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Streamflow changes over Siberian Yenisei River Basin

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Abstract

This study analyzes long-term (1935–99) monthly discharge data for the major sub-basins within the Yenisei River watershed in order to document significant streamflow changes induced by reservoir regulations and by natural variations/changes. The results show that both the unregulated upper basin and major lower streams of the watershed experienced streamflow decreases in the early melt period and discharge increases in the late melt season. These changes in snowmelt runoff pattern suggest a delay in snowcover melt in the Yenisei basin perhaps associated with cooling trends during the snowmelt months over central Siberia. This study also demonstrates that the reservoir regulation has significantly altered the monthly discharge regimes in northeast and the upper portions of the Yenisei basin. Constructions of four large dams in the northeast Yensiei regions reduced the summer peak flows in the Angara valley by 15–30% and increased the winter low flows by 5–30%. Operations of two large reservoirs in the upper Yenisei regions enhanced the winter flows by 45–85% and reduced the summer flows by 10–50%. These alterations lead to a streamflow regime change toward less seasonal variation over the eastern and lower Yenisei basin. Because of reservoir regulations, discharge records collected at the Yenisei basin outlet do not always represent natural changes and variations, they tend to underestimate the natural streamflow trends in summer and overestimate the trends in winter and fall seasons. Cold season discharge increase over the Yenisei river is not natural-caused, but mainly the effect of reservoir regulations in the Yenisei basin.

Keywords: Streamflow; Regime and change; Dams; Yenisei river; Siberia

1. Introduction

Fresh water discharge from northern-flowing rivers in the polar regions plays an important role in regulating the thermohaline circulation of the world's oceans (Aagaard and Carmack, 1989). Studies show that 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; Peterson et al., 2002). Climate over arctic regions has experienced significant changes during the past few decades. For instance, climate changes over Siberian regions include considerable winter warming (Chapman and Walsh, 1993; Serreze et al., 2000; Michaels et al., 2000), winter and fall precipitation increase (Wang and Cho, 1997), winter snow depth increase (Ye et al., 1998), and ground temperature rising and permafrost

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thawing (Pavlov, 1994). Climate models predict 1–4 °C surface air temperature increase in the 21st century over the earth, with even greater increase in the Arctic regions (Dai et al., 2001a,b). This warming trend will impact the structure, function, and stability of both terrestrial and aquatic ecosystems and alter the land–ocean interaction in the Arctic (Weller, 1998).

Efforts have been reported to investigate and understand the response of large northern river systems to climate change and variation (Vörösmarty et al., 2001; Magunson et al., 2000; Yang et al., 2002, 2003; Louie et al., 2002; Proshutinsky et al., 1999). Recent studies find that most northern rivers, including the largest arctic rivers in Siberia, show an increasing runoff trend, especially in winter and spring seasons, over the last several decades (Grabs et al., 2000; Zhang et al., 2001; Lammers et al., 2001; Nijssen et al., 2001a,b; Yang et al., 2002; Serreze et al., 2002). The causes for these changes are not all clear. It has been suggested that spring discharge increase in Siberian regions is primarily due to an early snowmelt associated with climate warming during snowmelt period (Nijssen et al., 2001a,b; Yang et al., 2002, 2003; Serreze et al., 2002), and changes in winter streamflow are perhaps associated with reduction in permafrost area extent and an increase in active layer thickness under a warming climatic condition (Yang et al., 2002; Serreze et al., 2002).

It is important to emphasize that, in addition to climate-induced river streamflow changes and variations, human activities, such as the construction of large reservoirs, inter-basin water diversions, and water withdrawal for urban, industrial and agricultural needs, will also impact river discharge changes over space and time (Miah, 2002; Ye et al., 2003; Vörösmarty et al., 1997; Revenga et al., 1998; Dynesius and Nilsson, 1994). Mainly due to low population and slow economic development in the high latitude regions, human impacts have been considered to be minor in the arctic river basins in comparison with mid to low latitude regions (Vörösmarty et al., 1997; Shiklomanov et al., 2000; Lammers et al., 2001). Shiklomanov et al. (1997) shows that the total water consumption in the Yenisei basin with the largest anthropogenic impact over Siberia is about 0.8–1.4% of total river runoff measured at mouth in 1995. The magnitude of this influence is unlikely to produce noticeable effects on discharge into the Arctic Ocean (Shiklomanov et al., 2000). Ye et al. (2003) recently quantified the effect of reservoir regulations in the Lena basin and found that, because of a large dam in west Lena river, peak discharge in the Vului valley has been reduced by 10–80% in the summer season and low flow has been increased by 7–120 times during the cold months. These alterations, plus a remarkable streamflow increase in May and a decrease in June over the Lower Lena basin, lead to a streamflow regime shift toward early peak flow at the Lena basin outlet (Yang et al., 2002; Ye et al., 2003).

To better define the seasonal discharge regimes and their changes, human activities, especially reservoir regulations in the high latitude regions, deserve more attention. This study will systematically analyze long-term monthly and yearly discharge records for the major sub-basins of the Yenisei river watershed. The emphases of this work are to document significant streamflow changes induced by large reservoirs and by natural variations, and to quantify the impacts of observed changes on regional hydrologic regimes. We also discuss the key processes of interaction and feedback between climate, permafrost and river systems of the northern regions. The results of this study will be useful to ongoing national and international efforts of assessing recent changes in the hydro-climatology of the pan-arctic landmass and the terrestrial ecosystems (Vörösmarty et al., 2001). They will also improve our understanding of hydrologic response to climate change and variation in the high latitude regions.

2. Basin information, data sets and method of analysis

The Yenisei river is one of the largest rivers in the Arctic. It originates from the Baikal Mountains in south Central Siberian Plateau and flows north, entering into the Arctic Ocean via the Kara Sea (Fig. 1). The drainage area of the Yenisei basin is about 2,554,482 km^2, approximately 36–55% of which is underlain by permafrost (Zhang et al., 1999). The Yenisei river contributes 573 km^3 freshwater per year, or about 22% of total freshwater flow into the Arctic Ocean (Grabs et al., 2000;

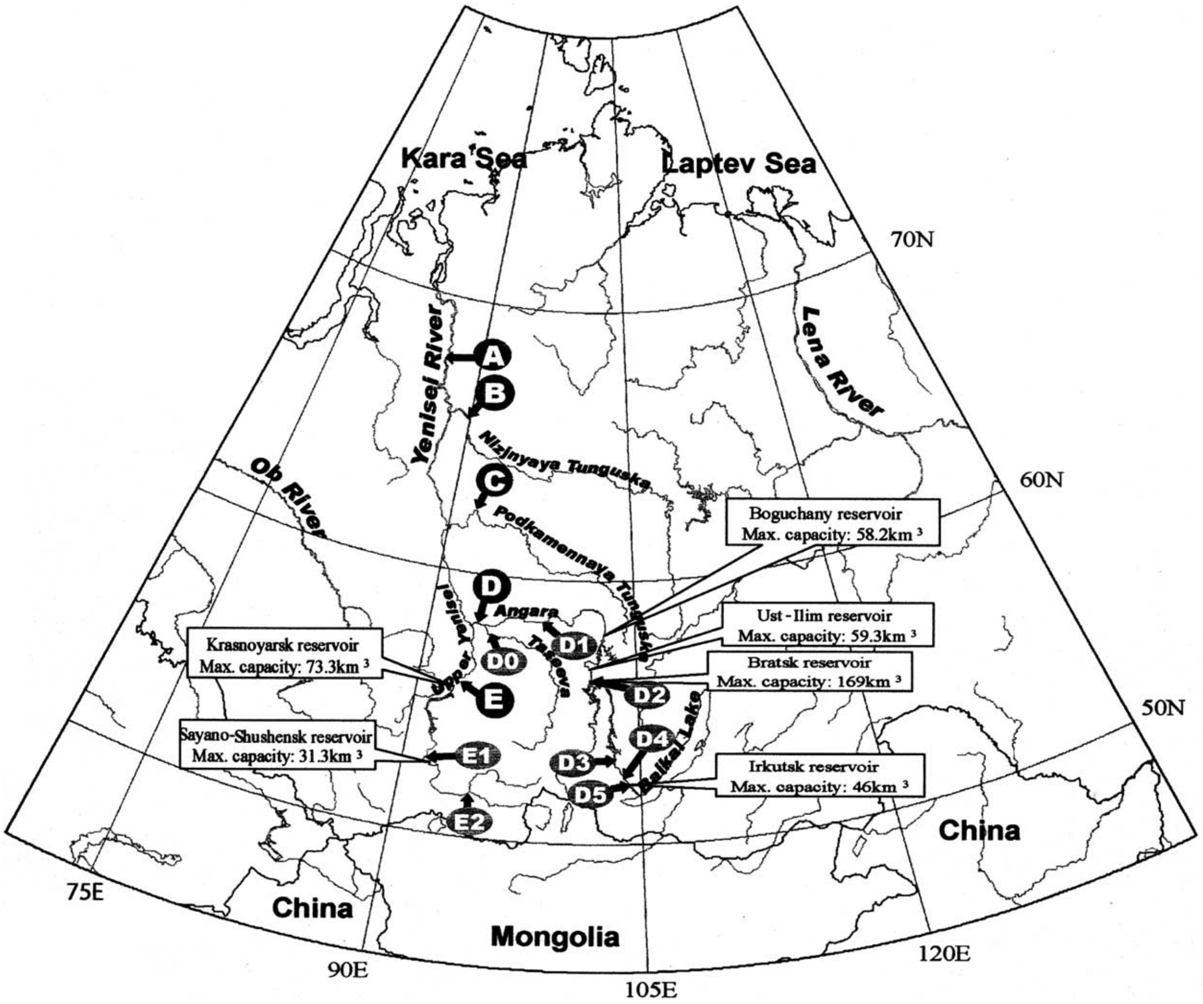

Fig. 1. The Yenisei River watershed. Also shown are reservoir location/information, and locations of hydrological stations used for this study. Letters represent station ID listed in Table 1.

