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Changes in Lena River streamflow hydrology: Human impacts versus natural variations

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[1] This study systematically analyzes long-term (1936–1999) monthly discharge records for the major subbasins within the Lena River watershed in order to document significant streamflow hydrology changes induced by human activities (particularly reservoirs) and by natural variations/changes. The results show that the upper streams of the watershed, without much human impact, experience a runoff increase in winter, spring, and (particularly) summer seasons and a discharge decrease in fall season. These changes in seasonal streamflow characteristics indicate a hydrologic regime shift toward early snowmelt and higher summer streamflow perhaps due to regional climate warming and permafrost degradation in the southern parts of Siberia. The results also demonstrate that reservoir regulations have significantly altered the monthly discharge regime in the lower parts of Lena River basin. Because of a large dam in west Lena River, summer (high) flows at the outlet of the Vilui valley have been reduced by up to 55% and winter (low) flows have been increased by up to 30 times. These alterations, plus streamflow changes in the upper Lena regions, lead to strong upward trends (up to 90%) in monthly discharge at the basin outlet during the low-flow months and weak increases (5–10%) in the high-flow season. Monthly flow records at the basin outlet have been reconstructed by a regression method to reduce reservoir impacts. Trend analyses and comparisons between the observed and reconstructed monthly flows show that because of reservoir regulations, discharge records observed at the Lena basin outlet do not always represent natural changes and variations. They tend to underestimate the natural runoff trends in summer and overestimate the trends in both winter and fall seasons. Therefore the cold season discharge increase identified at the mouth of the Lena basin is not all naturally caused, but the combined effect of reservoir regulation and natural runoff changes in the unregulated upper subbasins. This study clearly illustrates the importance of human activities in regional and global environment changes and points to a need to examine human impacts in other large high-latitude watersheds. *INDEX TERMS:* 1860 Hydrology: Runoff and streamflow; 1833 Hydrology: Hydroclimatology; 1823 Hydrology: Frozen ground; *KEYWORDS:* streamflow change, Lena River, climate impact, human influence

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1. Introduction

[2] River runoff is the primary freshwater source to the Arctic Ocean. Freshwater discharge from 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 [*Aagard and Carmack*, 1989; *Macdonald*, 2000]. Recent studies report that most northern rivers, including the largest Arctic rivers such as the Ob, Yenisei, and Lena basins, 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, 2001b; *Serreze et al.*, 2002; *Peterson et al.*, 2002; *Yang et al.*, 2002; D. Yang et al., Streamflow hydrology changes over the Siberian Yenisi River basin, submitted to *Journal of Hydrology,* 2003; D. Yang et al., Discharge characteristics and changes over the Ob River watershed in Siberia, submitted to *Journal of Hydrometeorology,* 2003; hereinafter referred to as D. Yang et al., submitted manuscript, 2003a, 2003b]. The causes for these changes are not all clear. Research suggests that spring discharge increase in Siberian regions is primarily due to early snowmelt associated with climate warming during snowmelt period [*Nijssen et al.*, 2001a, 2001b;

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Yang et al., 2002, 2003], and changes in winter streamflow are perhaps associated with a reduction in permafrost and an increase in active layer thickness under a warming climatic condition [*Yang et al.*, 2002; *Serreze et al.*, 2002].

[3] Climate over Arctic regions has experienced significant changes during the past few decades [*Chapman and Walsh*, 1993; *Ye et al.*, 1998; *Serreze et al.*, 2000]. It is important to investigate and understand the response of large northern river systems to climate change and variation [*Vörösmarty et al.*, 2001; *Maguson et al.*, 2000; *Yang et al.*, 2002; *Louie et al.*, 2002; *Proshutinsky et al.*, 1999]. However, in addition to climate-induced river streamflow changes and variations, human activities, such as the construction of large reservoirs, interbasin water diversions, and water withdrawal for urban, industrial, and agricultural needs, will also affect river discharge changes over space and time [*Miah*, 2002; *Vörösmarty et al.*, 1997; *Revenga et al.*, 1998; *Dynesius and Nilsson*, 1994]. Owing mainly 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 middle- to low-latitude regions [*Shiklomanov et al.*, 2000; *Lammers et al.*, 2001]. *Shiklomanov et al.* [2000] 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 the mouth in 1995. The magnitude of this influence is unlikely to produce noticeable effects on discharge into the Arctic Ocean [*Shiklomanov et al.*, 2000]. To better define the seasonal discharge regimes and their changes, human activities, especially reservoir regulations in the high-latitude regions, deserve more attention. It has been reported that because of reservoir regulations, winter seasonal runoff has increased by 50–60% and spring runoff has been reduced by about 10% in the Yenisei basin [*Shiklomanov et al.*, 2000].

[4] Studies suggest that anthropogenic diversions of the Lena River appear to be a minor factor, and the change in river discharge could serve as a reliable indicator of regional climate change and variation [*Shiklomanov*, 1997; *Shiklomanov et al.*, 2000; *Savelieva et al.*, 2000; *Semiletov et al.*, 2000; *Dynesius and Nilsson*, 1994]. In order to examine and document Lena basin streamflow hydrology changes induced by both human impact and natural variability, we need to define the natural streamflow variations and quantify the impact of reservoir regulation on discharge regime and change. The current study will systematically analyze long-term monthly and yearly discharge records for the major subbasins of the Lena River watershed. The emphases of this work are to document significant streamflow hydrology changes induced by human activities (particularly 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. They will also enhance our understanding of hydrologic response to climate change and variation in the high-latitude regions.

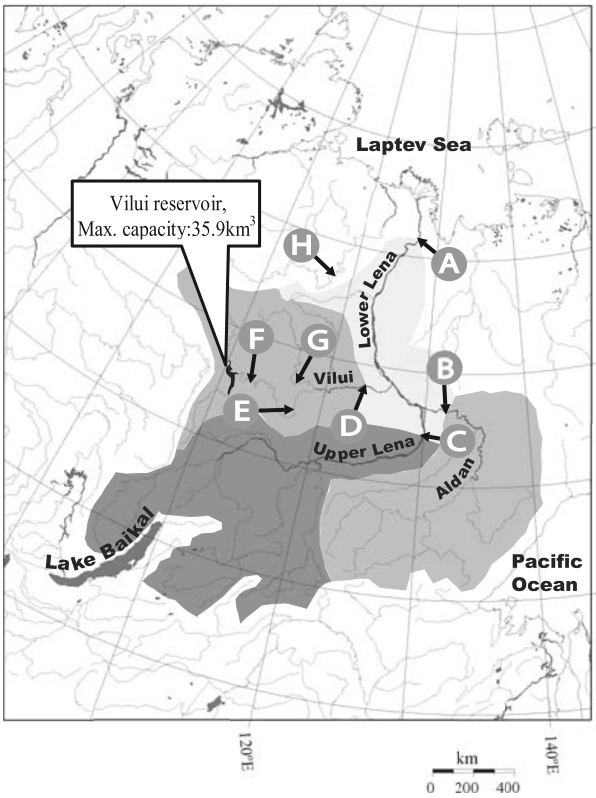


Figure 1. The Lena River watershed and locations of hydrological stations used for this study. Also shown are subbasin boundaries and reservoir location/information.

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

[5] The Lena River is one of the largest rivers in the Arctic. It originates from the Baikal Mountains in the south central Siberian Plateau and flows northeast and north, emptying into the Arctic Ocean via the Laptev Sea (Figure 1). The drainage area of the Lena basin is about 2,430,000 km^2, approximately 78–93% of which is underlain by permafrost [*Zhang et al.*, 1999]. The Lena River contributes 524 km^3 of freshwater per year, or about 15% of the total freshwater flow into the Arctic Ocean [*Shiklomanov et al.*, 2000; *Prowse and Flegg*, 2000]. The drainage is covered mainly by forest (84%), shrub (9%), grassland (3%), cropland (2%), and wetland (1%) [*Revenga et al.*, 1998]. Basin total population is about 2.3 million people, with one city (Yakutsk) having a population of more than 100,000. Compared with other large Siberian rivers, such as the Ob and Yenisei Rivers, the Lena basin has less human activities and much less economic development [*Dynesius and Nilsson*, 1994]. There is only one large reservoir (capacity greater than 25 km^3) in west Lena basin that was built during the late 1960s.

