Variation of hydrological regime with permafrost coverage over Lena Basin in Siberia

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[1] We use monthly discharge and permafrost data to examine the relationship between discharge characteristics and basin permafrost coverage for the nested subbasins of the Lena River in Siberia. There are similarity and variation in streamflow regimes over the basin. The ratios of monthly maximum/minimum flows directly reflect discharge regimes. The ratios increase with drainage area from the headwaters to downstream within the Lena basin. This pattern is different from the nonpermafrost watersheds, and it clearly reflects permafrost effect on regional hydrological regime. There is a significant positive relationship between the ratio and basin permafrost coverage. This relationship indicates that permafrost condition does not significantly affect streamflow regime over the low permafrost (less than 40%) regions, and it strongly affects discharge regime for regions with high permafrost (greater than 60%). Temperature and precipitation have similar patterns among the subbasins. Basin precipitation has little association with permafrost conditions and an indirect relation with river flow regimes. There exists a good relation between the freezing index and permafrost extent over the basin, indicating that cold climate leads to high coverage of permafrost. This relation relates basin thermal condition with permafrost distribution. The combination of the relations between temperature versus permafrost extent, and permafrost extent versus flow ratio links temperature, permafrost, and flow regime over the Lena basin. Over the Aldan subbasin, the maximum/minimum discharge ratios significantly decrease during 1942–1998 due to increase in base flow; this change is consistent in general with permafrost degradation over eastern Siberia.


1. Introduction

[2] River runoff is the primary freshwater source to the Arctic Ocean. Fresh water discharge from the northern-flowing rivers plays an important role in regulating the thermohaline circulation of the world’s oceans [Aagaard and Carmack, 1989]. Both the amount and the timing of freshwater inflow to the ocean systems are important to ocean circulation, salinity, and sea ice dynamics [Aagaard and Carmack, 1989; Macdonald, 2000]. Recent studies report significant changes in arctic hydrologic system, particularly cold season and annual discharge increases over large Siberian watersheds. These changes indicate hydrologic regime shifts due to large-scale climate variations, permafrost changes, and human impacts [Peterson et al., 2002; Yang et al., 2002; Ye et al., 2003; McClelland et al., 2004].

[3] In the cold regions, hydrological regime is closely related with permafrost conditions, such as permafrost extent and thermal characteristics. Ice-rich permafrost has a very low hydraulic conductivity and commonly acts as a barrier to deeper groundwater recharge or as a confining layer to deeper aquifers. Because it is a barrier to recharge, permafrost increases the surface runoff and decreases subsurface flow. Permafrost extent over a region plays a key role in the distribution of surface-subsurface interaction [Lemieux et al., 2008; Carey and Woo, 2001; Woo et al., 2008]. Permafrost and nonpermafrost rivers have very different hydrologic regimes. Relative to nonpermafrost 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 base flow and a higher summer peak flow [Woo, 1986; Kane, 1997; Yang et al., 2003].

[4] It is difficult to accurately determine changes in permafrost conditions. Our understanding of permafrost change and its effect on hydrological regime is incomplete.
For instance, there are uncertainties regarding the impact of ground ice melt and its contribution to annual flow changes over large Siberian rivers [McClelland et al., 2004; Zhang et al., 2005a]. Permafrost condition and streamflow characteristics vary within large watersheds in Siberia. Examination and comparison of hydrological regimes between subbasins with various permafrost conditions can improve our understanding of impact of permafrost changes on cold region hydrology. This paper examines the relationship between hydrological regime and permafrost coverage over nested subbasins within the Lena River in Siberia. It analyzes monthly discharge data, with a focus on the ratio of the maximum to minimum discharge (Qmax/Qmin) and its relation with permafrost condition, because this ratio reflects the hydrological regime. The objective of this study is to quantify the impact of permafrost on streamflow regime and change, and to specifically define a relationship between basin permafrost extent and streamflow conditions over the Lena watershed. We also examine relationship between basin air temperature and precipitation and their effect on permafrost extent and basin streamflow regimes. The result of this study will shed light on our knowledge of cold region hydrology and its change due to climate impact and human influence.