Shiklomanov et al., 2000; Prowse and Flegg, 2000). The drainage basin is covered mainly by forest (49%), grassland (18%), shrub (15%), cropland (13%), and wetland (3%; Revenga et al., 1998). Basin total population is about 5 million, with 10 cities having more than 100,000 population. Comparing with other large Siberian rivers, such as the Ob and Lena rivers, the Yenisei basin has significant human activities and advanced economic development (Dynesius and Nilsson, 1994). Several large reservoirs (capacity greater than 25 km^3) were built in the basin from mid 1950s–1980s (Revenga et al., 1998). This study focused on the six largest reservoirs located above the basin outlet that have the potential to significantly impact basin streamflow.

Since the late 1930's 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 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) for the period from 1935 to 1999. In this analysis, long-term monthly and annual discharge records collected at various locations in the Yenisei basin were used. Relevant station information is summarized in Table 1. It is known that winter discharge measurements under ice conditions are less accurate, with the potential errors being 15–30% over the arctic regions (Grabs et al., 2000). In the former USSR, winter streamflow under ice conditions was determined by a standard procedure that involves direct discharge measurement, adjustment of the open water stage–discharge relation according to climatological data, and comparison of streamflow with nearby stations (Pelletier, 1990). Application of this standard method in Siberian regions produces compatible and consistent discharge records over time and space.

The main objective of this study is to examine and document Yenisei basin streamflow changes induced by both human impact and natural variability. To achieve this goal, we need to define the natural streamflow variations and quantify the impact of reservoir regulation on discharge regime and change. The approaches and methods we used in this study are briefly summarized below. First, we compiled basin geophysical and hydrologic information and identified dam-regulated and unregulated (natural condition) sub-basins. Second, we calculated and compared long-term means of monthly discharge between pre- and post-dam periods so as to determine the reservoir impact on hydrologic regimes. Third, we analyzed and established monthly streamflow relation between upper and downstream stations before the reservoir operation and use this relation to reconstruct monthly discharge data at the Yenisei basin outlet. This reduces reservoir impact on regional streamflow hydrology and generates reliable streamflow data sets useful for regional climatic and hydrologic investigations. Finally, we carried out trend analysis by a linear regression on both observed and reconstructed monthly and yearly discharge records for the regulated and unregulated

Table 1
Hydrologic stations used in this study and dam information over the Yenisei basin

Station I.D. (see Fig. 1)	Station name/location	Lat. (N)	Long. (E)	Data period	Drainage area		Annual discharge			Dam Information
					× 1000 km^2	% of Yenisei basin	km^3	m^3/s	% of basin runoff	
A	Igarka/Yenisei basin outlet	67.43	86.48	1936–1995	2440	100.0	573.4	18,184	100.0	Large dams
B	Bol. Poro/Nizjnyaya Tunguska	65.63	90.02	1938–1989	447	18.3	108.4	3438	18.9	No dams
C	Kuz′movka/Podkamennaya Tunguska	62.32	92.12	1938–1988	218	8.9	49.9	1581	8.7	No dams
D	Tatarka/Angara–Taseeva tributaries	58.35	93.55	1953–1988	1040	42.6	144.1	4570	25.1	Large dams
D_0	Mashukovka/Taseeva tributary	57.82	94.32	1936–1988	127	5.2	24.3	769	4.2	No dams
D_1	Boguchanyu/Angara tributary	58.38	97.45	1936–1988	866	35.5	108.7	3446	19.0	Large dams
D_2	Bratskaya GES/Angara tributary	56.28	101.73	1962–1988	736	30.2	87.6	2777	15.3	Large dams
D_3	Angarsk[a]/Angara tributary	52.57	103.95	1964–1980	598	24.5	n/a	n/a	n/a	Large dams
D_4	Ostrov Ujnost′/Angara tributary	52.27	104.32	1970–1974	573	23.5	58.6	1858	10.2	Large dams
D_5	Irkutskaya GES/Angara tributary	52.23	104.30	1958–1988	573	23.5	67.4	2137	11.8	No dams
E	Bazaiha/upper Yeniei	55.98	92.80	1936–1989	300	12.3	90.3	2864	15.8	Large dams
E_1	Nikitino/upper Yesisei	53.02	91.48	1936–1989	182	7.5	47.1	1493	8.2	Large dam
E_2	Kyizyil/upper Yenisei	51.72	94.40	1936–1989	115	4.7	32.6	1035	5.7	No dams

[a] Note: missing data at this station in winter months.

sub-basins, and compared the results of trend and regime analyses. From this, we quantified and assessed streamflow changes induced by natural variations and human impacts within the Yenisei watershed.

3. Streamflow characteristics and change

In this section, we define streamflow seasonality and variation, examine the changes in monthly streamflow through trend analysis for the four major sub-basins (i.e. the Nizjnyaya Tunguska, Podkamennaya Tunguska, Angara–Taseeva, and the upper Yenisei sub-basins) and at the Yenisei basin outlet, and identify different characteristics of discharge changes among the sub-basins. We also document dams in the Yenisei basin and assess their impacts on streamflow regime and change through comparisons of long-term mean monthly discharges between the pre- and post-dam periods.

3.1. The Nizjnyaya Tunguska sub-basin

The Nizjnyaya Tunguska tributary (above station B in Fig. 1) occupies the eastern-central section of the Yenisei basin. The area of this sub-basin is 447,000 km^2 (or 18.3% of the Yenisei watershed), it contributes 19% of total Yenisei basin streamflow. Human activities in this region are insignificant. No major dams exist in this tributary.

The seasonal cycle of mean monthly discharge at the sub-basin outlet shows a very low flow (200–600 m^3/s) during November–April and a high flow (1700–20,000 m^3/s) season from May to October, with the maximum discharge usually in June due to snowcover melt floods (Fig. 2a). Generally watersheds with a high percentage of permafrost coverage have low subsurface storage capacity and thus a low winter base flow, and a high summer peak flow (Kane, 1997). For this sub-basin, the peak flow in June is about 120 times greater than the lowest discharge in April. The inter-annual variation of the monthly streamflow is generally small in the cold season and large in summer months (particularly in May and June) mainly due to floods associated with snowmelt and rainfall storm activities.

Trend analysis reveals no changes in discharge during October–April, a significant decrease in May, and increases during June–September. The trends are statistically insignificant except for May (50% confidence) and June (90% confidence). Streamflow decreases in May and increases in June indicate a possibility of snowmelt pattern change toward late spring over this northern sub-basin. As the result of the summer season streamflow increase, yearly discharge shows an upward trend, 563 m^3/s or 16%, during the period 1938–1999.

3.2. The Podkamennaya Tunguska sub-basin

This sub-basin, 218,000 km^2 above the Koz′moveka station (C in Fig. 1), or 8.9% of the Yenisei watershed, covers eastern parts of the Yenisei catchment. Annual mean discharge is about 50 km^3, contributing 8.7% of basin total flow. Natural conditions remain in most areas and no large reservoirs exist in this sub-basin.

Monthly streamflow of the Podkamennaya Tunguska sub-basin shows a different regime when compared with the Nizjnyaya Tunguska sub-basin. Monthly flows are low during November–April and high from May through October. The peak flows occur in May and June, with May having the highest flow (Fig. 2b). This shift of the highest peak flow from June to May reflects the response of river system to a warmer winter/spring climate and an early snowmelt in the southern parts of the Yenisei basin. The inter-annual variation of the Podkamennaya Tunguska basin monthly streamflow is similar to the Nizjnyaya Tunguska regions.

Trend analysis shows streamflow increases of 50–240 m^3/s (or 10–30%) during August–March except November with very little change. These increases are statistically significant at 90–99% confidence during December–March and changes in other months are less significant. Streamflow in summer season shows moderate decreases, 73 m^3/s or 27% in April and 200 m^3/s or 14% in July, no change in May, and a very remarkable increase of 2230 m^3/s (or 38% up) in June. The strong upward trend in June is identical to the trend found for the neighboring Nizjnyaya Tunguska sub-basin. This result may suggest changes in regional snowmelt and associated floods in the mid-lower