[6] Since the late 1930s hydrological observations in the Siberian regions, such as discharge, stream water temperature, river-ice thickness, dates of river freeze-up and break-up, have been carried out systematically by the

Table 1. List of Hydrologic Stations Used in This Study

				Drainage Area		Annual Runoff	
Station Code (see Figure 1)	Station Name/Location	Latitude, °N	Longitude, °W	X 1000 km^2	% of Lena Basin	km^3	% of Basin Runoff
A	Kusur station/Lena basin outlet	70.68	127.39	2430	100.0	528.0	100.0
B	Verhoyanski Perevoz/Aldan subbasin outlet	63.32	132.02	696	28.6	163.9	31.0
C	Tabaga station/Upper Lena	61.83	129.60	897	36.9	221.0	41.9
D	Hatyrik-Homo/Vilui valley outlet	63.95	124.83	452	18.6	46.0	8.7
E	Suntar station/mid Vilui valley	62.15	117.65	202	8.3	23.5	4.4
F	Chernyshevskyi station/upper Vilui valley	63.03	112.50	136	5.6	19.6	3.7
G	Malyukai station/Mapha tributary to the Vilui valley	63.50	117.03	87	3.6	12.7	2.4
H	Suhana station/the Olenek river	68.62	118.33	127	N/A	96.4	18.3

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. 2.0) (A database of pan-Arctic river discharge, available at www.r-arcticnet.sr.unh.edu/main.html) for the period from 1936 to 1999. In this analysis, long-term monthly and annual discharge records collected at various locations in the Lena basin were used. A station in the Olenek River adjacent to the Lena basin was also chosen for reconstruction of the Lena River downstream discharge. 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 Soviet Union, 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.

[7] 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 (human impact) and unregulated (natural condition) subbasins. Second, we calculated and compared long-term means of monthly discharge between predam and postdam periods so as to determine the reservoir impact on hydrologic regimes. Third, we analyzed and established monthly streamflow relationships between upstream and downstream stations before the reservoir operation and used this relation to reconstruct monthly discharge data at the Lena basin outlet. This minimizes the 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 and statistical significance test to identify long-term changes in streamflow hydrology. A linear regression was applied to monthly and yearly discharge records to determine changes in monthly and yearly flows as a function of time (year). The total trend was defined by the difference of flows shown on the regression line between the first year and the last year. The standard *t*-test was used to determine the statistical significance of the trends. The results of trend and regime analyses were compared among the subbasins to determine and understand basin integration. From this we quantified and separated the changes induced by natural variations and human impacts within the Lena watershed.

3. Changes in Streamflow Hydrology

[8] In this section we define streamflow seasonality and variation, examine the changes in streamflow hydrology through trend analysis for the three major subbasins (i.e., the Aldan/station B, Upper Lena/station C, and Vilui valley/stations D–F) and at the Lena basin outlet (station A) (Figure 1), and identify different characteristics of discharge changes among the subbasins. We also document dams in the basin and quantify their impacts on streamflow hydrology (such as seasonal cycle and trends) through data reconstruction and comparisons of both streamflow regimes and trends derived from the observed and reconstructed data.

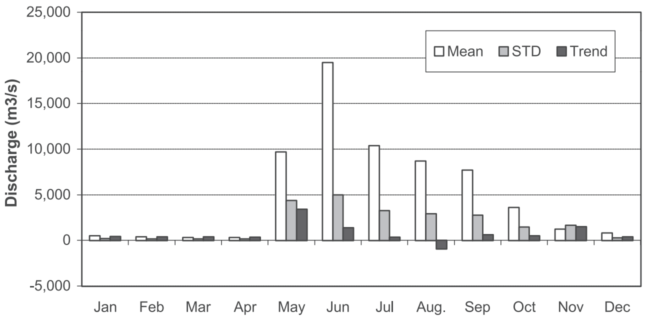
3.1. Aldan Tributary

[9] The Aldan tributary occupies the southeast corner of the Lena basin, close to the Pacific Ocean. The area of this subbasin is 696,000 km^2 (or 28.6% of the Lena watershed), and it contributes 30% of total Lena basin streamflow. Human activities in this region are insignificant. No major dams exist in this tributary.

[10] The seasonal cycle of monthly discharge near the Aldan's outlet (station B in Figure 1) shows a very low flow (320–1230 m^3/s) during November to April and a high runoff (3630–19,470 m^3/s) season from May to October, with the maximum discharge usually in June due to snow cover melt (Figure 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]. In the Aldan valley, the peak flow in June is about 60 times greater than the lowest discharge in April and twice the May runoff. The interannual variation of monthly runoff over the Aldan valley is generally small in the cold season (standard deviation around 140–1640 m^3/s), and large (standard deviation between 1500 and 5000 m^3/s) in summer months due mainly to floods associated with snowmelt and rainfall storm activities.

[11] Trend analysis of the monthly flow over the period 1942–1999 reveals a discharge increase in the Aldan basin during most of the months (Figure 2a). Total trends over this period were found between 150 and 300 m^3/s from December to April, or increased by about 50–120%. Streamflow

(a) Adlan Tributary at Verhoyanski' Perevoz



(b) Upper Lena at Tabaga

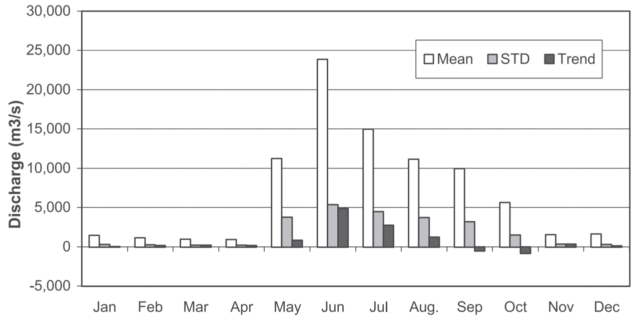


Figure 2. Long-term mean monthly discharge, standard deviation, and trend for (a) the Aldan tributary and (b) the upper Lena basin.

also increased in November by 1520 m/s (125%) and in May by 3430 m^3/s (35%). These positive changes are statistically significant at 90–99% confidence. On the other hand, relatively weak increases in monthly flows were detected during the high-flow season, i.e., June (7%), July (3%), September (8%), and October (14%), while a decreasing trend by 11% was discovered in August. The changes in streamflows over the summer/early fall seasons are statistically less significant (about 20–55% confidence) in comparison to those found for winter/spring months. As the result of the monthly streamflow changes, yearly mean discharge shows a visible upward trend, 740 m^3/s (or 14% rise), over the period 1942–1999. Positive runoff trends in winter, spring, and summer seasons and a negative trend in fall season have been reported for the Arctic rivers in other studies [*Grabs et al.*, 2000; *Semiletov et al.*, 2000; *Yang et al.*, 2002]. These changes in seasonal streamflow characteristics over the Aldan regions indicate a hydrologic regime shift toward early snowmelt and higher summer streamflow due to regional warming [*Serreze et al.*, 2000] and permafrost degradation in the southern parts of Siberia, where permafrost is the warmest and already discontinuous [*Pavlov*, 1994].

3.2. Upper Lena

[12] The upper Lena region, 897,000 km^2 (or 36.9% of the Lena watershed) above the Tabaga station (station C in Figure 1), covers the mountain regions in the southwest corner of the Lena catchment. It contributes 42% of basin total flow. Natural conditions remain in most areas, and no large reservoirs exist in this subbasin.