2. Basin Description, Data Sets, and Method of Analysis

[5] The Lena River originates from the Baikal Mountains in the south central Siberian Plateau and flows northeast and north, entering into the Arctic Ocean via the Laptev Sea (Figure 1). Its drainage area is about 2,430,000 km², mainly covered by forest and underlain by permafrost. The Lena River contributes 524 km³ of freshwater per year, or about 15% of the total freshwater flow into the Arctic Ocean [Yang et al., 2002; Ye et al., 2003]. Relative to other large rivers, the Lena basin has less human activities and much less economic development [Dynesius and Nilsson, 1994]. There is only one large reservoir in the Vilui subbasin. A large dam (storage capacity 35.9 km³) and a power plant were completed in 1967 near the Chernyshevskyi (112°15′W, 62°45′N). This reservoir is used primarily for electric power generation: holding water in spring and summer seasons to reduce snowmelt and rainfall floods and releasing water to meet the higher demand for power in winter [Ye et al., 2003]. Various type of permafrost exists in the Lena basin, including sporadic, or isolated permafrost in the source regions, and discontinuous and continuous permafrost in downstream regions (Figure 1) [Brown et al., 1997]. Approximately 78–93% of the Lena basin is underlain by permafrost [Zhang et al., 1999; McClelland et al., 2004].

[6] Since the late 1930s hydrological observations in the Siberian regions, such as discharge, stream water temperature, river ice thickness, dates of river freezeup and breakup, have been carried out systematically by the Russian Hydro-meteorological Services and 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, long-term monthly discharge records collected at 9 stations (A–H and K) along the main stem and 2 tributary stations (I and J) were used (Figure 1). Relevant information of these stations is given in Table 1.

[7] Permafrost data and information were obtained from the database of the digital permafrost map compiled by International Permafrost Association (IPA) [Brown et al., 2001].
1997, 2001]. The shapefiles were derived from the original 1:10,000,000 printed map. The IPA permafrost map was categorized as continuous (90–100%), discontinuous (50–90%), isolated (10–50%), and sporadic (0–10%). The coverage of permafrost (CP) in a basin has been determined differently [McClelland et al., 2004; Zhang et al., 1999]. Most studies consider permafrost existence [Smith et al., 2007; McClelland et al., 2004] and determined the total coverage of permafrost (4 types of permafrost) [McClelland et al., 2004]. In this study, basin and subbasin permafrost areas are determined by overlaying the permafrost map to the river network map. Basin/subbasin boundaries and drainage areas are derived from 1 km DEM data, the USGS GTOPO30 data set [Bliss and Olsen, 1996]. The drainage areas from the 1km DEM match well to those reported by the Pan-Artic River Discharge Database [Lammers et al., 2001], with the relative errors being less than 15% for the subbasins. The coverage of permafrost in a basin is defined as the weighted average of the 4 different types of permafrost. Considering the ranges of permafrost coverage, we take the mean coverage as representative coverage for every 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 methods of analyses include calculation of monthly mean discharge and hydrographs for the nested subbasins within the Lena watershed, determinations of ratio of monthly high to low flows, and examination of the relation between the ratio and permafrost coverage over the nested subbasins. We compare the ratio between pre-dam and post-dam periods to quantify and discuss reservoir impact on streamflow regime and change. We conduct trend analysis to define the long-term changes in hydrographs and use the Student t test to determine the statistical significance of the trends. Furthermore, we compare the ratio trends among the subbasins to understand the regional differences in streamflow characteristics and changes. We also use monthly precipitation (P) and temperature (T) data [Jones, 1994] for the Siberian regions and calculate the basin mean values for the upper Lena, Aldan and Viluy subbasins. Based on these data, we carry out analyses of basin precipitation and temperature and their relationships with basin permafrost extent and streamflow regime.

