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Discharge Characteristics and Changes over the Ob River Watershed in Siberia

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Discharge Characteristics and Changes over the Ob River Watershed in Siberia

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ABSTRACT

This study analyzes long-term (1936–90) monthly streamflow records for the major subbasins within the Ob River watershed in order to examine discharge changes induced by human activities (particularly reservoirs and agricultural activities) and natural variations. Changes in streamflow pattern were found to be different between the upper and lower parts of the Ob watershed. Over the upper Ob basin, streamflow decreases in summer months and increases in the winter season. The decreases in summer are mainly due to water uses along the river valley for agricultural and industrial purposes and to reservoir regulation to reduce the summer peak floods. The increases in winter streamflow are caused by reservoir impacts to release water for power generation over winter months. In the lower Ob regions, however, streamflow increased during midsummer and winter months and weakly decreased in autumn. These increases in summer flow are associated with increases in summer precipitation and winter snow cover over the northern Ob basin. Because of reservoir regulations and water uses in the upper parts of the Ob basin, it is a great challenge to determine hydrologic response to climate change and variation at the basin scale. Discharge records observed at the Ob basin outlet do not always represent natural changes and variations mainly due to impacts of large dams; they tend to underestimate the natural runoff trends in summer and overestimate the trends in winter and autumn seasons. This study clearly demonstrates regional differences in hydrologic response to climate changes and variations within a large watershed such as the Ob River. It also illustrates that, relative to climatic effects, human activities are sometimes more important and direct in altering regional hydrologic regimes and affecting their long-term changes particularly at both seasonal and regional scales. It is, therefore, necessary to consider human activities in regional/global environment change analyses and further examine their impacts in other large northern watersheds.

1. Introduction

Discharge from northern-flowing rivers is the primary freshwater source to the Arctic Ocean. 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), winter and fall precipitation increase (Wang and Cho 1997), winter snow depth increase (Ye et al. 1998), and ground temperature rising and permafrost thawing (Pavlov 1994). Climate models predict 1°–4°C surface air temperature increase in the twenty-first 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 made to investigate and understand the response of large northern river systems to climate change and variation (Fukutomi et al. 2003; Vörösmarty et al. 2001; Magnuson et al. 2000; Yang et al. 2002; 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; Lammers et al. 2001; Yang et al. 2002; Serreze et al. 2003; Peterson et

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al. 2002; Ye et al. 2003). 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 the snowmelt period (Nijssen et al. 2001a,b; Yang et al. 2002, 2003; Serreze et al. 2003), and changes in winter streamflow are perhaps associated with the reduction in permafrost and an increase in active layer thickness under a warming climatic condition (Yang et al. 2002; Serreze et al. 2003).