[13] Upper Lena region monthly streamflow shows a regime similar to that of the Aldan tributary, with the high flows from 5640 to 23,880 m^3/s during May to October and low flows around 900–1610 m^3/s during November to April (Figure 2b). The upper Lena region is larger than the Aldan tributary; both its high- and low-flow values are higher relative to those for the Aldan subbasin. The ratio of highest flow (in June) to lowest flow (in April) is only 26 over the upper Lena, though the ratio between June and May discharge remains the same as for the Aldan catchment. The higher cold season base flows in the upper Lena may indicate warmer winter conditions and less permafrost over this region. The interannual variation of the upper Lena basin monthly streamflow is very similar to the Aldan regions, i.e., high standard deviations in summer (about 3000–5400 m^3/s) and low (between 200 and 350 m^3/s) in winter.

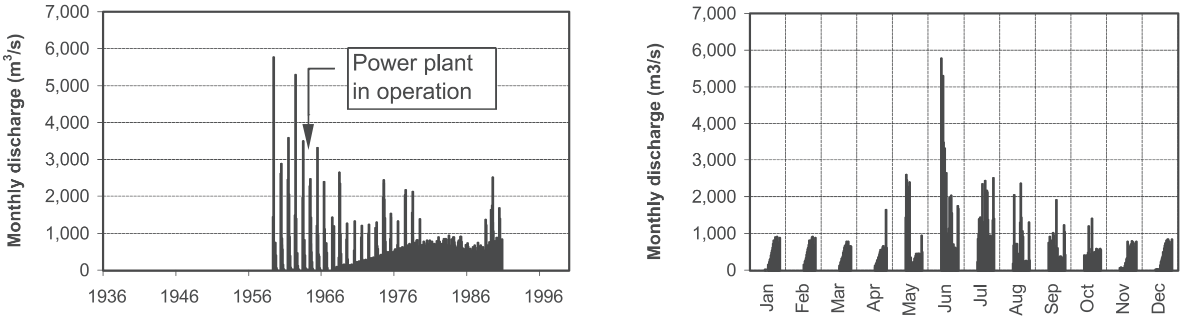
[14] Changes in monthly streamflow over the upper Lena are characterized by negative trends in September and October and positive trends during November to August (Figure 2b). The decreasing trends over the period 1942–1999, about 5% in September and 15% for October, are statistically less significant (confidence lower than 80%). However, the upward trends are strong and statistically significant (confidence greater than 80%) over most winter months, i.e., increases of 22% for November, 7% for December, 2% for January, and 13–21% during February to April. Over summer season, streamflows rise by 7% in May, 20% in June, 18% in July, and 11% in August. These positive changes are statistically significant at 80–95% confidence for both June and July, and less significant for May and August (40–50% confidence). Annual discharge at the Tabaga station shows an upward trend (1120 m^3/s, or 11%) during 1942–1999 due mainly to streamflow increases in the summer months.

3.3. Vilui Tributary

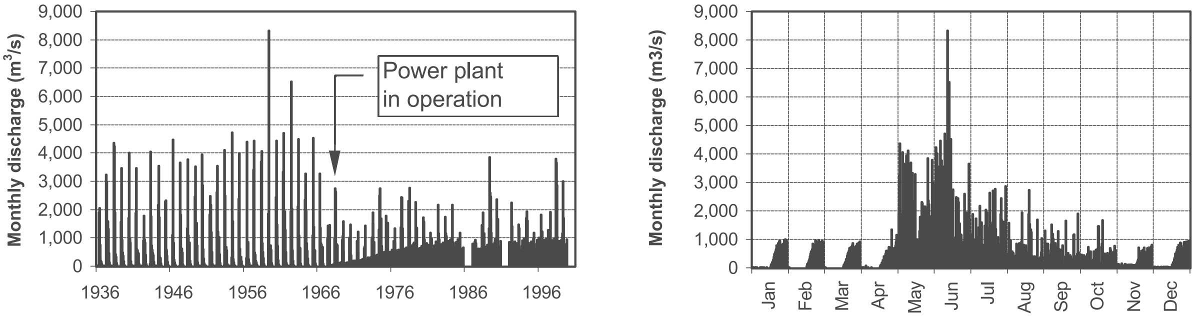
[15] The Vilui tributary, located in west Lena basin, area 452,000 km^2 (or 18.6% of Lena catchment), contributes 9% of yearly total runoff in the Lena River. Human impact through construction of a dam was reported in this area. In the 1960s, a large reservoir was built at the upper Vilui valley near Chernyshevskyi (112°15′W, 62°45′N). The rock-filled dam, 75 m high and 600 m long, was completed in 1967. The maximum reservoir capacity is 35.9 km^3, about 7% of total annual runoff (524 km^3) of the Lena River, or 1.8 times total discharge (20 km^3) at the Chernyshevskyi station in the Vilui valley. The reservoir reached its designed stage during the spring of 1972, with the total reservoir area exceeding 2100 km^2 [*Kane*, 1974]. The reservoir was used primarily for electric power generation. This reservoir has the capability to regulate the monthly to seasonal streamflow processes.

[16] To quantify the effect of reservoir on downstream discharge characteristics, we examine the long-term (1936–1999) monthly streamflow records at three gauging stations along the Vilui valley (stations D, E, and F in Figure 1). The monthly discharge records at these three stations (downstream of the reservoir) along the valley are shown in Figure 3. The left column of the figure presents time series (organized by year) of monthly streamflow during 1936–1999; the time (month/year) of power plant operation is marked with a downward arrow. The right column of the figure displays monthly streamflow time series (organized by month) for every month.

(a) Chernyshevskyi



(b) Suntar



(c) Hatyrik-Homo

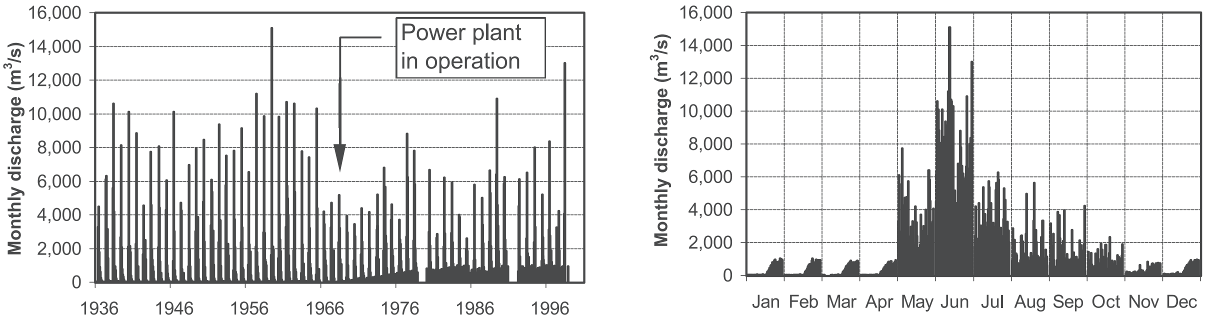


Figure 3. Changes in monthly discharge at three stations (downstream of the reservoir) along the Vilui valley. Monthly time series are shown in the left column, where arrows indicate power plant in operation. Seasonally regimes are displayed in the right column, each bar representing an individual monthly value for each year during 1942–1999.

[17] It is clear that downstream of the dam at the Chernyshevskyi station (station F in Figure 1), the effect of the regulation is most obvious (Figure 3a). Before the dam construction, winter low and summer high discharges were 10–180 and 3000–5800 m^3/s, respectively. After the completion of the dam in 1967, winter month discharge at this station has steadily increased up to 700–900 m^3/s until late 1970s, and summer peak flows had been reduced down to 1200–2500 m^3/s. During the early to middle 1980s, the regulation reached a nearly constant operational discharge (around 900 m^3/s) that completely eliminated the peak floods in the summer season. In late 1980s, the regulated ''normal'' discharges were about 800–1000 m^3/s and peak flows were kept again at 1500–2500 m^3/s.

