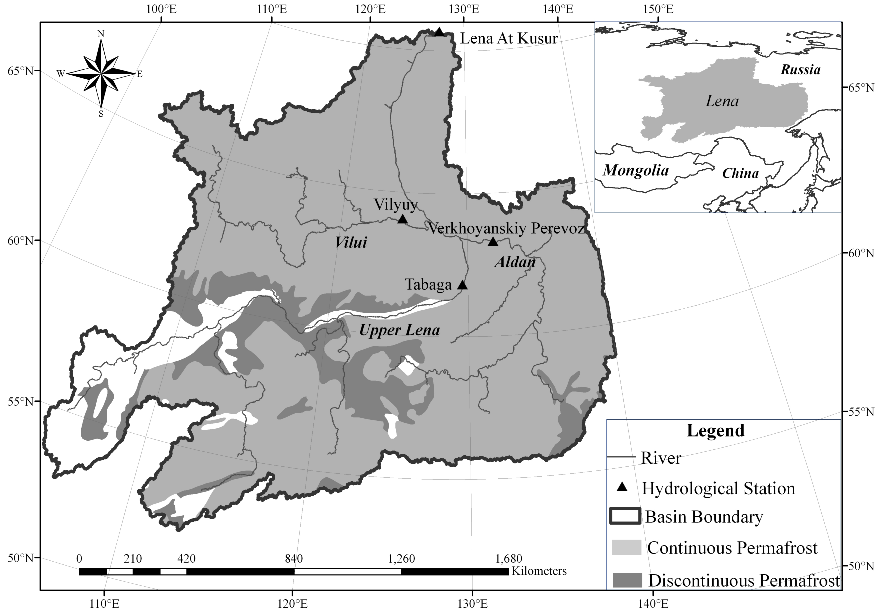

Fig. 1 Lena River basin map with the basin boundary and permafrost distribution.

has fewer human activities and much less economic development (Dynesius & Nilsson, 1994). There is only one large reservoir in the Vilui sub-basin; a large dam (storage capacity 35.9 km^3) and a power plant were completed in 1967 near the Chernyshevskyi (112°15′W, 62º45′N) (Ye *et al.*, 2003). The other two main branches, the upper Lena and Adam sub-basins, are affected little by human activities.

The drainage areas from the 1-km DEM match well to those reported by the Pan-Arctic River Discharge Database (Lammers *et al.*, 2001), with the relative errors being <15% for the sub-basins. The coverage of permafrost in a basin is defined as the weighed average of the four different types of permafrost. Considering the ranges of permafrost coverage, we use the mean coverage as representative coverage for each permafrost type, i.e. 95%, 70%, 30% and 5% permafrost coverage in continuous, discontinuous, isolated and sporadic areas, respectively. Variations from the mean CP are ±5%, ±20%, ±20% and ±5% for continuous areas, discontinuous areas, isolated areas, and sporadic permafrost, respectively. The upper Lena basin at Tabaga is covered by 72% permafrost and the Adam basin at Verkhoyanskiy Perevoz is covered by 92% permafrost (Table 1, Fig. 1).

Since the late 1930s hydrological observations in the Siberian regions, such as discharge, stream water temperature, river-ice thickness, dates of river freeze-up and break-up, have been carried out systematically by the Russian Hydrometeorological Services; the observational records were quality-controlled and archived by the same agency (Shiklomanov *et al.*, 2000). The discharge data are now available from the R-ArcticNet (v4.0) – a database of Pan-Arctic river discharge during 1936–2000 (Lammers *et al.*, 2001). In this analysis, we use the long-term monthly discharge records collected at Tabaga station in upper Lena and Verkhoyanskiy Perevoz station in Aldan sub-basin outlet (Fig. 1). Relevant information for these stations is given in Table 1.

Table 1 List of hydrological stations used in this study.

Station name/ Location	Latitude °N	Longitude °E	Data period		Drainage area (× 1000 km^2)	Annual runoff (km^3)	(mm)
Tabaga/Upper Lena	61.83	129.6	1936	1999	897	221.0	246.4
Verkhoyanskiy Perevoz/ Aldan sub-basin outlet	63.32	132.02	1942	1999	696	166.0	238.5

The methods of analyses include calculation of monthly mean discharge and hydrographs for the Tabaga station in upper Lena and the Verkhoyanskiy Perevoz station in Aldan sub-basin, determination of the ratio of monthly maximum to minimum flows (Qmax/Qmin), and the recession coefficient (RC, ratio of April to December discharge) during the cold season. We also use monthly air temperature (AT) data (Jones, 1994) for the Siberian regions, and calculate the basin mean values for the upper Lena, and Aldan sub-basins. Based on these data, we carry out analyses of changes in hydrological parameters (Qmax/Qmin and RC) and their relationships with basin mean temperature during 1937–2000.