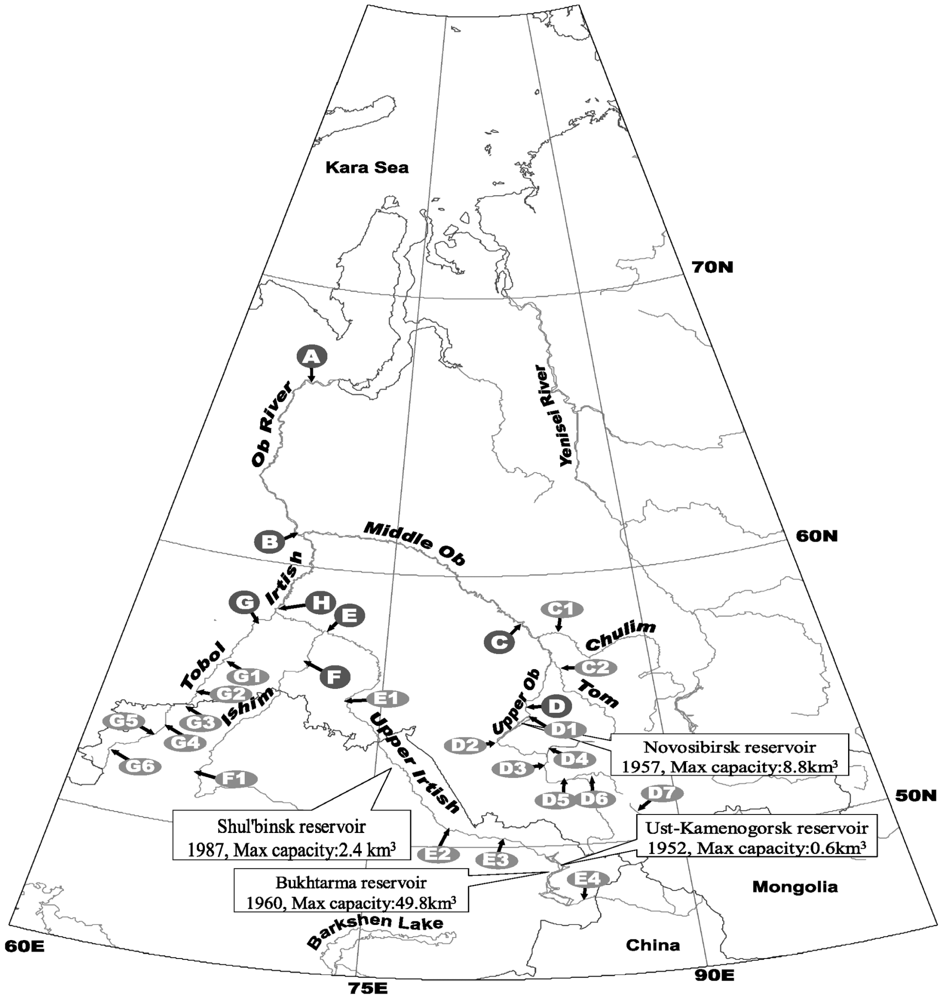
It is important to understand that, in addition to climate-induced river streamflow changes and variations, human activities, such as the construction of large reservoirs, interbasin water diversions, and water withdrawals for urban, industrial, and agricultural needs, will also impact river discharge changes over space and time (Miah 2002; Ye et al. 2003; Yang et al. 2004; Vörösmarty et al. 1997; Revenga et al. 1998; Dynesius and Nilsson 1994). Mainly because of 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 (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 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). Ye et al. (2003) and Yang et al. (2004) recently studied the effect of reservoir regulations in the Lena and Yenisei basins. They found that, for instance, because of a large dam in the Lena River basin, summer peak discharge in the Vului valley (a tributary in the west Lena basin) has been reduced by 10%–80%, and winter low flow has been increased by 7–120 times during the cold months. They also reported that, because of influences of large reservoirs, discharge records collected at the Lena and Yenisei basin outlets 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. Operations of large reservoirs may also affect annual flow regime particularly during and immediately after the dam construction (Ye et al. 2003; Yang et al. 2004).

To better understand the seasonal discharge regimes and their changes, human activities in the high-latitude regions deserve more attention in large-scale environmental change analyses. This study systematically analyzes long-term monthly and yearly discharge records for the major subbasins of the Ob River watershed. The emphases of this work are to document streamflow changes induced by human activities (such as irrigation and large reservoir regulations) 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 and hydrology in the northern regions. The results of this study will be useful to ongoing national and international efforts of assessing recent changes in the hydroclimatology of the pan-Arctic landmass and the terrestrial ecosystems (Vörösmarty et al. 2001). They will also improve our understanding of the hydrologic response to climate change and variation in the high-latitude regions.

2. Basin information, datasets, and analysis methods

The Ob River is one of the largest rivers in the Arctic. It flows north and west across western Siberia from its source in the Altai Mountains, emptying into the Arctic Ocean via the Kara Sea (Fig. 1). The total drainage area of the Ob basin is about 2 975 000 km^2, and the length is about 3 650 km, approximately 4%–10% of which is underlain by permafrost (Zhang et al. 1999). The Ob River contributes on average 402 km^3 freshwater per year, or about 15% of total freshwater flow into the Arctic Ocean (Grabs et al. 2000; Shiklomanov et al. 2000; Prowse and Flegg 2000). The drainage basin is classified as cropland (36%), forest (30%), wetland (11%), grassland (10%), shrub (5%), developed (5%), and irrigated cropland (3%) (Revenga et al. 1998). Basin total population is about 27 million, with 39 cities having a population of more than 100 000. Compared with the other two large rivers in Siberia, the Lena and Yenisei, the Ob River has intensified industry and agriculture developments (Dynesius and Nilsson 1994). Cities such as Omsk, Novokuzhnetsk, Novosobirsk, Barnaul, and Qaraghandy, Russia, in the southern (upper) part of the basin are major industrial and manufacturing centers. The steppe zones in the southern portion of the basin are the major wheat production regions in Russia. The west Siberian oil and gas field, located in the taiga and tundra zones of the middle and lower Ob, contribute about two-thirds of the country's crude oil and natural gas outputs (Revenga et al. 1998; Dynesius and Nilsson 1994). One large reservoir (capacity greater than 25 km^3) and three midsize dams were built in the Ob basin in the mid-1950s to 1980s (Revenga et al. 1998). The total maximum capacity of the reservoirs is 61.6 km^3, about 15% of the annual discharge at the Ob basin outlet. Hydropower plants were also established at the dam sites. Their total capacity for power generation was about 2 163 MW yr^{-1}. This study focuses on the reservoirs located above the basin outlet station that have the potential to substantially regulate basin streamflow, and it also examines the impact of agricultural water consumption.