[18] The impact of reservoir regulation is also visible in the middle and lower parts of the Vilui valley. Since the completion of the dam in 1967, winter season streamflow at the Suntar station (station E in Figure 1) has been increased from less than 200 m^3/s to 400–1000 m^3/s, and summer peak flows have been reduced from 3000–8000 m^3/s to 2000–4000 m^3/s (Figure 3b). Further downstream the influence of the reservoir became less obvious due to the runoff contribution from other tributaries. Winter runoff rise by about 500 m^3/s is still visible at the Hatyrik-Homo station (station D in Figure 1) near the Vilui outlet, and summer peak streamflow was substantially reduced from 4000–15000 m^3/s to 3000–12,000 m^3/s (Figure 3c).

[19] Reservoir regulation may alter seasonal discharge cycle [*Shiklomannov et al.*, 2000]. A comparison of the

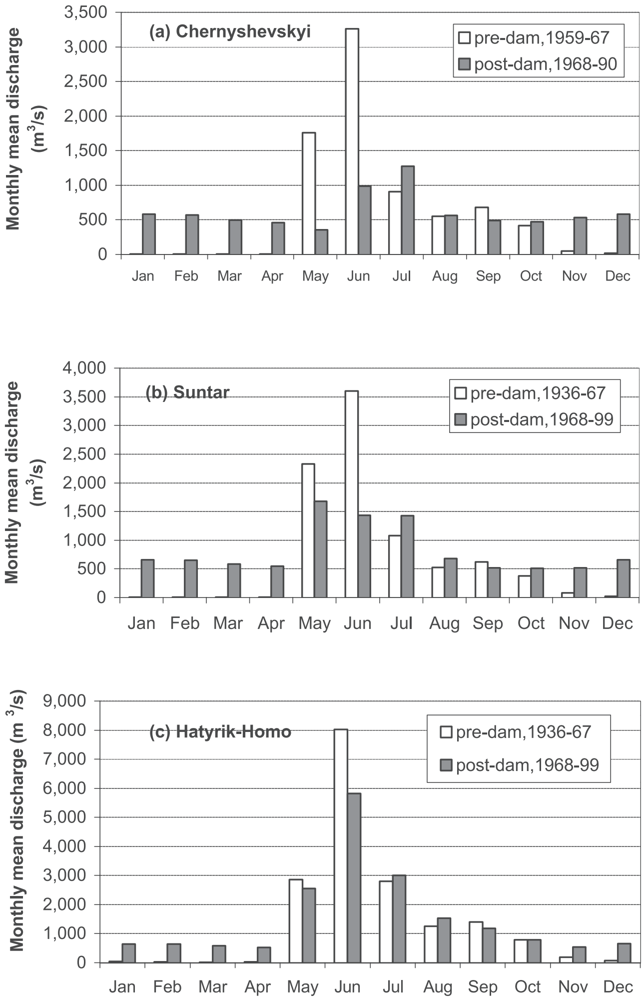


Figure 4. Comparison of long-term mean monthly discharges at the three stations in the Vilui valley between the predam and postdam periods.

long-term mean streamflow in the Vilui valley between the predam and postdam periods demonstrates very significant changes. At the Chernyshevskyi station, monthly streamflow has been increased by about 400–600 m^3/s (about 11–110 times the predam discharge) during November to April. Streamflow has been reduced by 1400 m^3/s (80%) in May and 2300 m^3/s (70%) in June. July discharge has increased by 300 m^3/s (40%), and small changes (less than 25%) were observed during August to October (Figure 4a). The Suntan station, about 350 km downstream of the Chernyshevskyi dam, experienced similar changes in monthly mean streamflow (Figure 4b). However, at the Hatyrik-Homo stations located 900 km downstream of the dam, the difference in May mean discharges has been substantially reduced due perhaps to increased runoff contribution in the postdam period from other unregulated areas within the Vilui valley. The impact of the reservoir regulation is most obvious during winter months and also in June. Mean monthly flow in June was reduced by 2200 m^3/s (or 28%) during the postdam period (Figure 4c).

[20] Over the period 1942–1999, monthly discharges in the regulated Vilui basin have upward trends for most months, except for June and September (Figure 5). The streamflow increases due mainly to reservoir regulation are 700–1200 m^3/s (2–4 times increase) from December to April. These changes are statistically significant at 99% confidence in the winter low streamflow season. In the snowmelt period of May and June, the peak flow in May did not show significant change, while June experienced a remarkably decrease (−30%) due perhaps to reservoir recharge. The weak downward streamflow trend (−5%) found in September is probably also associated with reservoir regulations. September is the end of the summer high-flow season, and reservoirs recharge for winter season water supply and usage for hydropower plant operation. As a result of monthly streamflow changes, yearly discharge has a moderate increasing trend (350 m^3/s or 24%) during 1942–1999.

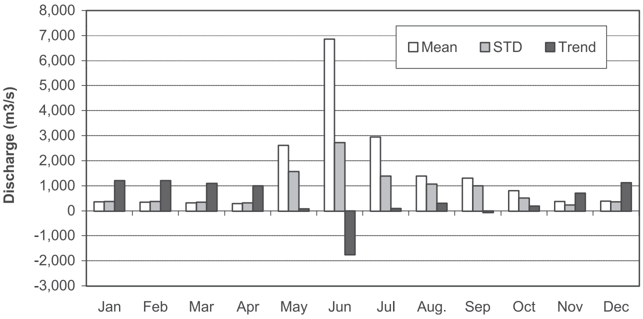


Figure 5. Long-term mean monthly discharge, standard deviation, and trend at the Hatyrik-Homo station in the Vilui subbasin.

[21] The Vilui reservoir, given its large capacity, may also impact the yearly streamflow characteristics. Figure 6a compares the annual discharge records between the Suntar (regulated) and the Malyukai (unregulated), i.e., station E versus station G in Figure 1. It shows that Suntar discharges are higher for most of the years. However, during 1968–

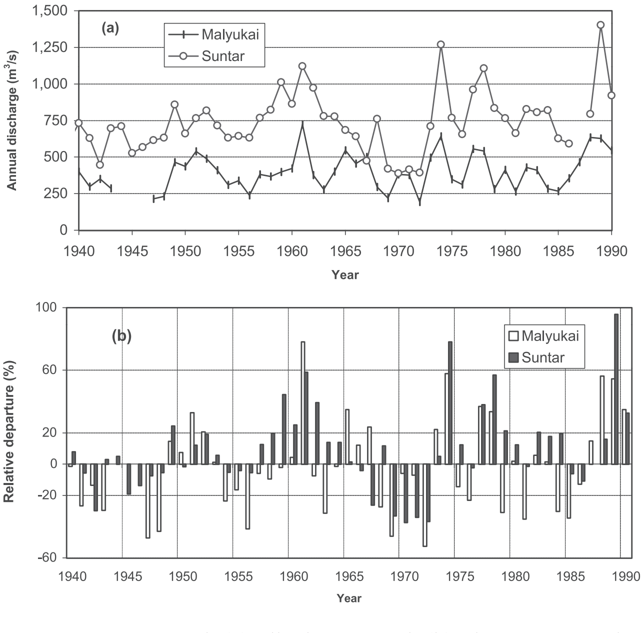


Figure 6. Annual (a) discharge and (b) departure at the Suntar and Malyukai stations, 1939–1990.

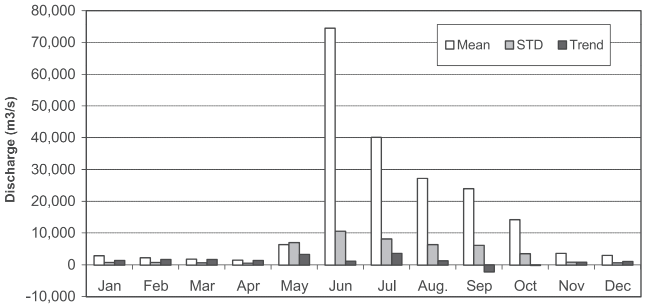


Figure 7. Long-term mean monthly discharge, standard deviation, and trend at the Lena basin outlet (Kusur station).