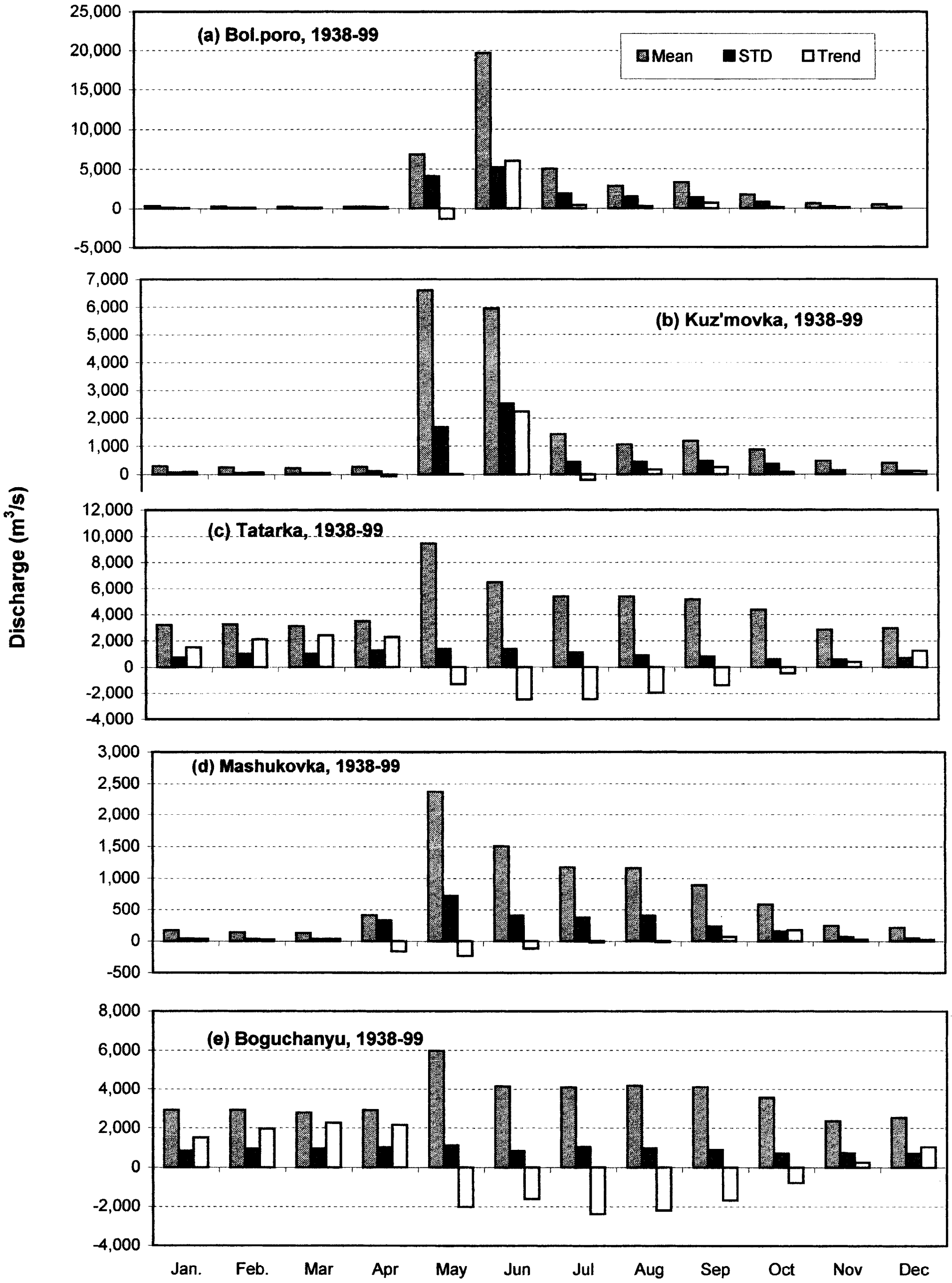

Fig. 2. Long-term mean monthly discharge, standard deviation and trend during 1938–99 for major sub-basins and at the Yenisei basin outlet.

Yenisei basin. Annual discharge of the Podkamennaya Tunguska basin shows a weak upward trend (208 m^3/s or 13%) mainly due to streamflow increases in the summer.

3.3. The Angara–Taseeva tributaries

The Angara–Taseeva sub-basin, consisting of the Angara and Taseeva tributaries, occupies the southeast corner of the Yenisei basin. The total area of this sub-basin is about 452,000 km^2 (18.6% of the Yenisei basin), which is the largest sub-basin within the Yenisei watershed. The annual streamflow from these tributaries is about 133 km^3, or 23% of yearly total runoff in the Yenisei river.

Monthly flow records observed at the sub-basin outlet, the Takarta station (D in Fig. 1), demonstrate different streamflow characteristics, with relatively higher winter base flows and lower summer peak flows (Fig. 2c). Variations of monthly flows are low for most months, including the summer peak flow season. Monthly flows show increasing trends during November to April, and decreasing trends from May to October. Annual flows have a moderate upward trend of 875 m^3/s or 20% during the study period of 1936–1999. These changes in monthly and yearly flows are related to both human impacts and natural variations within this large sub-basin.

Human activities such as mining and farming exist in these regions. There are no large reservoirs in the Taseeva valley. However, four large reservoirs were built along the Angara valley during 1950's–1980's. These dams were 45–125 m high and 700–1500 m long. The maximum reservoir capacities are between 46 and 170 km^3. The total capacities of the four reservoirs account for 58% of total annual runoff (573 km^3) of the Yenisei River, or three times of total discharge (110 km^3) at the sub-basin outlet of the Angara valley. The reservoirs were primarily used for hydro-power generations, and they have the capability to regulate monthly to seasonal streamflow processes. To quantify the effect of reservoirs on downstream discharge characteristics, we examine and compare the long-term monthly streamflow records between the regulated Angara valley and the unregulated Taseeva tributary.

Fig. 2d and e display the long-term mean monthly discharge, standard deviation and trend for the Angara and Taseeva tributaries. They show very different seasonal discharge patterns. The unregulated Taseeva tributary has a clear seasonal cycle, with high flows from May to October, and low flows during November through April (Fig. 2d). Variations of the monthly flow are small for November–March, and large during April–October. Streamflow trends show increases by 7–30% during September–March, decreases by 7–40% during April–June, and no changes in both July and August. Flow increases during January–March are statistically significant at 90–99% confidence; this may indicate streamflow response to winter warming over Siberian regions.

Streamflow data collected at the regulated Angara valley outlet, the Boguchanyu station (D1 in Fig. 1), represent the combined impacts of the large upstream reservoirs (Fig. 2e). It is evident that streamflow regime of the Angara valley is very different. Compared to other sub-basins, the flows from the Angara valley are higher in the cold season and lower in summer months. As a result, the ratio of max/min monthly flows is very low in comparison with other nearby stations, i.e. 2–8 vs. 20–60. Reservoir regulations tend to reduce the temporal variability of the monthly flows (Ye et al., 2003; Peters and Prowse, 2001). This feature can be seen clearly in the Angara valley. Variation in monthly flow at the Boguchanyu station is almost constant during the post-dam period. Over the observation period, monthly flow has a very strong increasing trend during the cold months (November–April) and a significant decreasing trend during May–October. These trends are much stronger than those found in the unregulated regions and they were caused by sudden changes in discharge due to dam regulations. Recent analyses of the Lena and Mackenzie basin hydrology show similar tendency of streamflow changes induced by reservoir impacts in the regulated sub-basins (Peters and Prowse, 2001; Ye et al., 2003).

To better understand streamflow regime and change in this regulated sub-basin, discharge records collected at five stations (D1–D5 in Fig. 1) along the main Angara valley were examined (Fig. 3). The Irkutskaya GES station (D5 in Fig. 1) is located in the upper Angara valley, situated below lake Baikal and above the Irkutsk reservoir that was built in 1956 for a maximum capacity of 46 km^3. The monthly streamflow records at this station show constant monthly flows, about 1800–2000 m^3/s, due to impact of large storage of the lake Bakail. The Ostrov Ujnost' station (D4 in Fig. 1), located downstream of the Irkutskaya GES station and above the dam of the Bratsk reservoir (built in 1964), has a short streamflow records during the post-dam period 1970–1974. Flow regime at this location is similar to Irkutskaya GES station. The monthly flows were about 2000 m^3/s during January–August,

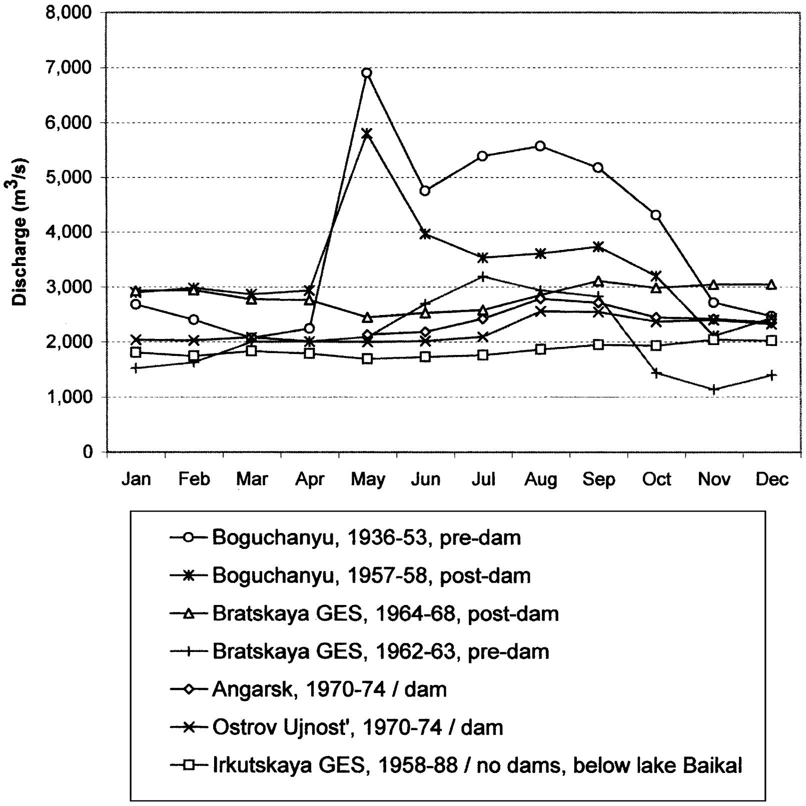

Fig. 3. Comparison of long-term mean monthly discharges at the five stations along the regulated Angara valley. Data periods and dam information are also presented.

and 2300–2600 m^3/s from September to December. The impact of reservoir regulation on streamflow is minor at this location. The Irkutsk reservoir was built mainly for generating power for city of Irkutsk and surrounding areas. The demand for power is higher in winter season and thus reservoirs release more water to meet the demand. The Angarsk station (D3 in Fig. 1) is located further downstream, the seasonal cycle of streamflow here is very similar to that seen at the Ostrov Ujnost' station.