Since late 1930s hydrological observations in the Siberian regions, such as water stage, discharge, stream water temperature, river ice thickness, and dates of river freeze-up and breakup, have been carried out systematically by the Russian Hydrometeorological Services, and the observational records were quality controlled



Novosibirsk reservoir
1957, Max capacity:8.8km^3

Shul'binsk reservoir
1987, Max capacity:2.4 km^3

Ust-Kamenogorsk reservoir
1952, Max capacity:0.6km^3

Bukhtarma reservoir
1960, Max capacity:49.8km^3

FIG. 1. The Ob River watershed. Also shown are reservoir location/information and locations of hydrological stations used for this study. Letters represent station IDs listed in Table 1.

and archived by the same agency (Shiklomanov et al. 2000). The discharge data are now available from the R-ArcticNet (version 2.0)—A Database of Pan-Arctic River Discharge (www.r-arcticnet.sr.unh.edu/main.html) for the period from 1936 to 1990. In this analysis, long-term monthly and annual discharge records collected at various locations in the Ob 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. In addition, subbasin-mean monthly temperature and precipitation data derived from the global datasets (New et al. 2000) were also used in the analyses.

To define the natural streamflow variations and quantify the impacts of reservoir regulation and water use on discharge regime and change, we first compiled basin geophysical and hydrologic information (including water consumption and withdrawal data) and identified dam-regulated tributaries, irrigation areas, and unmodified (natural condition) subbasins. Second, we analyzed monthly and annual discharge records along the main stream to identify reservoir impact and water consumption by human activities within the watershed. Third, 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. Fourth, we carried out trend analysis and statistical significance tests to identify long-term changes in streamflow regime. A linear trend analysis was applied to monthly and yearly discharge records. Changes in monthly and yearly flows as a function of time (year)

TABLE 1. List of the hydrologic stations used in this study.

Station ID (see Fig. 1)	River/station name	Lat (°N)	Lon (°E)	Data period	Drainage area		Annual discharge		
					(km²)	(% of Ob basin)	(m³ s⁻¹)	(km³)	(% of basin runoff)
A	Ob/Salekhard	66.63	66.60	1936–94	2 430 000	100.0	12 759	402.4	100.0
B	Ob/Belogorje	61.07	68.60	1936–90	2 160 000	88.9	10 147	320.0	79.5
C	Ob/Kolpashevo	58.30	82.88	1936–90	486 000	20.0	3 965	125.0	31.1
C1	Chulim/Baturino	57.78	85.15	1936–89	131 000	5.4	780	24.6	6.1
C2	Tom/Tomsk	56.50	84.92	1936–90	57 000	2.3	1 041	32.8	8.2
D	Ob/Novosibirsk	55.00	82.95	1936–68	252 000	10.4	1 916	60.4	15.0
D1	Ob/HPS Novosibirskaya	54.80	82.95	1958–90	232 000	9.5	1 621	51.1	12.7
D2	Ob/Kamen′na Obi	53.80	81.33	1936–90	216 000	8.9	1 653	52.1	13.0
D3	Ob/Baenaul	53.40	83.82	1936–90	169 000	7.0	1 490	47.0	11.7
D4	Ob/Talmenka	53.80	83.57	1943–90	20 600	0.8	136	4.3	1.1
D5	Ob/Phominskoje	52.45	84.92	1953–90	98 200	4.0	1 143	36.0	9.0
D6	Ob/Bijsk	52.55	85.28	1936–90	36 900	1.5	485	15.3	3.8
D7	Ob/Balikcha	51.28	87.72	1936–90	16 600	0.7	160	5.0	1.3
E	Irtish/Ust′-Ishim	57.70	71.17	1936–87	564 000	23.2	1 189	37.5	9.3
E1	Irtish/Omsk	55.02	73.30	1936–90	321 000	13.2	885	27.9	6.9
E2	Irtish/Semiyarskoje	50.88	78.32	1960–87	230 000	9.5	871	27.5	6.8
E3	Irtish/Shul′ba	50.38	81.13	1936–79	179 000	7.4	915	28.9	7.2
E4	Irtish/Buran	48.00	85.22	1938–87	55 900	2.3	299	9.4	2.3
F	Ishim/Ishim	56.10	69.47	1955–90	154 000	6.3	55	1.7	0.4
F1	Kameny Ka′er	52.02	66.28	1947–81	862 000	35.5	32	1.0	0.3
G	Tobol/Lipovka	57.82	67.40	1936–84	359 000	14.8	853	26.9	6.7
G1	Tobol/Yalutorovsk	56.67	66.35	1936–90	177 000	7.3	118	3.7	0.9
G2	Tobal/Kurgan	55.43	65.38	1936–89	98 800	4.1	41	1.3	0.3
G3	Tobal/Zverinogolovskoje	54.47	64.83	1938–89	83 800	3.4	27	0.9	0.2
G4	Tobal/Kustanai	55.43	63.65	1952–89	44 800	1.8	27	0.9	0.2
G5	Tobal/Sergeievka	52.95	63.20	1958–87	30 600	1.3	5	0.2	0.04
G6	Tobl/Grishenka	52.38	61.70	1937–87	13 400	0.6	8	0.3	0.1
H	Irtish/Tobolsk	58.20	68.23	1936–90	969 000	39.9	2 113	66.6	16.6