RESULTS

It is difficult to directly investigate the linkage between discharge and permafrost change over a large basin, because of the difficulty of identifying the permafrost distribution and change. Here we use the basin mean air temperature, instead of the basin permafrost change to examine the linkage between hydrological processes and permafrost changes.

Relationship between Qmax/Qmin and basin air temperature

Figure 2 shows the Qmax/Qmin and annual mean basin air temperature (AT) during 1937–2000 at the upper Lena and Aldan basins. There is a significantly negative relationship in the annual scale and more significant one for the 5-year moving average. Usually, air temperatures directly affect evaporation and snow melt, and consequently the hydrological regime. Air temperature can also directly affect permafrost distribution, which influences the hydrological regime in the permafrost basin (Ye *et al.*, 2009). Increases in temperature lead to permafrost degradation, consequently more infiltration of surface water and a flat discharge regime. The temporal relationship between Qamx/Qmin and AT during 1937–2000 (Fig. 2) shows a similar result to the spatial comparison between Qmax/Qmin and permafrost coverage in the Lena basin (Ye *et al.*, 2009).

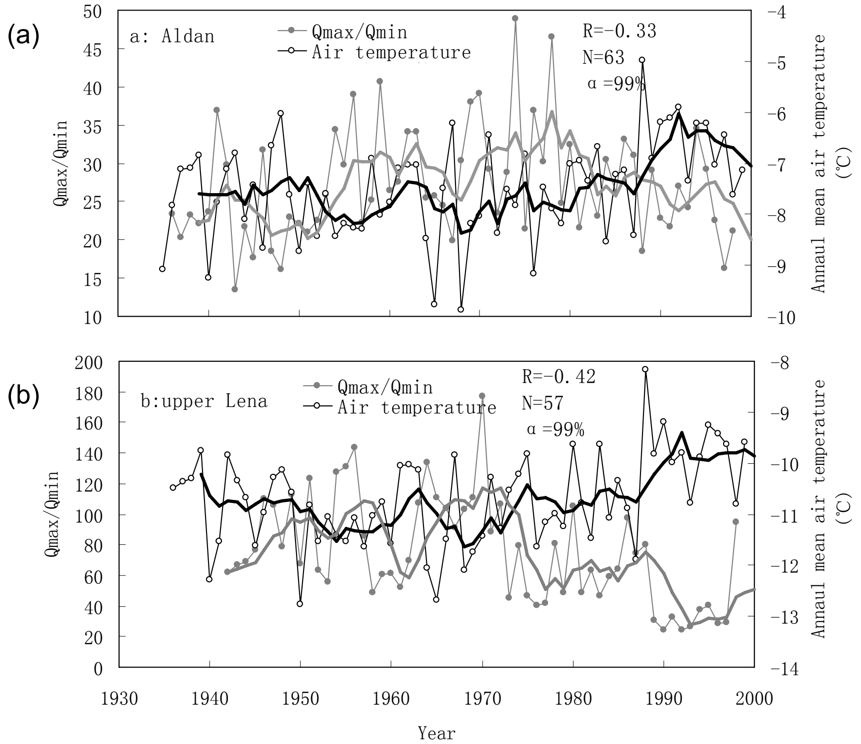

Fig. 2 The ratio of maximum *vs* minimum monthly discharge (Qmax/Qmin) and annual basin mean air temperature for: (a) Tabaga/Upper Lena and, and (b) Verkhoyanskiy Perevoz/Aldan sub-basin outlet, during 1936–2000 (The broad line is 5-year moving average).

Permafrost degradation is a slow response to climate change. Annual scale analyses may not reflect the relationship between climate change and permafrost.

The 1-year, 3-year, 5-year and 7-year moving average of basin temperature and Qmax/Qmin are used in the study. Table 2 shows the correlation coefficients of AT *vs* Qmax/Qmin, and AT *vs* Qapr/Qdec for the two sub-basins. The correlation coefficient increases as the moving average period increases. All relationships using the 7-year moving average are significant at 99% level. This result indicates slow responses of hydrological processes to climate warming and perhaps permafrost change.

Table 2 The correlation coefficient of annual basin mean air temperature with Qmax/Qmin and Qapr/Qdec, for 1-year, 3-year, 5-year and 7-year moving average.

Sub-basin	Parameter	1-year	3-year	5-year	7-year
Upper Lena	Qmax/Qmin	–0.33**	–0.37**	–0.33*	–0.37**
	Qapr/Qdec	0.26*	0.25*	0.27*	0.34**
	N	63	61	59	57
Aldan	Qmax/Qmin	–0.42**	–0.72**	–0.83**	–0.89**
	Qapr/Qdec	0.30*	0.65**	0.82**	0.88**
	N	57	55	53	51

Note: * and ** indicate 95% and 99% significant levels, respectively. N is sample number.