The Bratskaya GES station (D2 in Fig. 1) is located about 600 km below the Bratsk reservoir, which was completed in 1964, as one of the largest reservoirs in Siberian regions, with a maximum capacity of 169 km^3. The flow records collected at this station covered both the pre- and post-dam periods. A comparison of the mean flows between the pre- and post-dam periods shows significant changes in seasonal discharge pattern. Similar to reservoirs built and operated in the Lean basin, the Bratsk reservoir increased the winter (October–April) flows by 700–2000 m^3/s and reduced the summer (June–August) discharge by up to 700 m^3/s. As a result, the summer peak has been completely eliminated and monthly hydrograph lost its seasonal cycle, showing relative lower flows in summer and higher flows during winter. This winter high and summer low flow pattern clearly reflects the higher (lower) power demand in winter (summer).

In between gauging stations Bratskaya GES and the Boguchanyu, two reservoirs, maximum capacities 58–59 km^3, were built during 1950's–1960's. Comparisons of mean streamflow at the Boguchanyu station (D1 in Fig. 1) between the pre- and post-dam construction shows that both long-term mean hydrographs have similar seasonal patterns (Fig. 3), i.e. peak flow appearing in May due to snowcover melt, high flow in summer monthly owning to rainfall floods, and low flow in winter. However, it is clear that reservoir regulations during the post-dam period have enhanced late winter flows (February–March) by 800–1000 m^3/s, and significantly reduced flows during spring to fall seasons, particularly over July–September by about 1500–2000 m^3/s. These changes in monthly streamflow over this large regulated sub-basin may have impact on downstream discharge trend and variation even at the Yenisei basin outlet. This will be discussed later in basin integration and trend analyses.

The reservoirs in the Angara valley, given their large storage capacities, may also affect the yearly streamflow characteristics. Fig. 4 compares annual discharge records among the unregulated Mashukovka (D0 in Fig. 1) station, and the regulated Boguchanyu (D1 in Fig. 1) and Bratskaya GES (D2 in Fig. 1) stations. It shows no major changes or step-jumps in annual flows for the unregulated sub-basins. However, there are four low-flow periods in Boguchanyu station records. The first low period (drop) around 1954–1958 was perhaps associated with the filling of the Irkutsk reservoir, as annual flows were close to normal in the unregulated sub-basins. The second low-flow period during 1962–1965, also seen as normal flows in the unregulated regions but the lowest flows at

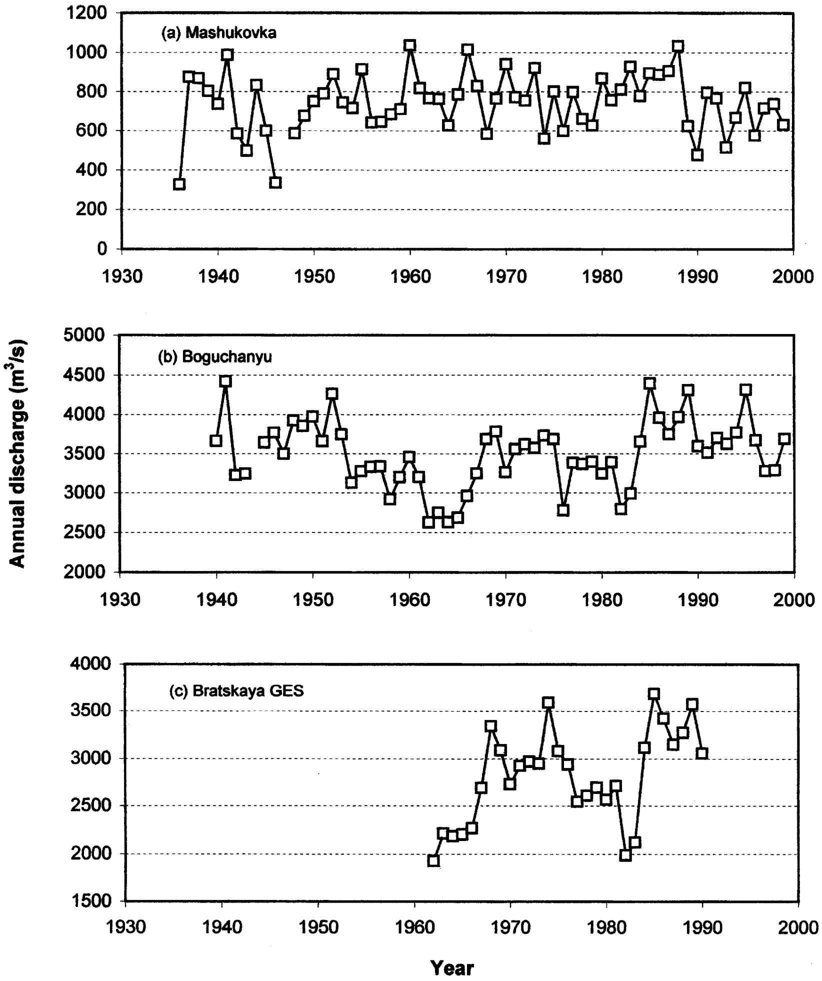

Fig. 4. Comparisons of annual streamflow records observed at three stations in the Angara valley, (a) Mashukovka (D0 in Fig. 1), (b) Boguchanyu (D1 in Fig. 1), and (c) Bratskaya GES (D2 in Fig. 1).

the Bratskaya GES station in the upstream Angara valley, coincided with the completion of the Bratsk reservoir in 1964. The third and fourth lows were observed in 1976 and 1982, respectively, and lasted for only 1 year. These low flows, associated with normal to high flows in the unregulated basins, were likely due to fillings of reservoirs, i.e. the Ust-llim completed in 1977 and the Boguchany built in 1983. Similar to Lena basin (Ye et al., 2003), the lower flow periods identified in the annual streamflow records may reflect reservoir regulation on yearly streamflow. With the data and information available to this study, it is difficult to accurately define the impact of the reservoir on annual flow. To eliminate the potential impact, reconstruction of monthly and yearly streamflow data should be considered.

3.4. The upper Yenisei basin

The upper Yenisei basin is located in the southwest corner of the mountain regions. The basin area is about 300,000 km^2 (12.3% of the basin total), and annual streamflow measured at the sub-basin outlet (E in Fig. 1) is close to 90.3 km^3, or 15.8% of the Yenisei river total runoff.

Flow data collected at the station Kyizyil (E2 in Fig. 1) in the source areas of the upper Yenisei basin show no abrupt changes over the past six decades (Fig. 5a). Two large reservoirs were constructed in 1960’s and 1980’s in the middle section of upper Yenisei basin. Their effects on seasonal streamflow regime are clearly seen in monthly discharge records measured along the upper Yenisei valley. For instance, a reservoir (the Sayano-Shnshensk) was built upstream in 1985, the dam was 245 m high and 1066 m long, maximum capacity of 31.3 km^3. The impact of this reservoir on streamflow at the upper Yenisei basin outlet is relatively weak because of runoff contributions from unregulated areas. However, changes in monthly flows at the Nikitino station (E1 in Fig. 1) located below the dam were significant. Since the operation of the dam, winter flows were increased from 800–1000 m^3/s to 1800–2200 m^3/s, and summer flows were reduced from 4000–8000 to 2000–5000 m^3/s (Fig. 5b).

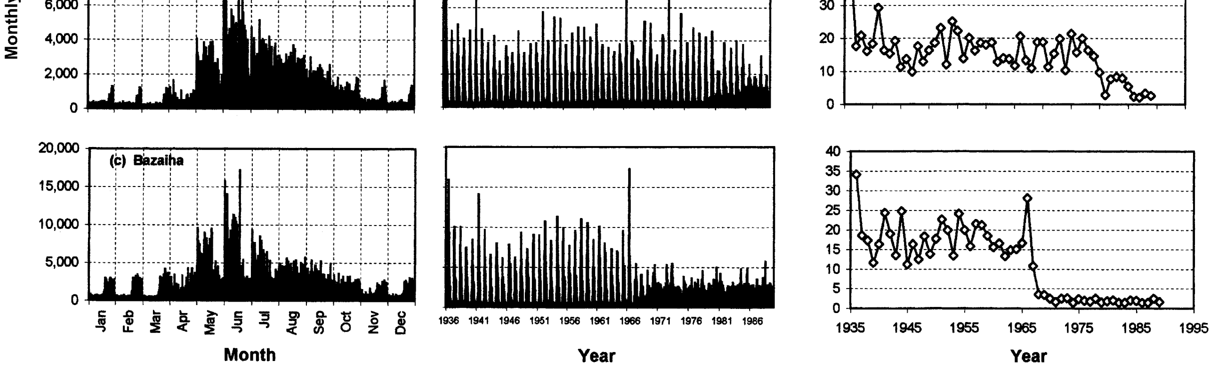

Fig. 5. Changes in monthly discharge at three stations in the Upper Yenisei basin. Seasonal regimes are displayed in the left column, each bar represents an individual monthly value for each year during 1936–1999. Monthly time series are shown in middle column. Ratios of max./min. flows are presented in the right column.

A large dam (height 124 m and length 1065 m) downstream was completed in 1967 at the Kransnoya reservoir (maximum capacity 73.3 km^3). An abrupt increase of winter (November–March) flows at the basin outlet station Bazaiha (E in Fig. 1), by 2000–3000 m^3/s, is evident, and a reduction in summer peak flows from 10,000–17,000 m^3/s to 2000–3000 m^3/s is also very clear (Fig. 5c). As a result, the monthly hydrograph changed very significantly, it became less variable over the seasons, showing almost no seasonal cycle at all. These changes in seasonal streamflow regime are best reflected in the ratio of maximum/minimum flows (Fig. 5c). The drop of the ratios from 10–30 to 2–5 due to reservoir effect is so distinctive that can be used to detect sudden changes in streamflow caused by human activities.