1971 the annual flows measured at Suntar were the lowest in the records, and were very close to the streamflow observed at the Malyukai station. This was the period when the power plant was completed and the reservoir was being filled for full operation. We calculated the mean annual flow amounts for the predam and postdam periods and found that both showed increases for the postdam period, but the rate of increase is higher at Suntar (6.2%) relative to Malyukai (3.5%). In addition, a comparison of yearly discharge departures between these two stations also indicates a noticeable change around 1976. Since 1976, Suntar station shows fewer negative discharge departure years (Figure 6b). These differences identified in mean streamflows and their variations between the two stations may indicate reservoir regulation on yearly streamflow. With the data and information available to this study, it is difficult to define the actual impact of the reservoir on annual runoff. To minimize this impact, reconstruction of monthly and yearly streamflow should be considered.

3.4. Lena Basin (Outlet) as a Whole

[22] 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 general circulation model (GCM) applications over large regions [*Arora*, 2001; *Nijssen et al.*, 2001a, 2001b; *Bonan*, 1998]. It is thus critical to understand the fundamental characteristics of monthly and yearly streamflow at basin outlet and to document any significant variations and changes.

[23] The seasonal cycle of monthly discharge at the Kusur station (station A in Figure 1) is presented in Figure 7. It generally shows a low-flow period during November to April and a high-runoff season from June to October, with the maximum discharge occurring usually in June due to snowmelt floods. The Lena River basin, mostly underlain by continuous permafrost (78–93%), has a very low winter flow and a very high peak flow in June, about 50–55 times greater than the minimum discharge. Monthly runoff variation is usually small (22–32%) in the cold season and large (15–115%) in summer months due to floods induced by snowmelt and heavy rainfall storms.

[24] Trend analysis of the observed monthly discharge records at the Kusur station shows significant changes in streamflow characteristics (Figure 7). During 1942–1999, discharge at this location has significantly (95–99% confidence) increased by 20–90% in the low-flow season (November to April). This increase demonstrates the combined effect of human influence and natural changes. Aldan basin (station B) base flow has slightly increased during the recent decades. The upper Lena (stations C) shows little changes in winter flow. More important, the Chernyshevskyi reservoir releases water in winter season (November–April) and leads to an upward trend at the basin outlet (Figure 8).

[25] May and June are the important months, as snow cover melts and generates peak floods. We discovered little changes in May flow over the regulated Vilui valley (station D), an increase in the upper Lena (station C), and a very strong rise in the Aldan subbasin (station B). These increases in May flow over the upper and west Lena regions results in a 51% increasing trend (statistically significant at 70% confidence) at the Lena basin outlet (Figure 8). June runoff changes are different among the subbasins. Streamflow has reduced due to regulation in the Vilui basin, but increased in both the upper Lena and Aldan subbasins. The increase in June outweighs the decrease and leads to a slight (1.5%) increase trend (statistically significant lower than 50%) at the Kusur station (Figure 8).

[26] July flows have upward trends over the entire watershed, including a 9% increase at the basin outlet. Streamflow in August increases in both the Vilui valley and the upper Lena, and also at the basin mouth by 8%, despite a 10% flow reduction over the Aldan subbasin. Flow trends in September are positive (8% increase) for the Aldan tributary and negative for both the upper Lena (−5%) and Vilui valley (−7%); the decreases outweigh the increase and lead to a 9% decrease at the basin outlet. October has a very weak (less than 1%) downward trend at the basin outlet, while increases are found for both the Aldan (14%) and Vului subbasin (23%), and a decrease (−15%) is observed for the upper Lena region (Figure 8).

[27] Relatively, flow trends found over the Lena basin are strong and statistically significant during the cold season and weak and less significant over the warm months. For instance, statistical significant levels of trends are higher than 95% during December to April, and are sometimes below 50% confidence, such as for June, August, and October. However, owing to the domination of summer flows, the weak increases in high flows are important. They

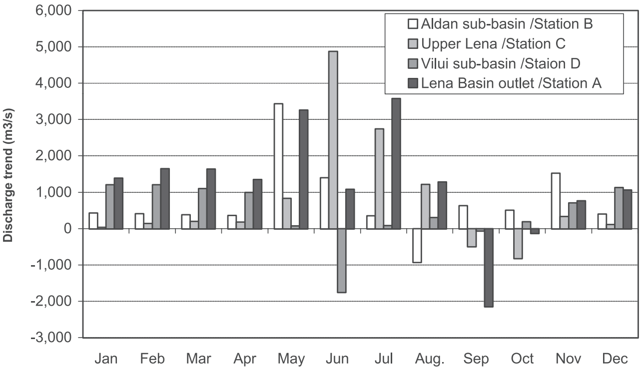


Figure 8. Trends of monthly discharge for major subbasins and at the Lena basin outlet.

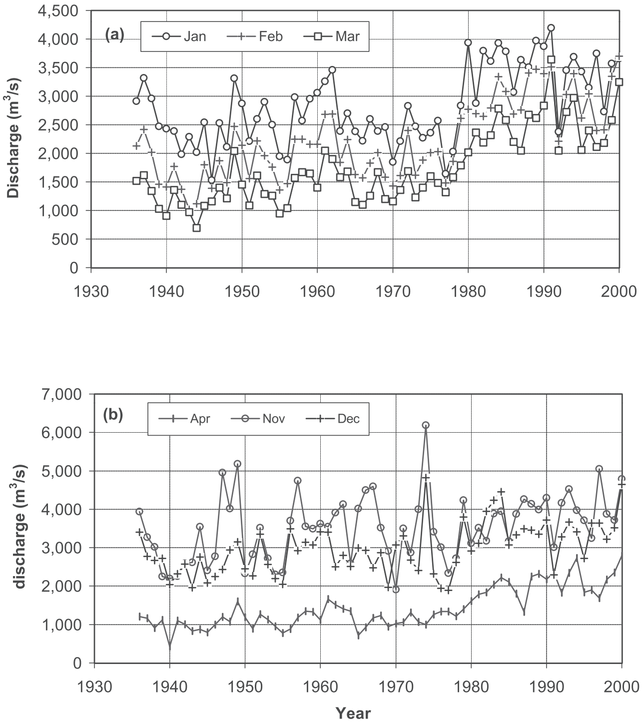


Figure 9. Winter season streamflow time series at the Kusur station, (a) January to March, and (b) November, December and April.

cause a rise of annual flow by 7% at the watershed outlet during 1942–1999.

3.5. Reconstruction of Streamflow Records at Basin Outlet

[28] It is important to point out that observed streamflow records 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. Generally, reservoir impact on streamflow regimes over Siberia is easier to detect in winter low-flow season than in summer high-flow months, because of a stronger influence of tributary inflow in summer season (i.e., high runoff contributions from the unregulated regions) below the point of regulation. Figure 9 presents winter season (November through April) monthly flow time series at the Kusur station. It clearly shows a step increase, about 30–75%, in monthly discharge around the late 1970s. Comparisons of April streamflow over the Lena regions/subbasins demonstrate little changes over the upper Lena region, a weak increase in the Aldan subbasin, and very strong rises in both the Vilui valley and at the Lena basin outlet (Figure 10). The consistence of the increasing trends over the Vilui and at Lena basin mouth may suggest a downstream transfer of the reservoir impact to the northern Lena regions.