3. Results

3.1. Hydrographs

[9] Figure 2 shows the mean monthly discharge at the 9 stations from the upper to lower Lena basin. They generally have similar runoff regimes, i.e., high discharge in summer and low flow in winter. However, the difference among them is very obvious. The large difference is seen in the peak flow, both in rate and timing. Lena river peak discharge is mainly related to snowmelt [Yang et al., 2007; Ye et al., 2003], as it varies over the basin. The mean peak flow is about 210 m³/s at the Kachug station located in the upper basin (station A in Figure 1), due to increasing drainage area, it gradually grows to 74,000 m³/s at the basin outlet (the Kusur station, K in Figure 1). The monthly peak flow occurs in May in the upstream source regions (stations A–D) and in June over the downstream regions (stations E–H and K), because early snowmelt in the source regions and later melt downstream [Yang et al., 2003, 2007].

[10] As expected, the minimum discharge increased with drainage area in the Lena basin. The lowest monthly flow is about 22 m³/s at the Kachug station (A in Figure 1) and it gradually increases to 1100 m³/s at the basin outlet (K in Figure 1). The lowest flow occurs in February in the headwaters (stations A–E), in March over the middle streams (F–G), and in April in downstream (stations H and K). This pattern, early low flow in the source regions and late low flow in lower basin, is related with the timing of snowmelt and hydraulic routing of flow. Also, the timing of snowmelt usually dictates the timing of discharge recession. Usually early (late) snowmelt is associated with early (late) peak and subsequently early (late) low flow. Figure 2 clearly illustrates the variation of hydrographs over the Lena basin. The difference in hydrographs reflects basin climatic and physical characteristics, particularly permafrost conditions. Among other measures, the high and low flows determine the hydrograph shape. The ratio of monthly maximum discharge (Qmax) to minimum discharge (Qmin) is a direct measure of hydrograph shape and hydrologic regime [Woo, 1986; Kane, 1997]. This ratio can also indicate streamflow regime changes caused by reservoir
regulation [Ye et al., 2003; Yang et al., 2004a, 2004b]. Ice jams in the northern regions affect hydrograph in spring. In this study, we use monthly maximum and minimum discharge to determine both the hydrograph shape and the calculation of the ratio. We did not use any daily (maximum and minimum) discharge. This may help to eliminate or smooth the ice jam effect on flow regime analysis.

Calculations of the Qmax/Qmin for the 9 stations in the Lena basin show variations from upstream to downstream. The mean Qmax/Qmin are about 13–16 in the source regions (stations A–E), and increases from 21 in middle upper Lena (station F) to 74 at the outlet station (stations K). The ratio increases with drainage area (Figure 3). This positive relationship is different from nonpermafrost regions/basins, where the ratio decreases with basin area.

### 3.2. The Relationship Between Qmax/Qmin Ratio and Coverage of Permafrost (CP)

The permafrost distribution varies from sporadic in the source regions to continuous permafrost over the Lena basin (Figure 1). The extent of permafrost gradually increases from 20% in the headwaters to 86% in downstream regions (Figure 3). The Qmax/Qmin ratios are low (10–20) for CP less than 40%, and moderate (20–30) for CP interval of 60–75%, and high (about 70–80) for CP greater than 86%. The ratios change with CP over the basin, i.e., increasing with the CP from upstream to downstream.

Dam regulation can significantly alter streamflow regime [Ye et al., 2003; Yang et al., 2004a, 2004b]. It is therefore critical to use pre-dam and natural flow data for regional hydrology analyses. Using the flow data from the upper Lena without dam regulation and the pre-dam data for the basin outlet, we conducted regression analysis between the Qmax/Qmin and CP. The result reveals a significant relationship (significant at 99%, Figure 4). This relationship clearly indicates the effect of permafrost distribution on discharge process. Permafrost regions/basins have low infiltration and limited subsurface storage capacity [Woo, 1986; Kane, 1997; Woo et al., 2008]. Relative to nonpermafrost or low permafrost basins, high permafrost basins...
have higher maximum discharge and lower minimum discharge, hence higher ratio of Qmax/Qmin. Figure 4 shows that the permafrost condition does not significantly affect streamflow regime over the low permafrost regions (i.e., CP < 40%), and it strongly affects discharge regime for regions with high permafrost coverage (i.e., CP greater than 60%). It is useful to determine this threshold of permafrost impact to regional hydrology, particularly in regions undergoing climate warming and permafrost degradation. Further analyses over broader regions are necessary to refine and verify the relation and threshold.