3.5. Yenisei basin (outlet) as a whole

Streamflow records observed at the watershed outlet reflect basin integration of both natural variation and changes induced by human impact, such as land surface change and regulation of dams within the watersheds. Discharge data collected at the river mouth are particularly important as they are often used for basin-scale water balance calculations, climate change analysis, and validations of land surface schemes and GCM applications over large spatial scales (Dai and Trenberth, 2002; Arora, 2001; Nijssen et al., 2001a,b; Bonan, 1998). It is critical to understand the fundamental characteristics of monthly and yearly streamflow at basin outlet, and to document their significant variations and changes.

The long-term monthly discharge records measured at the Igarka station (A in Fig. 1) is presented in Fig. 6. It generally shows a low flow period during November–April and a high discharge season from June to October, with the maximum streamflow occurring usually in June due to snowmelt floods. The data also clearly show abrupt changes in monthly flows. Around mid 1970's, monthly flows during November–April suddenly jumped upward by about 40–70%, while flows in May decreased from 40,000–60,000 m^3/s to 20,000–42,0000 m^3/s. These remarkable changes are likely due to constructions of large artificial impoundment within the watershed.

Monthly streamflow variation at the Yenisei basin outlet is usually small (22–32%) in the cold season and large (15–115%) in summer months owing to floods of snowmelt and heavy rainfall storms. Trend analyses of the monthly discharge records at the Igarka station show significant changes in streamflow characteristics (Fig. 7). Since mid 1930's,

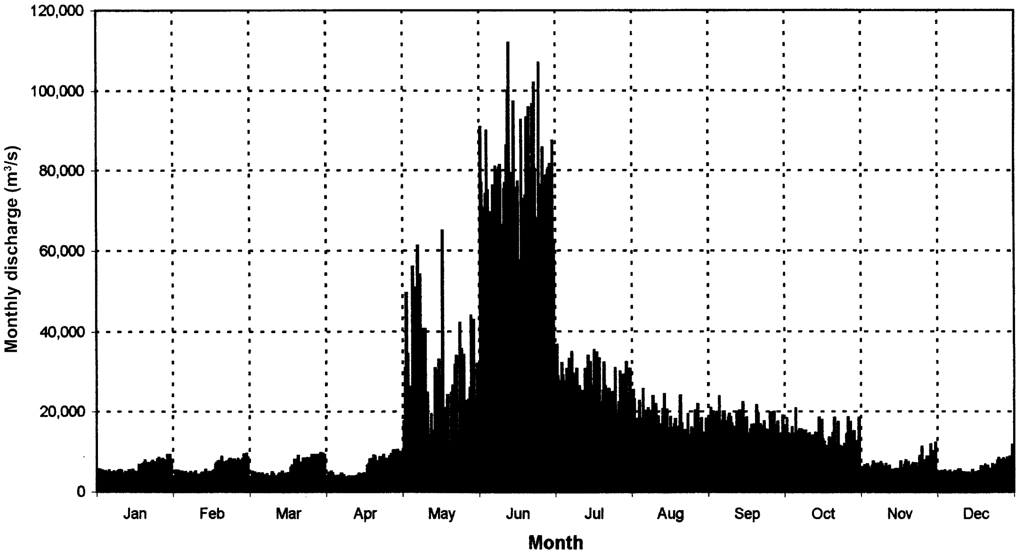

Fig. 6. Monthly flow regime at the Yenisei basin outlet station (Igarka). Each bar represents an individual monthly value for each year during 1936–1999.

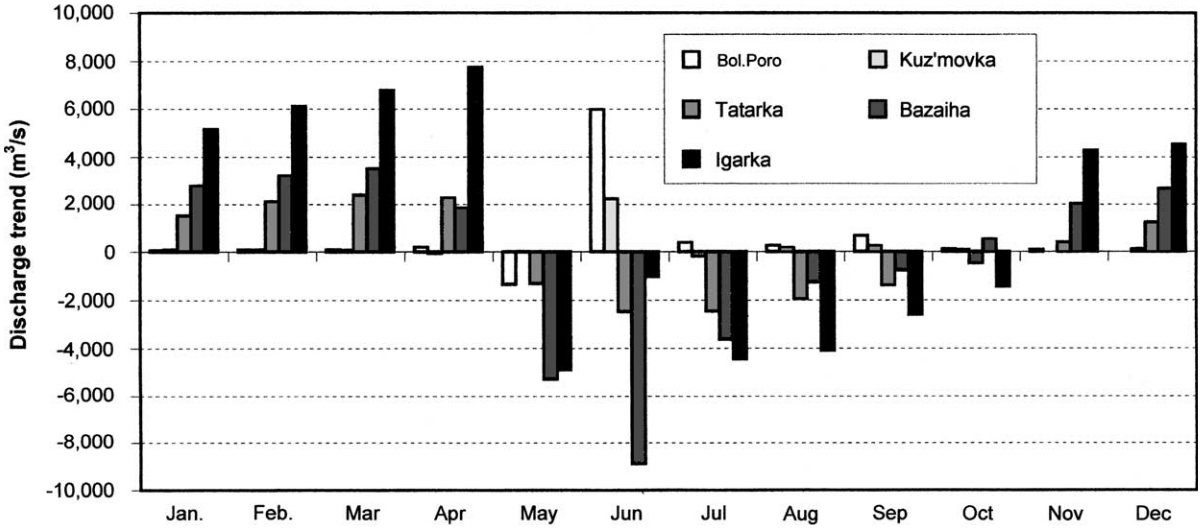

Fig. 7. Comparison of monthly discharge trends during 1938–1999 among the major sub-basins and at the Yenisei basin outlet.

discharge at this site has increased by 30–110% in the low flow season from November to April. These increases in winter month flows are identical to those found for the regulated sub-basins, such as the Angara–Taseeva sub-basin and the upper Yenisei basin. On the other hand, no major changes have been detected for the unregulated sub-basins (i.e. the Nizjnyaya Tunguska and Podkamennaya Tunguska sub-basins) over the winter season (Fig. 7). Therefore trends observed in winter flows at the Yenisei river mouth are mainly the consequence of large reservoir regulations, that is, reservoirs release water in winter season for power generations.

May and June are the important months as snowcover melts and generates peak flows. We discovered streamflow decreases in May from

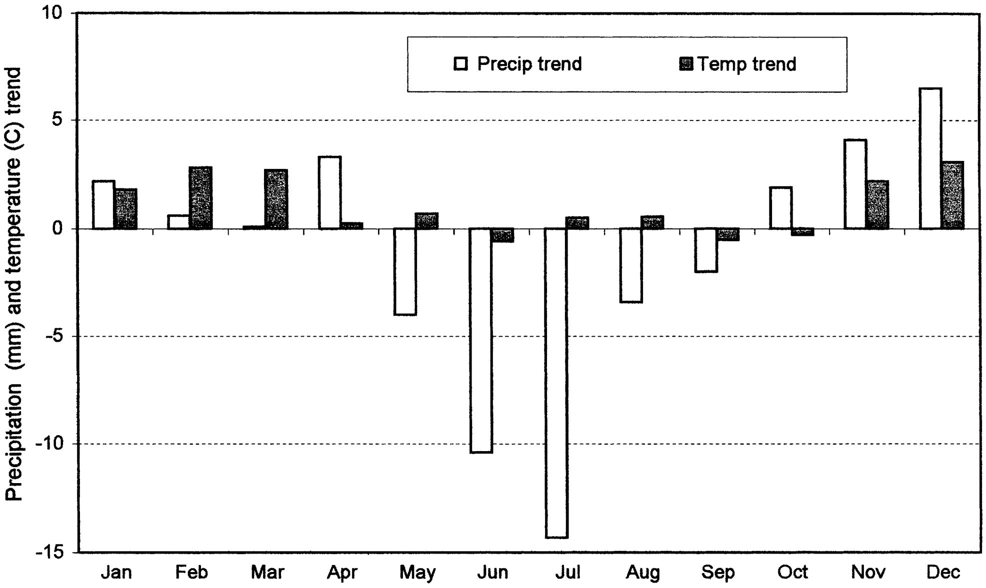

Fig. 8. Long-term trends in basin-mean monthly temperature and precipitation records over the Yenisei watershed during 1936–1998.

