Streamflow characteristics and changes in Kolyma basin in Siberia

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1. Introduction

The hydrological cycle of arctic rivers play a crucial role in the global climate system [*Berezovskaya et al.,* 2004]. The Arctic Ocean receives large amount of freshwater from river discharge. The quantity and timing of freshwater discharge of the northern rivers is crucial, it affects the thermoline circulation of the world's ocean [*Aagaard and Carmack,* 1989], ocean circulation, salinity and sea ice dynamics [*Aagaard and Carmack,* 1989;*Macdonald*,2000]. A better understand of hydro-climate system is essential, since the last few decades have shown significant changes. *Ye et al*. [2003] reported an increase in Siberian Lena river discharge during winter months and shift in peak discharge timing. Recent studies have focused on mechanisms driving these changes. Reservoir regulation has been found to have most direct effects on hydrologic regimes and changes [*Ye et al*., 2003; *Yang et al*., 2004a, b]. This study systematically analyzes long-term monthly and yearly discharge for the Kolyma river watershed. The outcome of this study will improve our understanding of hydrologic response to climate change in the arctic regions.

2. Dataset and method of analysis

The Kolyma watershed situated in the eastern Siberia is one of the major north flowing rivers [*Tsuyuzaki et al.*, 1999]. The river is 2410 km long; it rises in the Kolyma and the Chreskogo ranges and flows into the Arctic Ocean at Kolymskoye. The Kolyma River discharges 100.82 Km^3 mm/year into the Arctic Ocean. 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 since the late 1930s by the Russian Hydrometeorological 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 (v. 3.0) - A Database of Pan-Arctic River Discharge (www.r-arcticnet.sr.unh.edu/main.html). Within the Kolyma basin, a hydrologic observing network consisting of 13 stations has been set up since mid 1930s.

To examine the hydrological regimes and changes over the Kolyma basin, we divided the basin into upper, middle and lower sub-basins secondly; we calculated and compared long-term monthly mean discharge, standard deviation and trend for the major stations. Trend analysis for monthly and yearly streamflow was determined by a linear regression. Then, we compared the mean streamflow between the pre and post-dam periods, so as to quantify the effects of reservoir operation within the basin and at the basin outlet. Finally, we discuss the relationship between monthly climate and branch of Kolyma

hydrology changes over the basin as a whole.

3. Results

Streamflow analyses for major stations are discussed and the effect of dam on the seasonal variation of discharge regime is documented.