[29] To better understand and quantify the effect of reservoir regulation on monthly and seasonal discharge distributions at the basin outlet, reconstruction (or naturalization) of

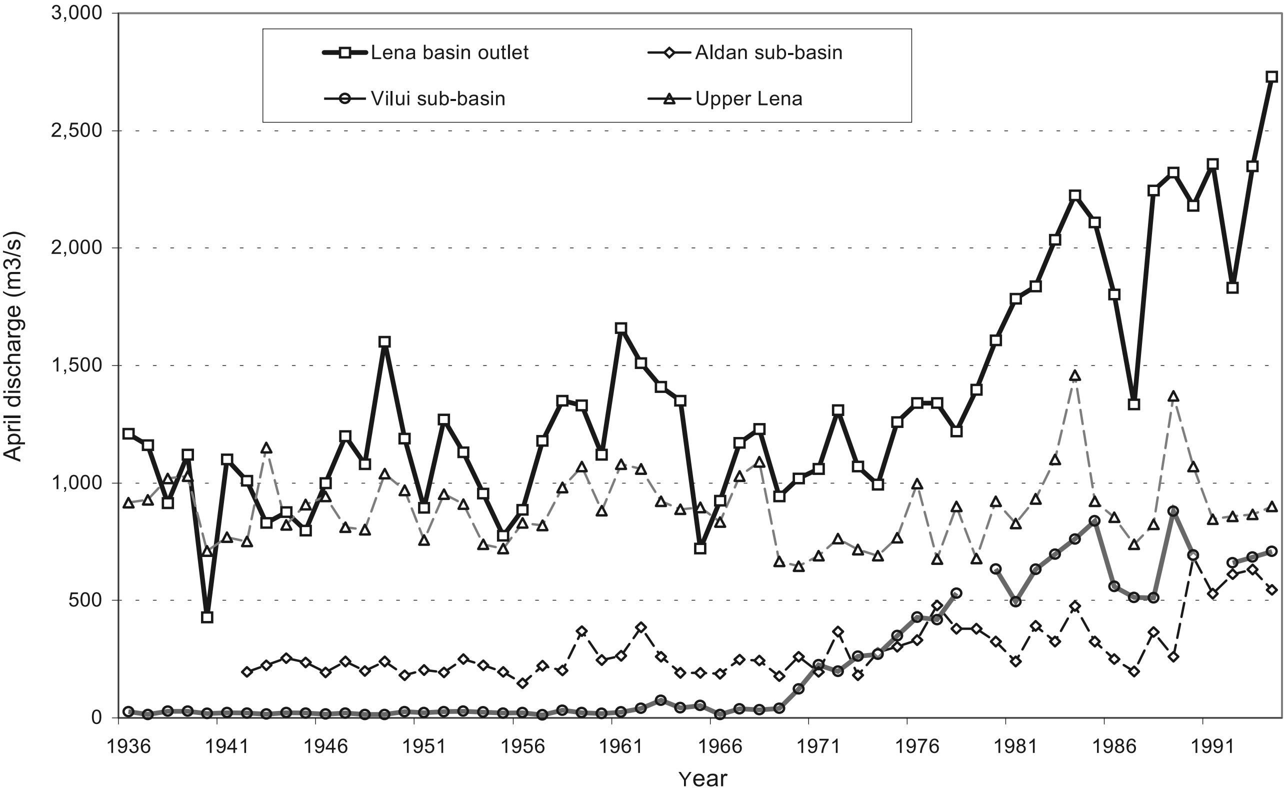


Figure 10. Comparison of April discharge records among the Lena regions/subbasins, 1936–1994.

streamflow records is necessary. Various methods, including hydrologic and hydraulic flow models, have been developed for naturalizing streamflow data in regulated watersheds [*Hicks*, 1996; *Hicks et al.*, 1992]. In addition to dam and reservoir information, basin/channel geometry databases and upstream inflows are necessary to apply the flow models. Recently *Peters and Prowse* [2001] used a combination of hydrologic and hydraulic flow models to investigate the effects of reservoir regulation on the lower Peace River in Canada. Unfortunately, we have access to only very limited basin information and data of both reservoir design/operation and basin/channel geometry for the Lena River. These limited information and data sets available can hardly satisfy the minimal requirements of basin-scale flow models. We therefore decided to use statistical methods to determine the relationship of upstream and downstream flows for the predam period and apply this relation to reconstruct (or naturalize) downstream flow data for the study period. This simple approach enables us to estimate the impact of reservoir regulations on streamflow hydrology over northern parts of the Lena watershed.

[30] Selections of the input streamflow variables are important for the regression analyses. We choose three stations (Verhoyanski Perevoz at the Aldan subbasin/station B; Tabaga at the upper Lena/station C; and Suhana at the adjacent Olenek River/station H) located in the unregulated areas to represent the natural discharge conditions (Figure 1). A stepwise regression was carried out to select input variables. To consider the routing time of flow within the basin, time lags of 0–2 months between the downstream and upstream monthly flows were used in the stepwise regression. The results show a strong (statistically significant at 90% confidence) 1-month-lagged correlation, and a weak 2-month-lagged correction between the downstream station (Kusur) and upstream natural flows during the predam period from 1942 to 1967. Routing time up to 2 months has been reported for large Arctic river basins [*Arora and Boer*, 1999]. The lagged correlations found in this analysis reflect the time of flow routing within the Lena River basin.

[31] On the basis of the results of stepwise regression, we determined to use five input variables for the monthly regression model, i.e., monthly flows at stations Verhoyanski Perevoz (station B), Tabaga (station C), and Suhana (station H), and 1-month-ahead monthly flows at stations Tabaga and Verhoyanski Perevoz. We then used the multiregression approach to obtain the best (least squares) relationships for every month. Statistical tests of the developed relationships show that they are significant at 95–99% confidence. These high levels of statistical significance indicate close relationships among the upstream and downstream flows. We found that the regression results are reasonable for most months, except for May when the linear regression underestimated streamflow perhaps because of the impact of river ice. An exponential model was then chosen for this month, which generated better results.

[32] Comparisons of the reconstructed data with the observed streamflow records for the predam periods show good agreements for most months (Figure 11). The difference between reconstructed and measured mean monthly streamflow is very small, usually less than 15%. The *t* test has been used to quantify the statistical significance of the reconstructed data. The results show that agreements are statistically significant at 95% confidence. We also calculated the standard errors for the reconstructed monthly data and found the errors are generally less than 15%, except for November (17%) and May (46%). The high error of the reconstruction in May is probably associated with the difficulties of winter flow observations under ice conditions, when the potential errors in flow observations are 15–35% [*Grabs et al.*, 2000], particularly during the breakup periods in the Arctic regions.

[33] It is important to point out that the standard errors of reconstruction are much smaller in comparison to dam impacts, i.e., 10–15% standard errors versus a step increase of 30–75% in winter month discharge at the basin outlet. This result demonstrates that the simple regression method used in this study can systematically reduce the effect of reservoir regulation on monthly discharge, and generate reliable monthly streamflow time series consistent with the monthly discharge records for the predam period. Streamflow data are available for the period from 1936 to 1999; we used the upstream monthly flow records as inputs to the regression relationships and reconstructed the monthly discharge time series at the basin outlet (Kusur station) for the study period.

[34] Reconstructed monthly discharge data usually reflect smoothed natural variability and change. To demonstrate the effects of reservoir regulation, we compare both monthly streamflow regimes and trends derived from the observed and reconstructed monthly data. The results show that reconstructed long-term mean discharges are lower (by 120–1740 m^3/s or 5–30%) than the observed data during November to May, and are higher (by 200–3700 m^3/s or 2–5%) from June to October (Figure 12a). The *t* test indicates that the differences in mean flows are statistically significant at 90–95% confidence levels during February through June.