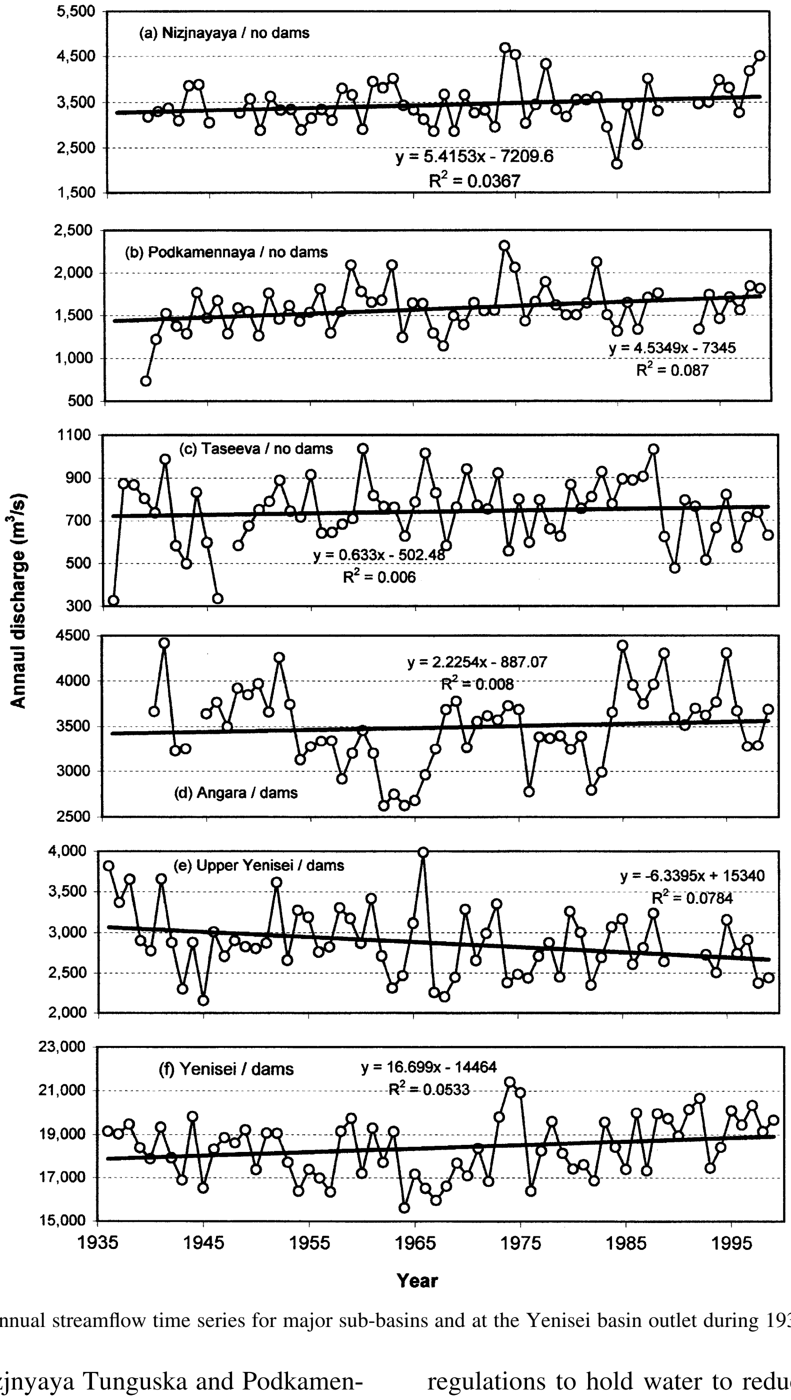

Fig. 9. Annual streamflow time series for major sub-basins and at the Yenisei basin outlet during 1936–1999.

the unregulated Nizjnyaya Tunguska and Podkamennaya Tunguska sub-basins due to cooling trends in April and May temperatures over the basin. On the other hand, strong flow decreases in May were also found in the regulated regions due to reservoirs regulations to hold water to reduce snowmelt floods by up to 100% during the spring melt periods. The combination of May flow reductions in both the regulated and unregulated sub-basins within the Yenisei watershed led to a very strong downward

Table 2
Summary of regression analyses for reconstruction of monthly flow at the basin outlet

Parameter	Regression model: $Q = A + B1*Q1 + B2*Q2 + B3*Q3 + B4*Q4$												
	Sub-basin/station names	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
A		1887.37	2351.72	2572.65	3933.57	7483.39	25252.34	3098.83	4681.85	4820.23	2970.19	7811.56	3580.29
B1	Nizjnyaya Tunguska at Bol. Porog/Q1	0.68	0.00	0.00	−3.44	3.07	1.98	1.74	1.39	1.68	2.26	−2.52	1.40
B2	Podkamennaya Tunguska at Kuz'movka/Q2	3.52	3.74	1.60	1.24	1.53	0.00	3.24	1.55	0.00	0.00	1.80	0.00
B3	Taseeva at Mashukovka/Q3	12.27	10.23	0.00	1.22	−5.88	21.86	4.33	3.96	2.28	5.23	2.72	3.47
B4	Yenisei at Kyizyil/Q4	0.00	0.00	6.75	−0.93	0.00	−4.30	2.68	2.65	4.41	6.50	−4.13	0.00
R		0.64	0.51	0.39	0.76	0.96	0.89	0.85	0.87	0.79	0.74	0.61	0.49
Significant level (%)		97	92	81	99	99	99	99	99	99	99	95	91
Sample number		16	16	16	16	16	16	16	16	16	16	16	16

trend (−50%), or close to 1500 m^3/s, at the basin outlet. June discharge changes are different among the sub-basins. Flows in June increased in the unregulated sub-basins located in the lower Yenisei regions. This increase is associated with snowmelt pattern change toward a late start of the melt season, i.e. a shift of snowmelt peak toward late melt in June. On the other hand, flows in June decreased in the regulated sub-basins, particularly from the upper Yenisei regions by about 140%. The flow increase in June outweighs the decrease, causing a weak increasing trend (10%) at the Yenisei basin outlet. During July–October, little changes in monthly flows (<10–20%) have been found in the unregulated areas, and decreases up to 70–80% have been discovered for the regulated sub-basins, resulting in a downward trend (10–15%) at the Yenisei basin mouth (Fig. 7).

Basin-mean monthly temperature and precipitation trends are presented in Fig. 8. It shows temperature warming by 2–3 °C during November–March, and very little change from May to October. Precipitation increased by 2–7 mm during November–March, and decreased by 3–15 mm from May to September. It is important to notice the consistency between precipitation and streamflow trends (Figs. 7 and 8), particularly during the mid summer months when both precipitation and river streamflow decreased very significantly over the Yenisei basin as a whole. Strong precipitation decreases over summer months enhanced the dam impacts to reduce the summer season streamflow at the basin scale.

Annual streamflow trends are important for climate change analyses. Serreze et al. (2002) reported an increase trend in yearly total runoff over large Siberian watersheds including the Yenisei basin. Yang et al. (2002, 2004)) recently found that annual flow increased by 5–7% during last several decades in the Ob and Lena river basins. Fig. 9 presents long-term trends of yearly mean flows during the study period for the major sub-basins and at the Yenisei watershed outlet. It shows moderate increases of 10–15% in the unregulated sub-basins, such as the Nizjnyaya Tunguska (Fig. 9a) and the Podkamennaya Tunguska (Fig. 9b) tributaries in the northeast parts of the basin, and the Taseeva valley (Fig. 9c) in the southern mountain regions. On the other hand, the regulated sub-basins demonstrate

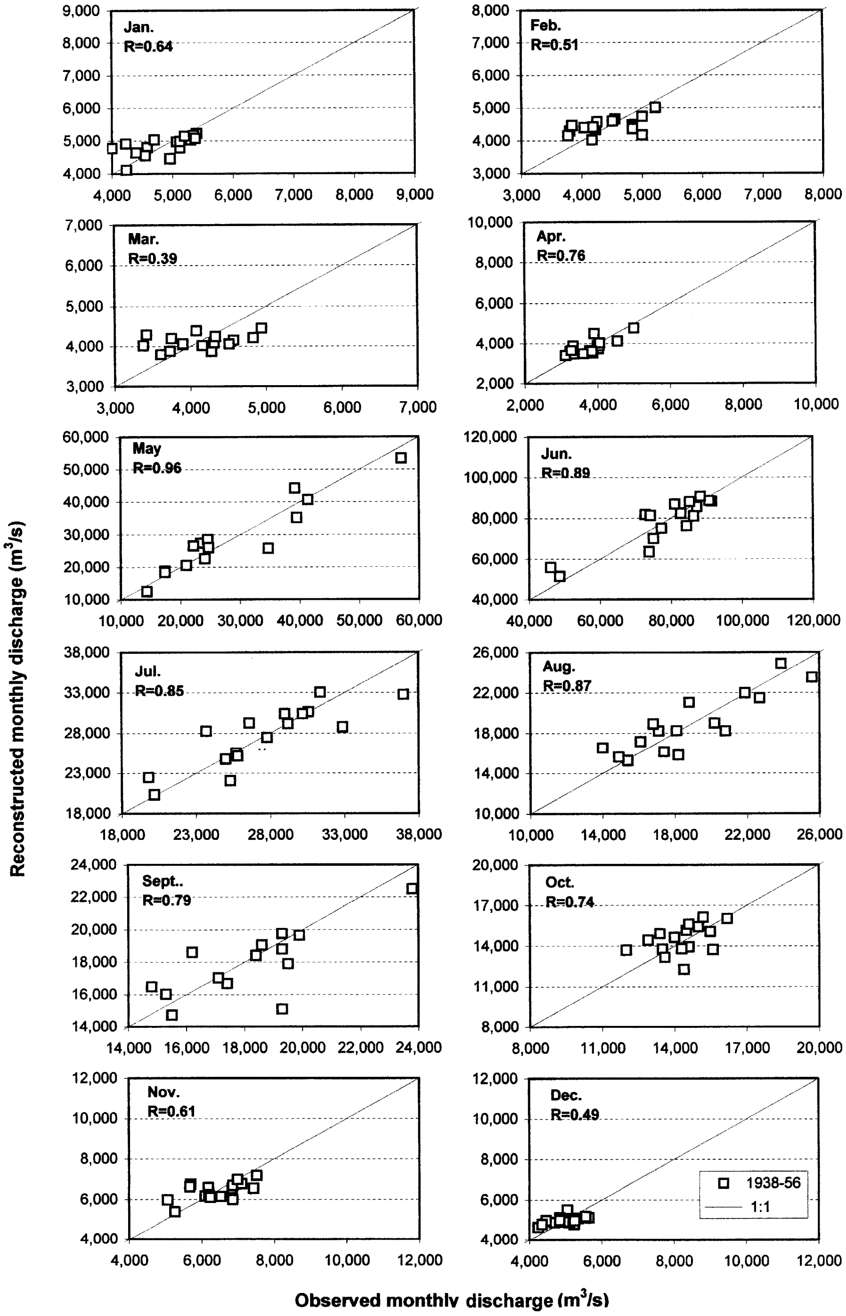

Fig. 10. Tests of reconstructed monthly discharge against observed flows at the Yenisei basin outlet for the pre-dam period, 1938–1956.