were determined by a linear regression. 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. Finally, we used global 0.5° × 0.5° monthly temperature and precipitation data (New et al. 2000) and river network grids (Fekete et al. 2001) over the Ob basin to generate subbasin-mean monthly temperature and precipitation time series for 1935–90. We related temperature and precipitation records to streamflow data and explained streamflow changes and trends. With these data and information of human activities, we quantified the changes and variations in seasonal streamflow patterns within the Ob basin and assessed (when possible) the individual contribution of temperature, precipitation, and human impact to observed streamflow trends.

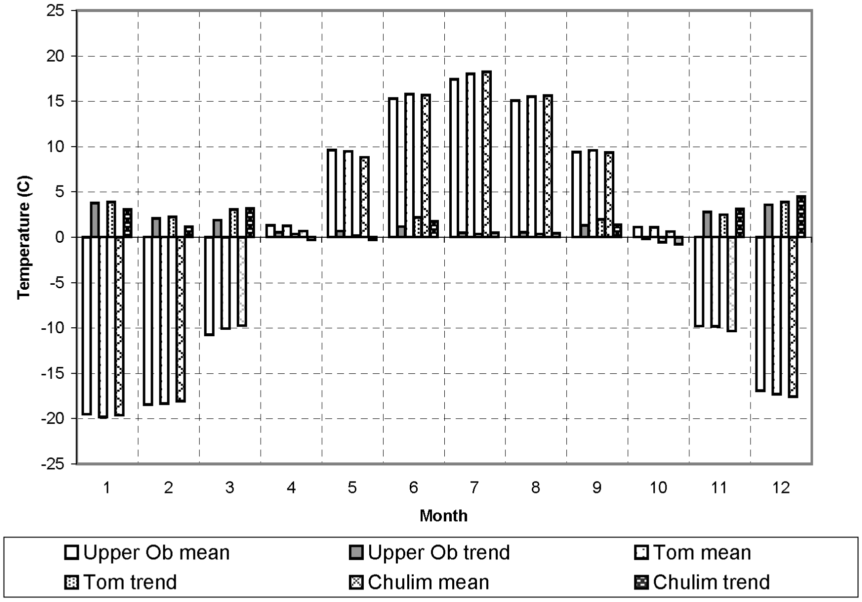
3. Streamflow characteristics and change

In this section we define streamflow seasonality and variation and identify different characteristics of discharge changes among the subbasins/regions, that is, the upper Ob, the Irtish tributary, the mid-Ob, and basin as a whole.

a. The upper Ob regions/basins

The upper Ob tributary occupies the southeast section of the Ob basin. The area of this subbasin above the Kolpashevo station (C in Fig. 1) is 786 000 km² (or 20% of the Ob watershed); it contributes 31% of total Ob basin streamflow. The upper Ob basin has three main branches, that is, the upper Ob valley and the Tom and Chulim tributaries. The biggest city in Siberia, Novosibirsk, with population of 1.6 million, is located in the subbasin. In these regions water withdrawals are made to support urban populations, mining, and faming activities.