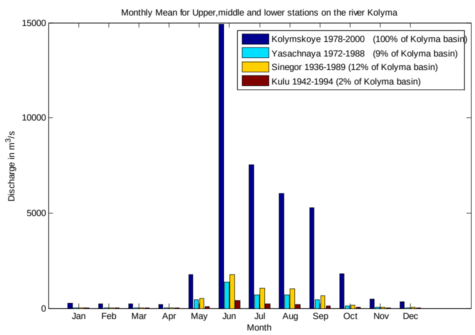

Figure 1 Monthly mean for stations on main branch of Kolyma

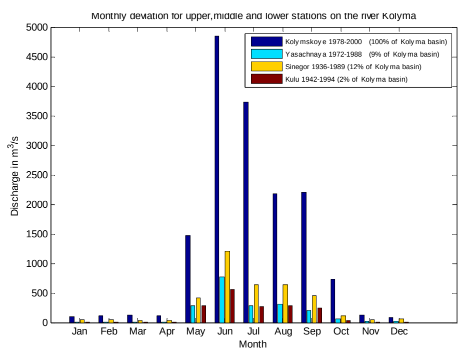

Figure 2 Standard deviation for stations on main branch of Kolyma

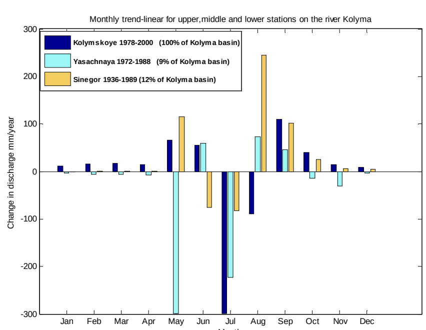

Figure 3 Trend analyses for stations on main branch of Kolyma

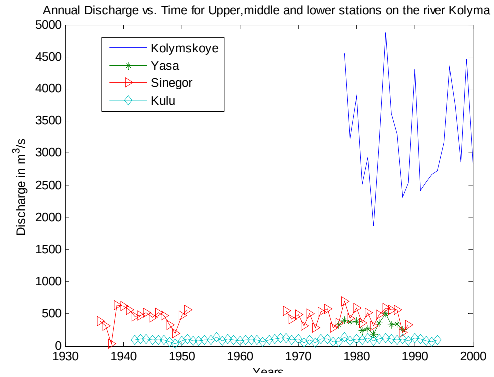

Figure 4 Annual discharge analyses

3.1 Kulu (Upper basin)

The Kulu (61° 1' N, 147° 42' E) station represents the source area of the Kolyma River .No dams exist in this upper sub-basin of 10,300 km^2 (or 2% of the Kolyma Catchment). Streamflow data are available during 1942-1994. The seasonal cycle shows the highest flow in June (405 m^3/s) and the lowest flow in April (1 m^3/s) (Figure 1). The inter-annual variation of monthly discharge, measured by standard deviation is small from October to April (16.5-0.8 m^3/s), and large during June to August (199.2 – 77.9 m^3/s) (Figure 2). During 1942-1994, streamflow increased in November by 2.2 m^3/s and in May by 37.6 m^3/s, respectively, except for January with little change of -0.05 m^3/s (Figure 3). On the other hand, discharge decreased in June by 24.6 m^3/s (or -5.8%) and July by 26.8 m^3/s (or -10.5%) (Figure 3). August and September showed a strong increase by 79.9 m^3/s (53%) and 33.3 m^3/s (27.1%), respectively. The annual discharge from1942-1994 increased by 10% (Figure 4).

3.4 Sinegor'e (Upper basin: Station closet to the dam)

The Sinegor'e station (65°26' N and 51°58' E) is situated in the upper Kolyma basin. This Station has a drainage area of 61,500 km^2. Flow data are available from 1932 to 1989, with missing data during 1952-1967 (a gap of 15 years). The seasonal cycle of monthly mean streamflow (Figure 1) shows high discharges (532-160 m^3/s) from May to October, with the maximum discharge in June (1762 m^3/s), and very low flows from November (54 m^3/s) to April (10 m^3/s). A reservoir was built in the main river valley above the Sinegor'e station in the early 1980s. The dam is 130 m high, 780 m long and its volume is 10×106 m^3. It is a rock-filled dam (with a soil core) with a surface area of 441×10^3 km^2 [*Petrov* and *Losev*, 1977]. To quantify the dam impact on streamflow regime and its change, we compare the mean monthly flows between the pre and post-dam periods. The results (Figure 5) show discharge decreases during the post-dam period by 498 - 397 m^3/s (or about 85-36%) during May to July, and increases by 136 – 134 m^3/s (525 - 1151%) from December to January. Monthly discharge records clearly show sudden changes in streamflow right after the dam completion due to reservoir regulation. Similar discharge changes have been found in other regulated Siberian watersheds, such as the Lena, Yenisei and Ob basins [*Ye et al.,* 2003; *Yang et al.,* 2004). *Yang et al.* [2003a, b] also reported that dam regulation affects long-term streamflow trends in Siberian large rivers, with winter time increase and summer time decrease. Due to many missing discharge data at this station, dam impacts on streamflow trends will not be discussed here.

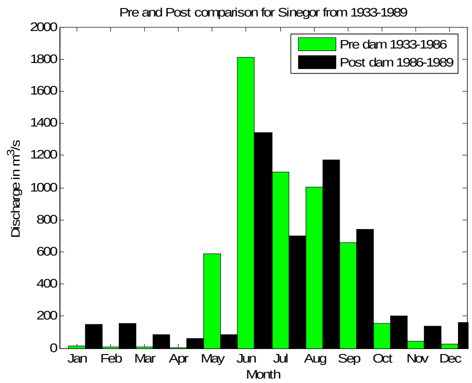

Figure 5 Pre and post dam discharge comparison for Sinegor'e

3.5. Yasachnaya at Nelemnoy (Middle basin: Western tributary)

The Yasachnaya station (52°29' N, 103°44' E) is located on the western tributary of the river Kolyma. It has a drainage area of 32,000 km^2, and contributes 6% of the total Kolyma discharge. The data range was from 1977 to 1988, with only two years of post-dam period. Yasachnaya lacks sufficient data in post-dam (after 1986) period; hence it is difficult to analyze the effect of the dam regulation. Monthly mean flow was typical, with highest discharge in June (1,367 m^3/s) and lowest in April (18 m^3/s). The standard deviations showed the same variation as monthly mean flows. The monthly discharge records overall did not show significant increases for the cold season (November-April) and very slight variations during the high flow months (May-July). Flow records at the Yasachnaya station show different trend with respect to the upper basin. Most months have discharge decrease, ranging from -30 m^3/s in November to -303 m^3/s in May during 1977-1988. Three months showed positive trend 60.1 m^3/s in June, 74.3 m^3/s in August and 14.0 m^3/s for October. The annual flow decreased by 10% during the twelve years (1977-1988).