little changes over the Angara tributary (Fig. 9d) and weak decreasing trends of 5–7% in the upper Yenisei valley (Fig. 9e). The positive streamflow changes are statistically significant at 80–90% confidence, while the decreasing trends are less significant at 50–70% confidence. As a result of flow increases from the unregulated regions, the Yenisei basin (as a whole) has a weak increase

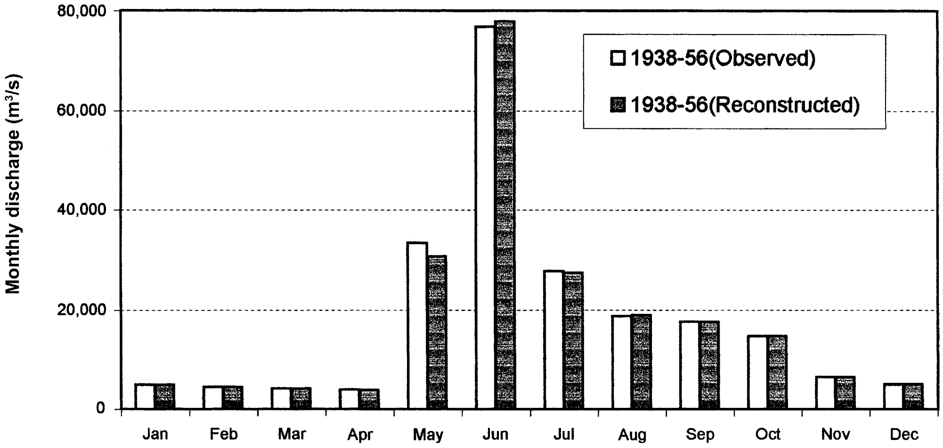

Fig. 11. Comparison of mean monthly streamflow between the observed and reconstructed discharge records at the Yenisei basin outlet during pre-dam period, 1938–1956.

(about 3%) in annual flow at the basin outlet during 1935–1999 (Fig. 9f).

3.6. Reconstruction of streamflow data at basin outlet

To reduce the effect of reservoir regulations on monthly and seasonal discharge distributions at the Yenisei basin outlet, reconstruction of streamflow records is necessary. A stepwise regression of monthly discharge among upstream and downstream stations was used. Four stations (B, C, D0 and E2 in Fig. 1) located in the unregulated areas were chosen to represent the natural discharge conditions for the Nizinyaya Tunguska sub-basin, Podkamennaya Tungusk tributary, Taseaeva valley, and the upper Yenesei reach. Monthly flow data at these stations during the pre-dam period from 1938 to 1956 were used as input candidates to the regression model.

Results of the regression analyses are summarized in Table 2. They generally show a close relationship (statistically significant at 80–99%) of natural discharge between the basin outlet station and the upstream stations during the pre-dam period. Tests of the reconstructed monthly data versus the observed monthly streamflow records for the pre-dam periods show good agreements for most months (Fig. 10). The difference between reconstructed and measured monthly mean streamflow is generally very small, less than 15% for most months during the pre-dam period (Fig. 11). This indicates that other factors controlling flow regimes and changes are less important relative to reservoir regulations. It also suggests that reconstruction has systematically reduced the effect of reservoir regulation on monthly discharge, and generated reliable monthly streamflow time series consistent with the monthly discharge records for the pre-dam period. Using this monthly relation, we reconstructed the monthly discharge at the basin outlet for the study period from 1936 through 1999. We found the regression results are reasonable for most months, except for May in some years when the linear regression occasionally underestimated streamflow perhaps due to impact of river ice (Fig. 12).

Reconstructed monthly discharge data usually reflect smoothed natural variability and change. A comparison of the monthly measured flows with the reconstructed flows confirms that the overall effect of reservoir regulations is to enhance winter season flow and reduce summer month discharge (Fig. 12).

Comparisons of monthly mean streamflow and their trends between the observed and reconstructed monthly data are displayed in Fig. 13. Relative to the observed data, the reconstructed mean flows are lower from November to May, and higher during June–October, except July with very similar flows (Fig. 13a). The reconstructed records have weak increasing trends during both January–March and August–October, they show decreasing trends from April to July. These changes in reconstructed flow records are much smaller in magnitude and less statistically significant relative to the trends found for the observed flow data. This suggests that observed discharge trends (positive) have been overestimated by 5500–8500 m^3/s from November through April due to reservoir releasing water in winter months, and measured flow trends (negative) during May–October have also be exaggerated by up to 4000 m^3/s in July and August because of reservoirs holding water to reduce spring snowmelt and summer rainfall floods (Fig. 13b). These results demonstrate that dams can

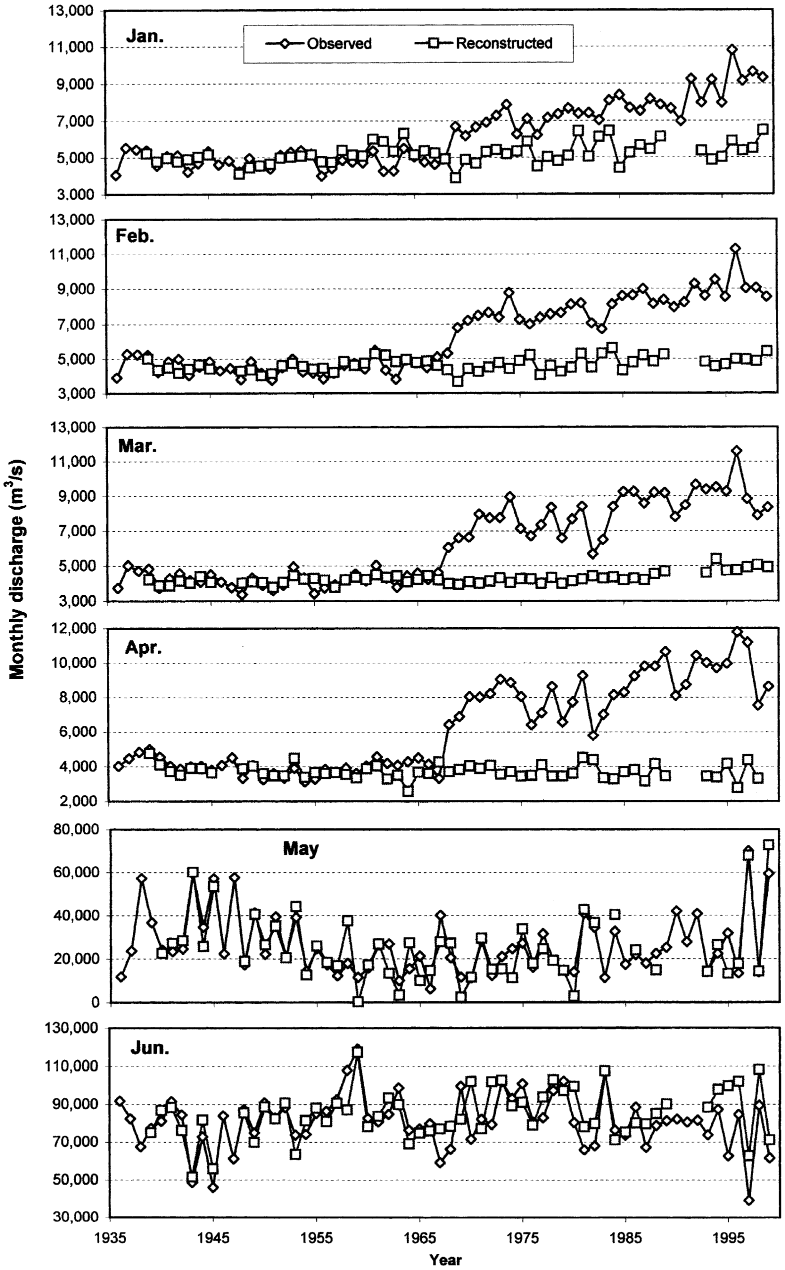

Fig. 12. Comparison between the observed and reconstructed monthly discharge records at the Yenisei basin outlet during the study period, 1936–1999.