[35] Comparisons of trends between the observed and reconstructed monthly flows over the period 1942–1999 show that although both time series have increasing trends for most months (except in September and October), the magnitudes of flow trends are very different between the reconstructed and the observed records. Relative to the reconstructed data/trends, observed monthly flows overestimated trends by 420–1100 m^3/s from November through April and underestimated trends by 1400–4800 m^3/s during May to October (Figure 12b). The trend differences identified between the reconstructed and observed monthly flows are generally consistent with the overall effect of reservoir regulations, i.e., enhancing winter season flows and reducing summer month discharges. It is important to note that the biggest trend differences are found in May, July, and September. Reconstructed data show a lower upward trend in May (statistical significance at 99% confidence) and a much stronger (16%) increase tendency in July (90% confidence). In September, the reconstructed flows show a strong increasing trend, while the observed records have a decreasing trend (Figure 12b). These results of trend differences, indicating less runoff increase during the snowmelt period (May) and a stronger streamflow rise over peak summer rainfall season (July to September), have important implications for regional climate and ecological systems.

[36] To minimize the potential reservoir impact on annual streamflow, an annual discharge time series was generated

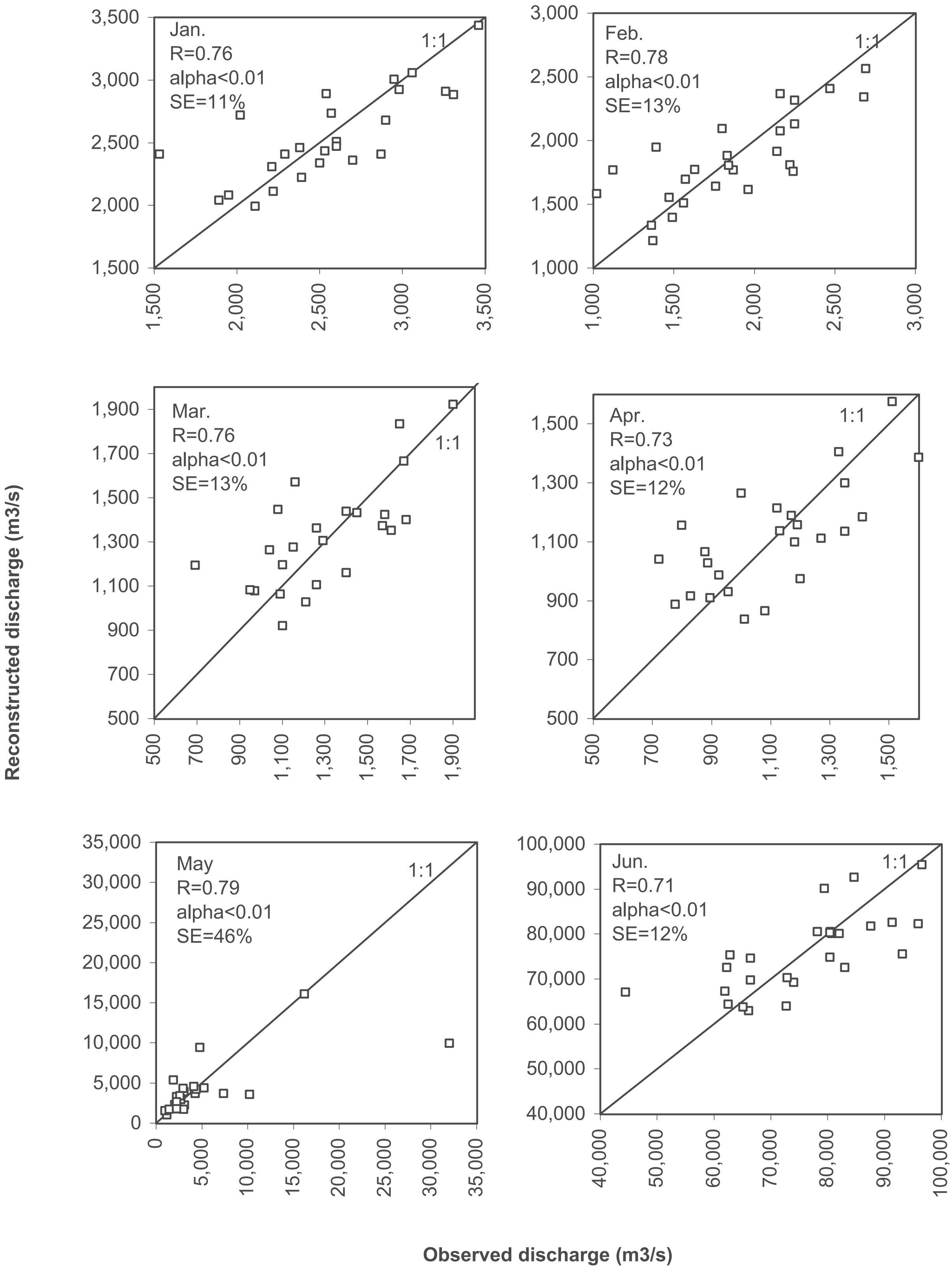


Figure 11. Comparison between the observed and reconstructed monthly discharge at the Lena basin outlet (Kusur station). Correlation coefficient (*R*), statistical significance (alpha), and standard errors (SE) of the reconstruction are also shown.

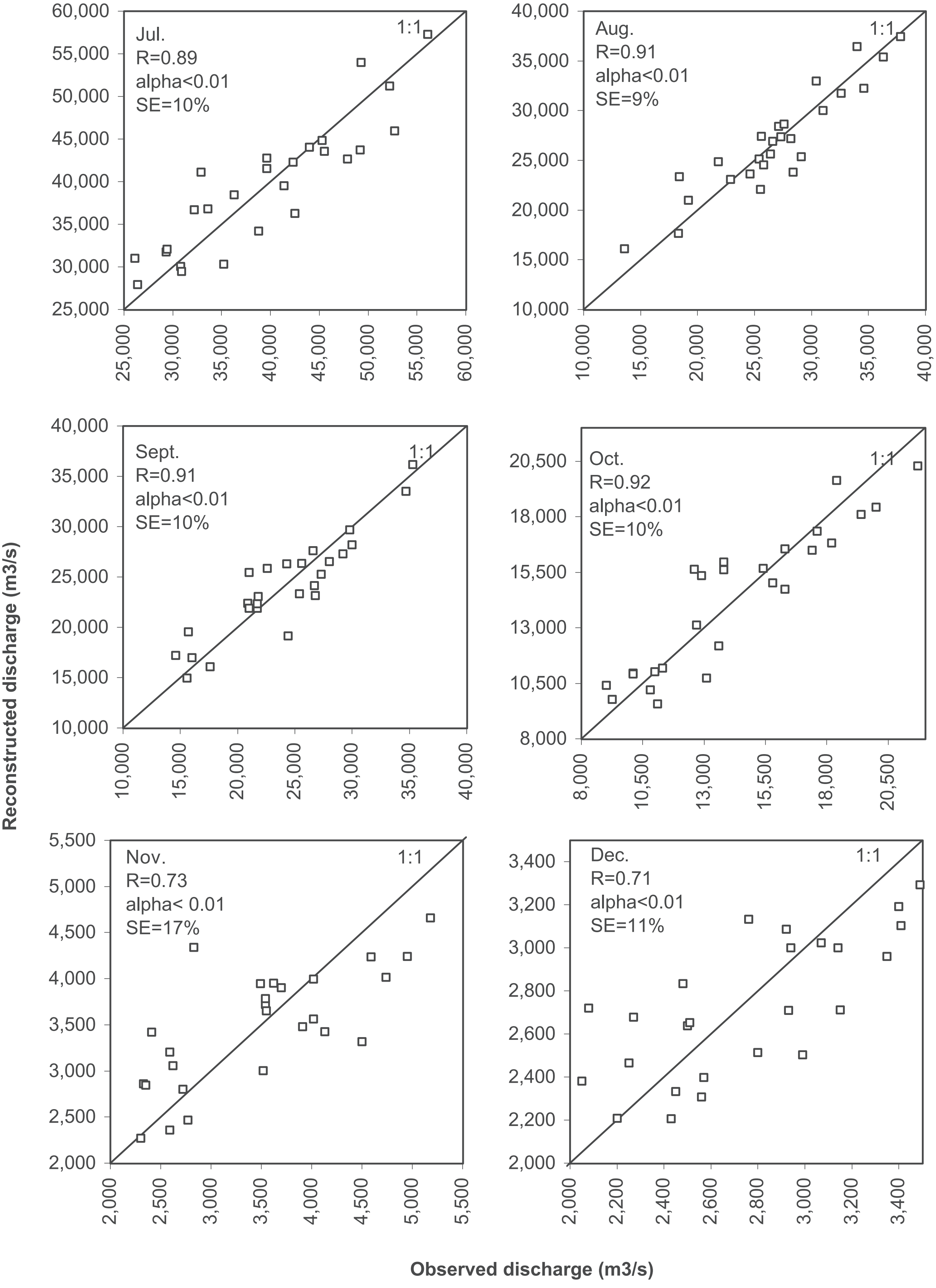
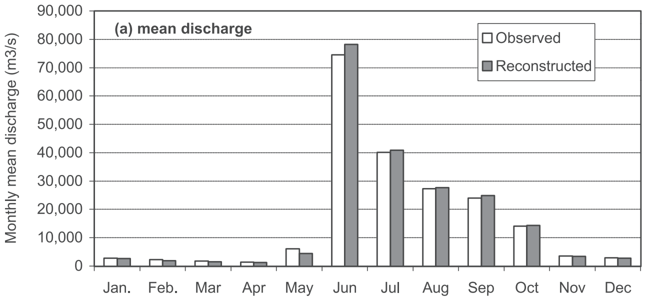