3.6. Kolymskoye (Lower basin: Kolyma basin Outlet)

The Kolymskoye station is located above the mouth of the Kolyma River; it is here the river discharges into the Arctic Ocean. The monthly flow data at the Kolymskoye station are available during 1978-2000. The monthly mean discharges (Figure 1) were low from November to April (47 m^3/s to 18 m^3/s), and high during May to June (178 m^3/s - 754 m^3/s), with the highest monthly discharge in June (1490 m^3/s) during the snowmelt season. The discharge from August to October was 602 m^3/s to 180 m^3/s. The peak flow in June was found to be 80 times greater than the lowest flow in April. The significant difference between peak flow and low flow discharge is characteristic of watersheds with permafrost coverage. Following the pattern of monthly mean discharge, the standard deviations of monthly flow are low for November to April (128.8 – 109.4 m^3/s) and higher for May to June (1464.2 – 4844.2 m^3/s) (Figure 2). Comparisons of the long-term mean streamflow between the pre and post-dam periods demonstrate significant changes (Figure 6). In the post-dam era, peak flows decreased by 217 m^3/s (1.4%) in June, 3710 m^3/s (37%) in July, and 1189 m^3/s (17%) in August. Discharge increased by 1051 m3/s in September and by 433 m3/s in October, respectively. The most significant impact of reservoir regulation was observed during the winter months from November to April, when flows increased by 32% (127 m^3/s) in December to 208% (164 m^3/s) in April. The impact of reservoir regulation is most obvious during the cold season (November to April, flow increases) and also in June (flow decrease). Monthly flow records do not show a significant change during the post-dam period (1986-2000). The station is 1902 Km from the reservoir; the distance subdues the dam regulation, resulting in slight change in the flow data. Increasing trends from November to April were observed (Figure 3), the highest increase was seen for April by 400%, followed by March and February at 350% and 275% respectively. Negative trends were found for July (-49%) and August (-22%) (Figure 3), and a weak increase (6%) was seen in June. The remaining months have positive trends of 40% -109 %. Annual discharge at Kolymskoye shows a decrease by -1.5% during 1978-2000 (Figure 4). The increase in low flow month's discharge in Kolymskoye apart from dam impact could be due to warming, the overall temperature in the basin showed an upward trend and the decrease during the peak discharge months could be due to precipitation decrease.