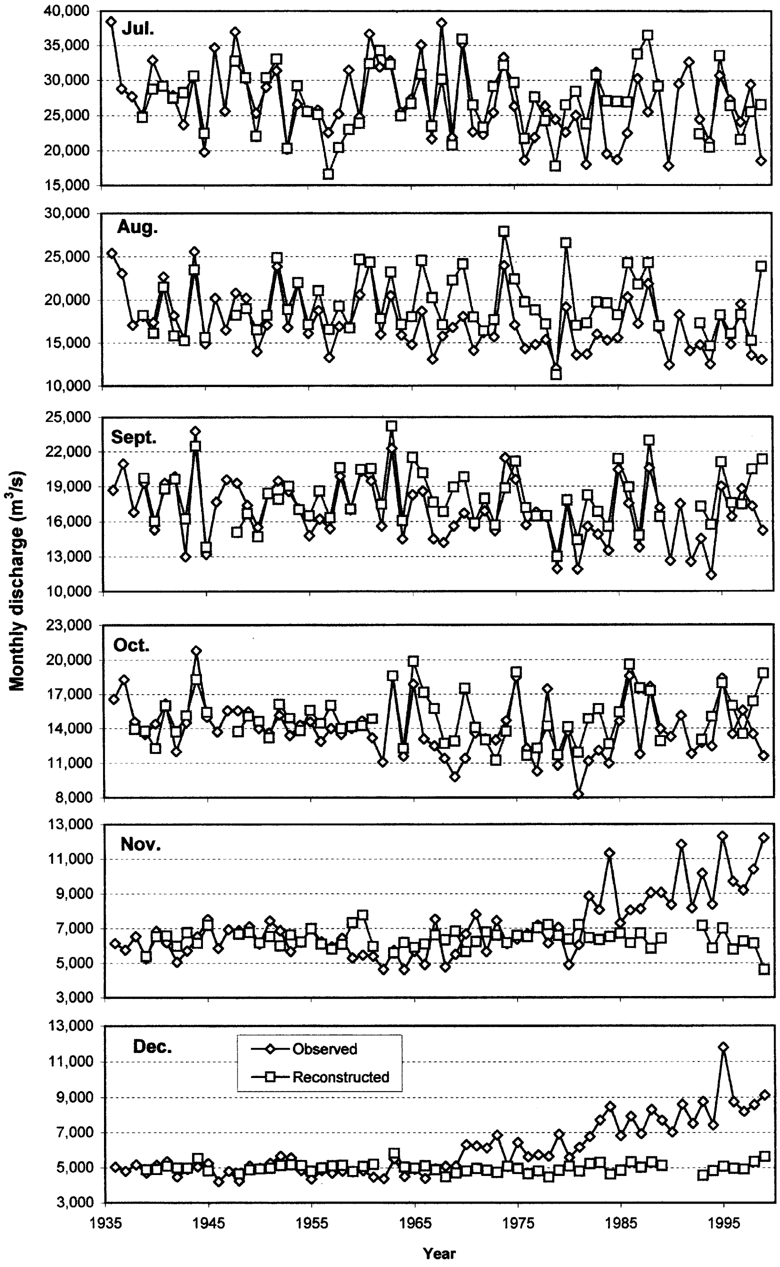

Fig. 12 (*continued*)

very significantly affect flow trends by altering the seasonal flow regime over the large northern basins.

Ye et al. (2003) reported that, in addition to monthly flows, reservoir regulations may affect yearly flow characteristics in the Lena watershed. To minimize the potential reservoir impact on annual streamflow at the Yenisei basin outlet, an annual discharge time series was generated using the reconstructed monthly data. Comparisons between the observed and reconstructed annual records show similar flow amounts for most years, although the observed annual flows were much lower than

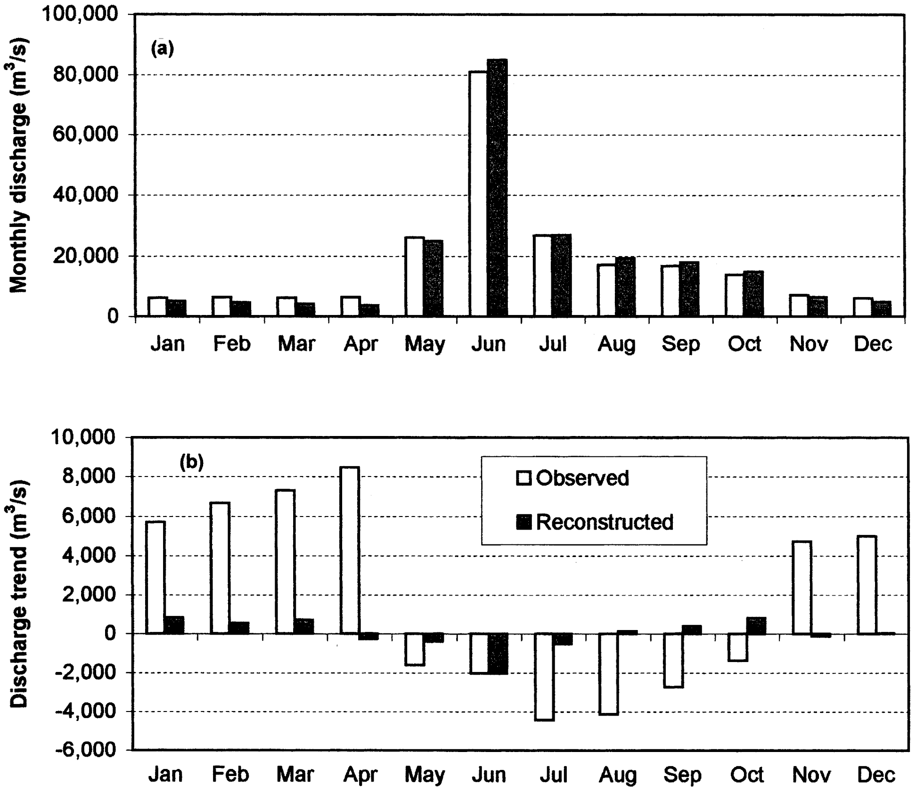

Fig. 13. Comparisons of (a) monthly mean discharges and (b) their trends between observed and reconstructed records at the Yenisei basin outlet during 1936–1999.

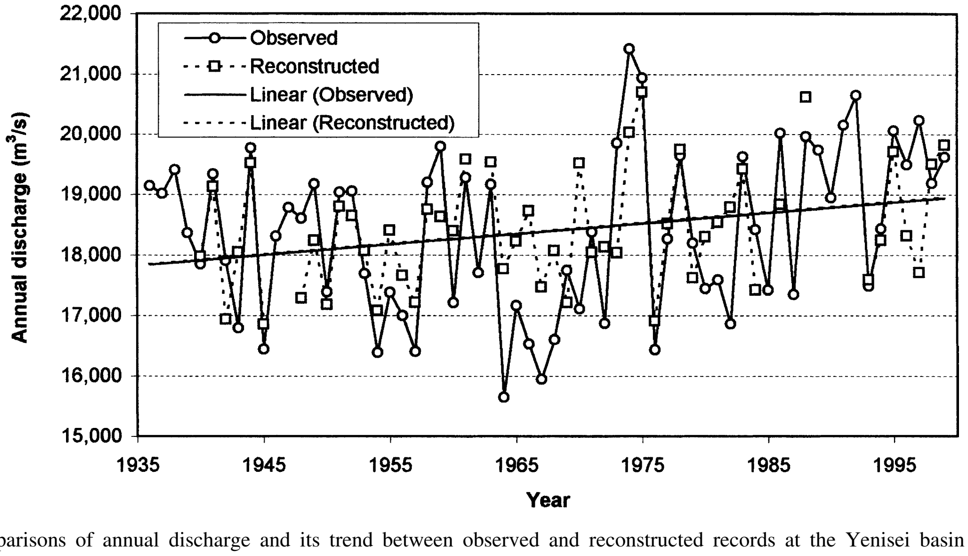

Fig. 14. Comparisons of annual discharge and its trend between observed and reconstructed records at the Yenisei basin outlet during 1936–1999.

the reconstructed data around mid 1960's, perhaps indicating water use for filling the reservoirs during the post-construction periods. In addition, the long-term trends are very similar between the observed and reconstructed annual data during the study period (Fig. 14).

4. Conclusions

Based on systematically analyses of long-term monthly discharge records for the major sub-basins within the Yenisei River watershed, this study found different changes in streamflow hydrology over the Yenisei watershed. We detected that both the unregulated upper basin and major lower streams of the watershed experienced streamflow decreases in the early melt period and flow increases in the late melt season. These changes in snowmelt runoff pattern suggest a delay in snowcover melt in the Yenisei basin perhaps associated cooling trends during the snowmelt months over central Siberia. They clearly illustrate regional differences in hydrologic response to climate change and variation.

The results of this study also demonstrate that the reservoir regulation has significantly altered the monthly discharge regimes in northeast and the upper portions of the Yenisei river basin. Because of four large dams in northeast Yenisei regions, peak discharge in the Angara valley has been reduced by 15–30% in the summer season and low flow has been increased by 5–30% during the cold months. Operations of two large reservoirs in the upper Yenisei regions enhanced the winter flows by 45–85% and reduced the summer flows by 10–50%. These alterations lead to a streamflow regime change toward less seasonal variation over the eastern and lower Yenisei basin. It is clear that due to reservoir regulations, discharge records observed at the Yenisei basin outlet do not always represent natural changes and variations, they tend to underestimate the natural streamflow trends in summer and overestimate the trends in winter and fall seasons. Therefore, we conclude that cold season discharge increase identified over the Yenisei basin is not natural-caused, but the effect of reservoir regulations over the northeast and upper parts of the Yenisei basin.

Monthly flow records at the Yenisei basin outlet were reconstructed by a regression method to reduce the reservoir impacts. It is important to emphasize that both the observed and reconstructed discharge records are necessary and useful for various research applications. The observed discharge data represent actual changes in streamflow hydrology, they are valuable and can be directly used for calculating fresh water budget of the ocean systems and land/shelf dynamics and modeling. On the other hand, reconstructed data eliminate the effect of reservoir regulations on streamflow, they reflect smoothed changes of natural causes, and are necessary particularly for examining the linkages, interactions, and feedbacks among climate, hydrology, and ecology systems.

Increase of winter streamflow has been reported for the Lena and Ob rivers (Serreze et al., 2002; Yang et al., 2002; Ye et al., 2003) where the human impacts are also significant (Dynesius and Nilsson, 1994; Revenga et al., 1998). It is interesting to note that winter discharge increase has not been observed for the less-developed Mackenzie and Yukon rivers (Serreze et al., 2002). Studies show that fresh water discharge from northern-flowing rivers plays an important role in regulating the thermohaline circulation of the world's oceans (Aagaard and Carmack, 1989; Macdonald, 2000). The alteration of the seasonal hydrograph to enhance winter inflow at the expense of summer inflow, a by-product of damming for power plant operations, could stall convection on the shelf (Macdonald, 2000). The impact of river streamflow change to ocean systems needs further research. This study illustrates the importance of human activities in regional and global environment changes, and points to a need to further investigate human impacts in other large high-latitude watersheds.

Acknowledgements

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