The Qmax/Qmin–CP relation has been derived for the nested basins from the upper Lena to the basin as a whole. To test the relationship, two independent subbasins within the Lena watershed (i.e., the Aldan and Vilui subbasins, stations I and J in Figure 1) have been included in Figure 4. These two tributaries have very high CP, 92% and 95% for the Aldan and Vilui, respectively. There is a reservoir in the upper Viliu valley, with a storage capacity of 36 km³, or about 77% and 7% of annual discharge at Vilui outlet and Lena basin mouth. Operation of this dam has changed streamflow regimes [Ye et al., 2003]; it reduced the peak flows by about 30% and enhanced low flows by about 27 times at Vilui outlet (station J in Figure 1). Because of these changes, the ratio of Qmax/Qmin sharply decreases from 536 to 38 at the Vilui outlet (station J in Figure 1) and from 75 to 45 at the Lena outlet (K in Figure 1), respectively (Figure 4).

The Qmax/Qmin ratios are high, 75 for the Aldan (Station I) and 536 for the Vilui (Station J) during the pre-dam period. The higher ratio for the Vilui is due to continuous permafrost and very low winter flows in the northern parts of the Lena basin. The ratios and CP of these two subbasins are generally consistent with the relationship, showing higher Qmax/Qmin ratios with higher CP. Furthermore, we include the Yasachnaya Kolyma watershed in eastern Siberia for a comparison. This basin has high permafrost extent (about 94%) and fits well with the curve derived from the Lena basin (Figure 4). These results may indicate a general applicability of the relation over the northern basins. It is, however, important to recognize the limitation of this relation. The Qmax/Qmin ratios can be very high due to very low base flow over continuous permafrost regions. For instance, winter base flow is extremely low in the very cold Arctic coast watersheds with almost 100% permafrost coverage, such as the Yana and Olenka basins near the Lena River.

### 3.3. Qmax/Qmin Ratio Changes Over Time

It is difficult to survey permafrost change over large regions. It is easy to calculate the ratio of Qmax/Qmin over a basin where discharge data is available. The relationship between the Qmax/Qmin ratio and CP directly links streamflow regime with basin permafrost coverage. The changes in the ratio over time and space perhaps can, therefore, reflect basin permafrost changes.

Figure 5 shows the time series of Qmax/Qmin ratio during 1935–2000 at 3 tributary stations and at the Lena river outlet. The ratio at the Tabaga station (H) in the upper Lena varies from 16 to 48, with a mean of 28. The ratio does...
not show any trend, although it is obviously lower during 1980–1998, with a mean of 26 due to higher Qmin. The ratio in the Aldan subbasin ranges from 24 to 177, with a mean of 75. It has significantly (95% confidence) decreased by 54 (−75%) during 1942–1998 due to a strong increase in Qmin. There are no dams in this tributary. The decrease of the ratio is mainly due to increases in winter flows [Ye et al., 2003]. The ratio for the Vilui tributary varies between 6 and 1,000. It has sharply decreased since 1966 when the dam went operational. The mean ratios are 531 and 15 for pre- and post-1967, respectively. The drop in ratio is caused by the operation and regulation of the Vilui reservoir around 1967 [Ye et al., 2003], i.e., enhancing winter flows and reducing summer flows downstream of the dam. The ratio at the Lena river outlet varies from 24 to 164, with a mean of 60. It decreases over time, with the total trend of −58 (nearly 95%) at 99% confidence during 1935–2000. This decrease is mainly caused by reservoir regulation in the Vilui valley.

Over the Lena basin, the Qmax/Qmin ratio has a very strong decreasing trend for the Aldan valley. This change in ratios depends on the max and min discharge. Monthly flow data (Figures 6a and 6b) show that peak flow did not change much, and the low flows during November to April increased significantly by 50–117%, (99% significant level) over the study period and the total trend was 114% for the Qmin during 1942–1999 (Figures 6a and 6b). Low flow changes are particularly strong during 1976–1999, with a step rise from 200–400 m³/s to 600–800 m³/s in April. There are large fluctuations in the low flow records over the study period. It is important to note the consistency in the interannual variation of low flow among the months, i.e., high flows in early winter translating to high flows in late winter.