Figure 11. (continued)



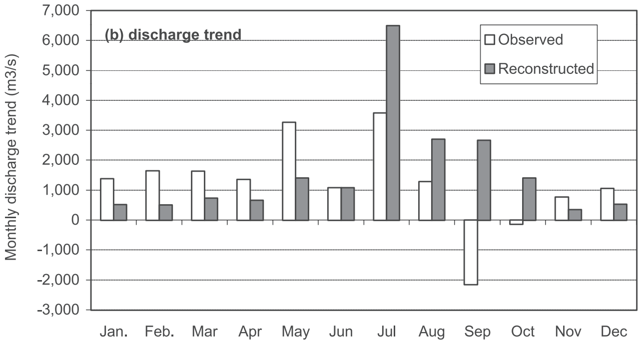


Figure 12. Comparisons of (a) monthly mean discharges and (b) their trends between observed and reconstructed records at the Lena basin outlet.

using the reconstructed monthly data. Comparisons between the observed and reconstructed annual records show that the naturalized yearly flows are higher since the mid-1970s. Although both the observed and reconstructed yearly records have increasing trends during 1942–1999, the rate of increase is much higher for the reconstructed data, i.e., 2499 m^3/s versus 1218 m^3/s (Figure 13). This result is reasonable, as, relative to the observed data, the reconstructed monthly flows have higher trends during most of the high flow months (Figure 12b), and these higher monthly trends transfer into a higher trend in yearly flow. It is important to emphasize that this remarkable difference identified in the yearly flow trends may demonstrate that reservoir regulations not only impact monthly/seasonal flow regimes, but also affect yearly flow characteristics at the basin scale.

4. Conclusions

[37] The goal of this research is to document significant streamflow hydrology changes induced by human activities, particularly reservoirs, and by natural variations/changes. On the basis of systematic analyses of long-term monthly discharge records for the major subbasins within the Lena River watershed, we found that the upper streams of the watershed, without much human impact, experience a runoff increase in winter, spring, and (particularly) summer seasons and a discharge decrease in fall season. We also found that the reservoir regulations have significantly altered the monthly discharge regimes in the lower parts of the Lena River basin. Because of a large dam in west Lena River, summer month flows at the Vilui valley outlet (almost 1000 km downstream of the dam) have been reduced by up to 55% and winter low flows there have been increased by up to 30 times. As a result of the combination and integration of streamflow hydrology changes over the upper and west Lena regions, strong upward trends (up to 90%) were seen at the basin outlet during the low-flow months and weak increases (less than 10%) were found in the high-flow season. These changes in seasonal streamflow characteristics over the Lena basin are somewhat consistent with the results of general circulation model predictions and large-scale hydrologic models [*Nijssen et al.*, 2001a, 2001b; *Arora*, 2001]. They suggest a hydrologic regime shift toward early snowmelt and higher summer streamflow due perhaps to regional climate warming and permafrost degradation particularly in the southern parts of the high latitudes.

[38] Monthly flow records at the basin outlet were reconstructed by a regression method to reduce reservoir impacts. It is important to point out that both the observed and reconstructed discharge data are necessary and useful for various research applications. The observed discharge data represent actual changes in streamflow hydrology (amount and timing), and they are valuable and can be directly used for calculating the freshwater budget of the ocean systems and land/shelf dynamics and modeling. On the other hand, reconstructed data reduce the effect of the human activities on streamflow hydrology, they reflect smoothed changes of natural causes, and they are essential in particular for examining the linkages and interactions among climate, hydrology, and ecology systems. Trend analyses and comparisons between the observed and reconstructed monthly flow data demonstrate that because of reservoir regulations, discharge records observed at the Lena basin outlet do not always represent natural changes and variations. They tend to underestimate the natural runoff trends in summer and overestimate the trends in winter and fall seasons. Therefore we conclude that cold season discharge increase identified over the lower Lena regions is not all naturally caused, but is a result of the combined effect of reservoir regulation and natural runoff changes in the unregulated upper subbasins.

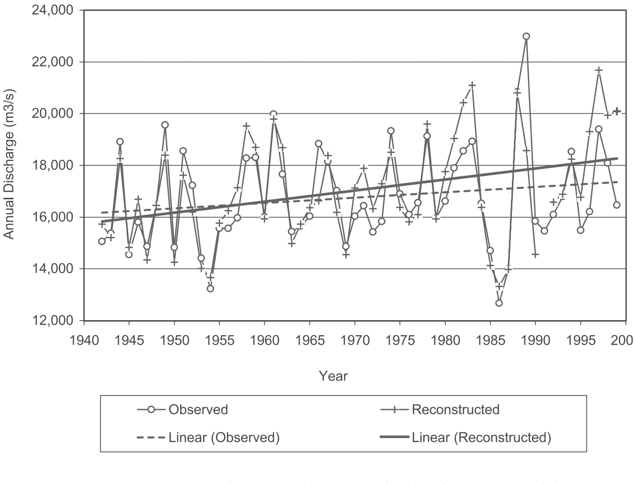


Figure 13. Comparisons of annual discharge and its trend between observed and reconstructed records at the Lena basin outlet.

[39] Similar increase of runoff in winter season has been reported for the Yenisei and Ob Rivers [*Serreze et al.*, 2002; D. Yang et al., submitted manuscript, 2003a, 2003b], where the human impacts are very strong due to farming, mining, and other activities [*Dynesius and Nilsson*, 1994; *Revenga et al.*, 1998], although no major change in winter flow has been observed for the less developed Mackenzie basin in northern Canada. Studies show that freshwater discharge from northern flowing rivers plays an important role in regulating the thermohaline circulation of the world's oceans [*Aagard and Carmack*, 1989]. A study by *Macdonald* [2000] suggested that timing of freshwater input is likely to be a more important consideration than total inflow. The alteration of the seasonal hydrograph to enhance winter inflow at the expense of the summer inflow, a by-product of damming for power plant operations, could stall convection on the shelf [*Macdonald*, 2000]. The impacts of river discharge changes to ocean circulation and climate need further research [*Peterson et al.*, 2002]. This study clearly illustrates the importance of human activities in regional and global environment changes and points to a need to examine human impacts in other large high-latitude watersheds. More efforts are also needed to study the interannual variations of monthly discharge and their responses to surface climate (such as temperature, precipitation, snow cover, and soil moisture conditions) and atmospheric circulation.

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