Basin-mean temperature and precipitation and their long-term changes are shown in Fig. 2 for the major tributaries. Similar climate characteristics exist over the upper Ob regions. Monthly temperatures are cold (−10° to −20°C) from November to March, slightly above 0°C in April and October, and warm (10°–17°C) from May to September (Fig. 2a), while monthly precipitation ranges from 20 to 30 mm in the cold months to 60 to 70 mm in the warm season (Fig. 2b). Long-term temperature changes show warming trends during most months, except in April and October with very weak cooling trends. Winter warming is very strong over these regions, up to 2°–5°C during 1936–90 (Fig. 2a). Precipitation decreased during most months and weakly increased from December to February (Fig. 2b).


a) sub-basin mean temp and trend, 1936-1990

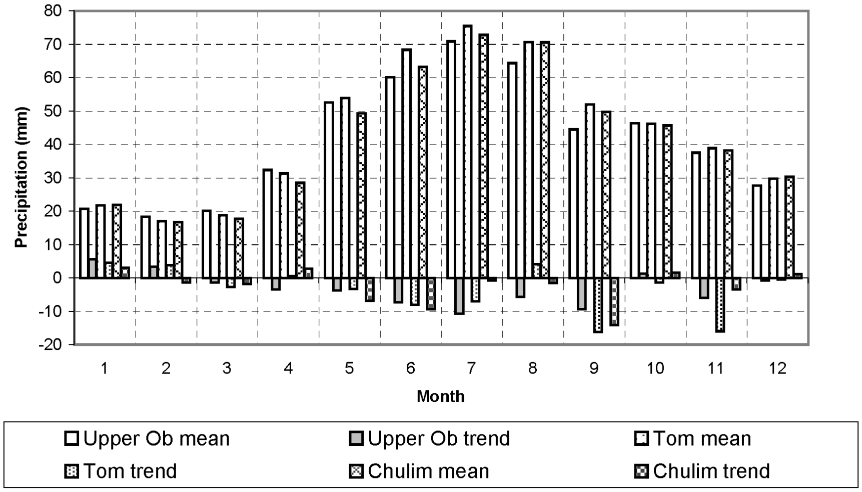

b) Sub-basin mean precip and trend, 1936-1990

FIG. 2. Long-term subbasin (a) mean temperature (°C) and (b) precipitation (mm), and their total trends during 1936–90 for the upper Ob regions.

To understand discharge regime and its change over the upper Ob regions, long-term mean monthly flow, standard deviation, and trend are calculated and presented in Fig. 3 for the tributaries and the subbasin as a whole. Monthly discharge at the subbasin outlet (the Kolpashevo station; C in Fig. 1) shows a low-flow (1000–1800 $m^3 s^{-1}$) period from November to April, a high-flow season during May to July (with peak flows about 12 000 $m^3 s^{-1}$ in May), and a gradual decline from August through October (Fig. 3a). The peak flow in May caused by snowmelt is about 12 times greater than the lowest discharge in March. The interannual variation of monthly streamflow is generally small in the cold season and large in summer months (particularly in June) mainly due to floods associated with snowmelt and storm activities. Trend analyses reveal that streamflow decreased in all months except for February and March with slight increases, and the decreases were particularly strong (statistically significant at 95%–99% confidence) during May to August. Because of large decreases in summer and autumn streamflow, annual discharge at station Kolpashevo shows a significant (99% confidence) downward trend of -1254 $m^3 s^{-1}$ over the study period (1936–90).