Relationship between recession coefficient and basin temperature.

The hydrological process is mainly a recession in the clod season from December to April without rain supply. The recession is controlled by the water released from the ground water reservoir. The ratio of April to December discharge (Qapr/Qdec) is defined as the recession coefficient. Figure 3 shows the annual basin mean temperature and Qapr/Qdec during 1936–2000. There is a good

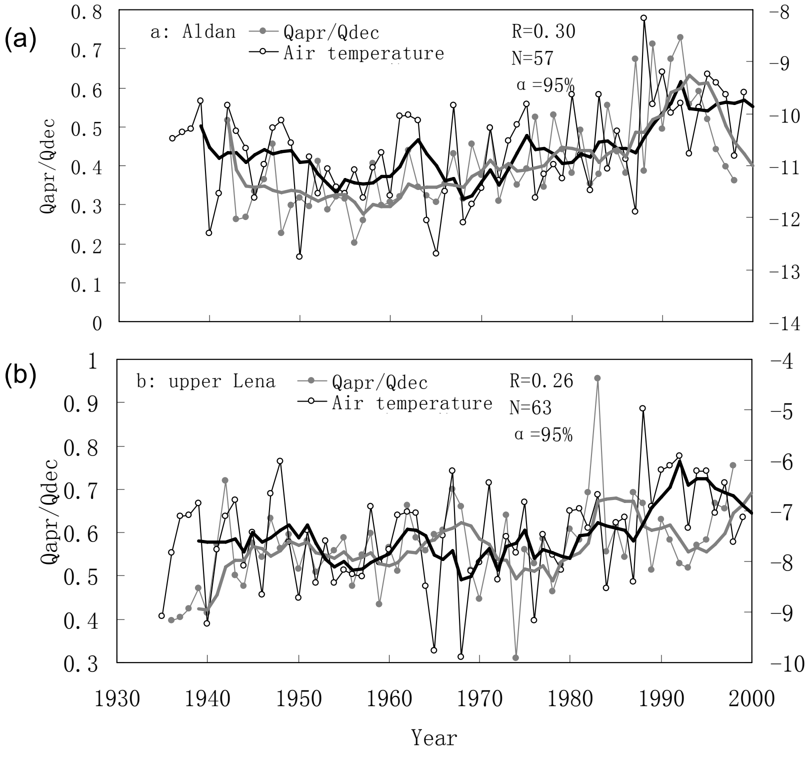

Fig. 3 The recession coefficient in cold season (Qapr/Qdec) and annual basin mean air temperature at: (a) Tabaga/Upper Lena, and (b) Verkhoyanskiy Perevoz/Aldan sub-basin outlet during 1936–2000 (the broad line is 5-year moving average).

relationship between them on annual scale, 95% significant level. The 5-year moving average is more consistent. This result indicates the discharge recession would become slow as climate is warming up. The large coefficient implies large capacity and regulation of the groundwater reservoir, which may be caused by permafrost degradation, especially permafrost disappearance in a warming climate. Permafrost degradation does not enhance the infiltration rates, but enlarges the infiltration area, and consequently the groundwater reservoir capability. Similar results have also been found in some rivers with permafrost distribution in northwest China (Niu *et al.*, 2011).

The 1-year, 3-year, 5-year and 7-year moving average of annual basin mean air temperature and Qapr/Qdec have been analysed (Table 2). The result is similar to that of Qmax/Qmin and AT. This again indicates the permafrost degradation is a slow response to climate change, and the hydrological parameters caused by permafrost change also slowly respond.

CONCLUSION

Monthly discharge and annual basin mean temperature data are used to examine the relationship between discharge process and climate change over the Lena River in Siberia. The ratio of maximum to minimum discharge (Qmax/Qmin) has decreased over time, while the recession coefficient (Qapr/Qdec) in the cold season has increased in the two branches – upper Lena and Aldan – during 1936–2000 (Ye *et al.*, 2009). These results suggest hydrological process change due to climate change and permafrost degradation. The annual basin mean air temperature increased from 1940 to 2000. There is a significant relationship between Qmax/Qmin *vs* AT, and Qapr/Qdec *vs* AT. The positive relationship between Qapr/Qdec and AT, and the negative relationship between Qmax/Qmin and AT gradually become significant from the annual scale to the 7-year mean. These results imply that both the Qmax/Qmin and Qapr/Qdec change may be related to climate warming and perhaps permafrost degradation. Permafrost degradation means that the impermeable stratum of the permafrost will disappear and lead to more surface water to infiltrate to groundwater. Permafrost degradation also extends the infiltration area and enlarges the groundwater reservoir, enhances reservoir regulation, and slows the recession process. A warmer climate will lead to a flatter discharge regime in cold regions.

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