In addition, regression analyses of the low flows show high correlations (R² = 0.73 to 0.94) between the consecutive months during November to April (Figure 7). This result is expected, as the winter hydrology is dominated by discharge recession.

The ratio of monthly flows between consecutive months, or monthly recession coefficient (RC), is a quantitative measure of recession processes. The mean monthly recession coefficients for this subbasin ranges from 0.62 in early winter (December/Nov) to 0.92 in later winter (Apr/March), indicating fast (slow) recession in early (late) winter (Figure 7). The time series of recession coefficient over the study period shows significant increases (at 99% confidence) in most winter months, except an insignificant decrease for December/November (Figure 8). Increasing RC over time suggests decreases in recession rate. Dis-
charge recession is generally a process of storage release. Studies report significant permafrost changes in this region, including warming of ground temperatures and deepening of active layer depth [Pavlov, 1994; Frauenfeld et al., 2004; Zhang et al., 2005b; Romanovsky et al., 2007]. There seems to be a general coherency between hydrology and permafrost changes over this region, which deserves more research attention.

4. Discussion

[21] In addition to permafrost conditions, other factors, such as geography, geology, and climate also influence streamflow regimes in the northern regions. Data availability is a limitation for most arctic research, including this study. To understand the climate effect on permafrost and basin hydrology, we have obtained monthly precipitation and temperature data from CRU [Jones, 1994] for the Siberian region and calculated the basin mean values for the upper Lena, Aldan, and Vilyuy subbasins. Using these data, we examine precipitation and temperature patterns over the subbasins and their relationships with basin permafrost extent and streamflow regime.

[22] Results of analyses of basin precipitation data show little association of precipitation with permafrost conditions (Figure 9), this is because temperature mostly controls large-scale permafrost distribution [Nelson and Outcalt, 1983]. We discovered similar precipitation patterns over the 3 subbasins within the Lena watershed (Figure 10a), although the discharge patterns differ among the subbasins. This association of precipitation with flow regime is reasonable, as in the northern regions and watersheds, snowfall accumulates over winter season and snowpack melt in spring produces the highest floods.

[23] Monthly mean temperatures also have similar patterns among the subbasins (Figure 10b). To relate temperature with permafrost conditions, previous studies use various temperature indexes, including seasonal and yearly means and the freezing index (FI). FI is defined as the cumulative degree days of negative temperature over a year. This index is often used to calculate the freezing depth [Nelson and Outcalt, 1983, 1987]. Calculations of the FI, using basin mean monthly temperature data, show a range from $-140$ to $-175^\circ\text{C}$ for the 3 tributaries.

[24] There is a good relation between the FI and permafrost extent (coverage of permafrost, CP), i.e., CP increase with FI for the 3 tributaries (Figure 11a). This result, as expected, indicates cold climate leads to high coverage of permafrost. This relation is very important, as it relates basin thermal condition with permafrost distribution. Our analyses have already established the relationship between permafrost extent and flow regime. The combination of relations between T-CP and CP ratio links temperature, permafrost, and flow regime over the Lena basin.

[25] In addition, the Qmax/Qmin ratio increases with the FI (Figure 11b) over the Lena basin. This is reasonable, as
rivers in cold regions have very low base flows and very high peak flows, consequently high Qmax/Qmin ratio. It is important to mention that monthly T data have been used in this analysis for the determination of FI over the subbasins. There might be uncertainties in the FI calculations particularly during the early and late winter periods when the monthly T is close to 0°C. Daily T data can better define the FI, but the data was not available to this study for the Lena basin. It is expected that the relationship of T with CP and Qmax/Qmin ratio may improve when daily T data are used in future analyses.

Figure 7. The relationship of discharge between the consecutive months in low-flow periods at Aldan during 1942–1999.