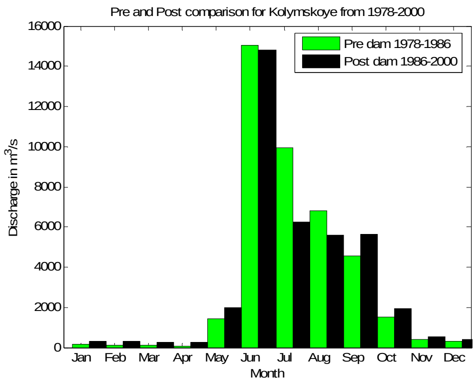

Figure 6 Pre and post dam discharge comparison for Kolymskoye

3.7. Eastern tributaries

There are five major unregulated tributaries in the eastern part of the Kolyma basin. Among the five sub-basins, two control stations, i.e. the Bol'shoy Anuy at Konstantinovo valley and the Oloy at Utuchan river, were analyzed in this study in order to understand the streamflow characteristics and changes mainly due to natural causes over the eastern Kolyma basin. The two stations were chosen since they are on the main eastern tributary. The Bol'shoy Anuy station (68°9'N and 161°9'E) has a drainage area of 49,600 km^2. Flow data are available during 1978-2000. The monthly mean flows were characteristic of the Kolyma basin, with high discharges (292 - 67 m^3/s) from May to October - the maximum discharge in June (1272 m^3/s), and very low flows from November (16 m^3/s) to April (2 m^3/s) (Figure 7). Trend analyses show flow decreases in March (-0.1 m3/s), May (-17.2 m^3/s),July (-425.5 m^3/s), August (-134.5 m^3/s) and October (-19.6 m3/s), and positive trends in June (238.8 m3/s), September (82.0m^3/s), November (3.1m3/s), December (2.3 m^3/s), January (1.1 m^3/s) and February (0.1 m^3/s) (Figure 8). These monthly flow changes caused an annual discharge decrease of 7.8% during 1978-2000.The Oloy station at the Utuchan valley (65°40' N and 162°25' E) controls a drainage area of 49,600 km^2. Flow records colleted during 1975-1988 show that monthly mean streamflows are high (40-35 m^3/s) from May to October, with the maximum discharge in June (488 m^3/s), and very low from November (13 m3/s) to April (7m^3/s) (Figure 7). Inter-annual variations show highest fluctuations in June (126.9 m^3/s) and lowest in April (0.4 m^3/s). Discharge data records during 1975-1988 indicate increasing trends (0.2–9.8 m^3/s) from November to April, and decreasing trends of 0.8 m^3/s in June, 33.9 m^3/s in July, and 85.5 m^3/s for September, respectively. As the results of monthly flow changes, annual discharge weakly decreased by 2.7 m^3/s for the period of 1975-1988.

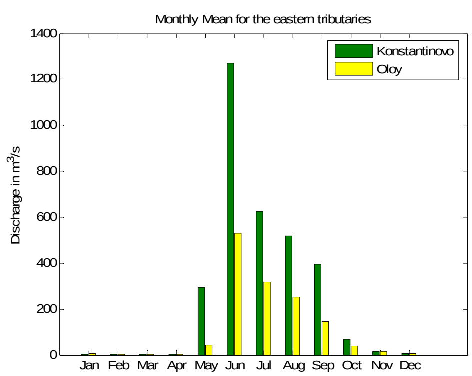

Figure 7 Monthly mean for Konstantine and Oloy

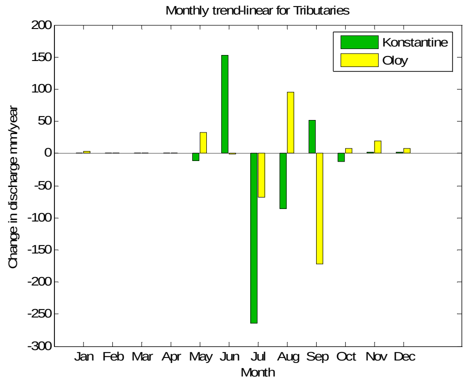

Figure 8 Trend analyses for Konstantine and Oloy

3. Conclusions

Climate over the Arctic regions has significantly changed in the last decades [*Chapman and Walsh*, 1993; *Serreze et al.,* 2000]. This study investigates Kolyma River hydrologic regimes and changes induced by reservoir regulation and climatic change. Streamflow records show that the Kolyma basin has the basic characteristic of permafrost regions, with low flow from November to April and high discharge during May to August.

Long-term changes in monthly discharge are different over the upper, middle and lower parts of the basin. In the upper basin without dam regulation, streamflow increased in most months. The increase were weak during November to May, and strong for August and September, while flow decreased weakly in June and July over the Kulu valley (source of the Kolyma basin). The two eastern tributaries did not show consistency in streamflow trends. In the Konstantine valley, discharge decreased weakly in March, May and October, and strongly in July and August; and increased strongly in both June and September, and weakly during November-February and in April. On the other hand, streamflow in the Utuchan tributary increased weakly during November-May and in October, and strongly in August; and decreased slightly in July and strongly in September. Dams have a major influence on watershed storage, discharge regime and change [*Vorosmarty et al*., 1997; *Yang et al., 2004*; *Ye et al.,* 2003]. Long-term monthly discharge data revealed that, over the mid-lower parts of the basin (downstream of the dam),streamflow increased during low flow season, and decreased in the high flow months, because reservoirs store water during the peak flow season and release water during the low flow season. These changes are somewhat consistent with river runoff decrease over the Kolyma basin as a whole, although discharge changes in the unregulated sub-basins are perhaps mainly due to natural causes, such as climate fluctuations. However, given the very weak changes in climate over the basin, the weak decreases in yearly runoff at the basin outlet is more likely due to dam impact, such as infiltration and evaporation water losses from the large reservoir [*Jansen*, 1988]. Regardless of the cause, it is important to note that Kolyma river discharge into the Arctic Ocean has decreased slightly over the past twenty year at the outlet.

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