5. Conclusions

This study found significant winter flow increase over the Aldan subbasin. Other analyses also reported base flow rise over the large northern watersheds, such as the Lena basin [Ye et al., 2003] and Yukon river [Walvoord and Striegl, 2007]. Base flow changes are likely related with changes in subsurface processes and frozen ground conditions in northern regions. Liu et al. [2003] documented significant of winter discharge in the source areas of the Songhuajiang river with high permafrost extent in the northeast China, and related this change to the warming of ground temperatures and deepening of active layer depth. Studies show that active layer increase affects runoff characteristics in a small headwater catchment (Mogot River) in the southern mountainous region of eastern Siberia [Yamazaki et al., 2006] and in the Kuparuk River basin [McNamara et al., 1998]. McNamara et al. [1998] reported a long recession to the slow drainage of water from a thawing active layer in northern Alaska. These changes in base features may be due to changes in storage capacity and amount in the thawed active layer [Woo et al., 2008].

There is little direct measurement of basin storage capacity and amount over the northern regions. It is therefore difficult to accurately determine their changes over time. The basin storage capacity is a measure of groundwater reservoir. A large storage capacity leads to a slow recession. For a given storage capacity, a large storage amount results in a fast recession. Over the Aldan subbasin, the recession slows down from early winter to early spring (Figure 7) maybe due to decrease in storage amount over winter. River discharge increased over the Aldan basin in winter during 1940–1999 (Figure 6b), suggesting storage amount did increase over time. This increase should lead to a fast recession, but, in fact, recession slows down in most winter months (Figure 8). This may imply the increase of basin storage capacity. In addition, Ye et al. [2003] found that discharge increase in November is the strongest over the winter months over the Lena basin. This suggests more storage of water in November over the basin and a fast recession. However, RC decreased in December/November, this may imply that the negative effect of increased storage amount on RC may overcome positive effect of increased storage capacity. More research is necessary to investigate the linkage between changes in subsurface storage and river streamflow.

Monthly discharge regimes vary over the Lena basin, although it is generally high in summer and low in winter. The ratios of Qmax/Qmin are a direct measure of hydrologic regime. They increase with drainage area from the headwaters to downstream within the Lena basin. This pattern is different from the nonpermafrost watersheds. The ratios also change with basin permafrost coverage, suggesting that permafrost affects regional hydrology. Regression analysis between the Qmax/Qmin ratio and basin permafrost coverage reveals a significant relationship at 99% confidence. This relationship quantifies the effect of permafrost distribution on discharge process. It shows that permafrost conditions do not significantly affect streamflow regime over the low permafrost (less than 40%) regions, and it strongly affects discharge regime for regions with high
Figure 8. The monthly recession coefficient between the consecutive months in low-flow period at Aldan during 1942–1999.
(greater than 60%) permafrost coverage. It is important to define this relation of permafrost impact to regional hydrology, as this knowledge will be useful for further investigation into permafrost effect on basin hydrology over the large northern regions. Temperature and precipitation have similar patterns among the subbasins. Basin precipitation has little association with permafrost conditions. There is a reasonable relation between the FI and permafrost extent over the basin, indicating that cold climate leads to high coverage of permafrost. This relation relates basin thermal condition with permafrost distribution. The combination of the relations between T-CP and CP-Qmax/Qmin links temperature, permafrost, and flow regime over the Lena basin.

[29] The variations in the Qmax/Qmin ratios reflect hydrologic regime changes. Trend analyses of the ratios show different results over the Lena basin. The ratios significantly decrease in the Vilui valley and at the Lena basin outlet due to dam regulation. In the unregulated upper Lena regions, the ratios do not show any trend during

Figure 9. The basin annual precipitation versus CP for the three tributaries (Upper Lena, Aldan and Vilui) in the Lena River basin.

Figure 10. (a) The basin monthly mean precipitation and (b) the temperature for three tributaries in Lena River.
1936–1998. This may imply that the permafrost changes in the region were not sufficient enough to affect hydrological processes. In the Aldan tributary without regulation, the ratios significantly decrease due to increase in base flow during 1942–1998. This change is consistent with permafrost degradation over the eastern Siberia. This consistency to some extent verifies permafrost influence on basin streamflow process and change. Our efforts continue to refine this relationship for various climate and permafrost conditions in the high latitude regions.

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