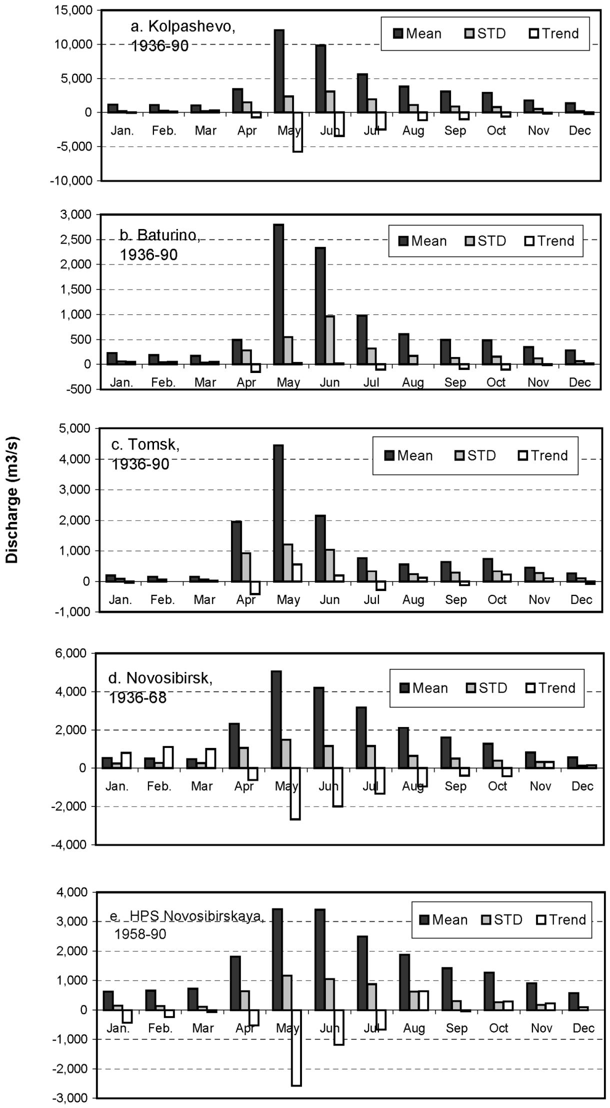


FIG. 3. Long-term mean monthly discharge ($m^3 s^{-1}$), standard deviation (STD), and its total trend during 1936–90 for the upper Ob regions.

Similar seasonal streamflow cycles exist over the upper Ob regions (Figs. 3b,c). In both the Chulim and Tom tributaries (stations C1 and C2 in Fig. 1), flows are low during most of the months, except for May to July in the Chulim tributary, and April to June for the Tom tributary. The peak flows in May for these two tributaries are caused by snowmelt. Monthly flows in the Chulim tributary show little changes during most months, except for April, July, September, and October with weak decreases (Fig. 3b). April flow decreases in the Chulim tributary are associated with precipitation increase and a weak cooling in temperature. This wetter and cooling tendency during the snowmelt period may reduce snowmelt intensity in April, leading to a flow decrease. July flow decreases in this valley are mainly due to temperature warming in summer months, and the downward trends in September and October are caused by strong precipitation decreases by 15 mm in September during 1936–90 (Figs. 2a,b).

Monthly flows in the Tom tributary show no major changes from August to March, a significant downward trend in April, a remarkable increase in May, a weak rise in June, and a moderate decrease in July (Fig. 3c). Flow trends in spring indicate snowmelt pattern changes in the Tom valley. Climate records show a weak precipitation increase in April and a moderate decrease in May, while temperatures in these 2 months have little changes (Figs. 2a,b). Increases in snowfall during the melt season generally delay snowmelt rate because of a higher albedo of fresh snow accumulation on top of the melting snowpack. The weak increase in April precipitation over the Tom region delayed the snowmelt process and caused a shift of snowmelt runoff toward late melt season, that is, a decrease of streamflow in the early snowmelt period (April) and an increase in the late melt period (May). Yearly flows in the Tom and Chulim tributaries have no significant trends, partly because of the cancellations of the positive and negative monthly trends.

In the upper Ob valley, streamflow data collected during 1936–68 at the Novosibirsk station (D in Fig. 1) show a low-flow period from November to March, high flow from April to July, and discharge recession from August to October. The peak flow always occurs in May because of snowmelt, about 13 times higher than the March flow (Fig. 3d). Trend analyses for 1936–68 show strong increases (statistically significant at 95%) from November to March and very strong decreases (statistically significant at 95%) from April to September, with the maximum decrease of 2600 $m^3 s^{-1}$ in May (Fig. 3d). For the recent decades (1958–90), discharge data measured at an upstream station, the HPS Novosibirskaya (station D1 in Fig. 1), show flow increases in August, October, and November, weak decreases in September and from January to April, and very strong reductions from May to July (Fig. 3e). These changes are statistically significant at 95%–99% confidence for most months. The strong decreases during summer months are associated with strong precipitation decreases and the weak temperature rise over the upper Ob valley (Figs. 2a,b), and they cause a downward trend (8%) in annual flow.

It is important to note that 1) the Tom and Chulim tributaries do not have major downward trends in summer or yearly flows, and 2) the decreasing trends in both summer season and yearly flows in the upper Ob valley are consistent with the downward trends found downstream at the upper Ob subbasin outlet, that is, the Kolpashevo station (C in Fig. 1). Therefore flow decreases in the upper Ob valley are responsible for the negative streamflow trends observed at the upper Ob subbasin outlet. Human activities such as farming and industrial developments exist in the upper Ob valley. In addition to climatic factors, the strong discharge decreases dis-

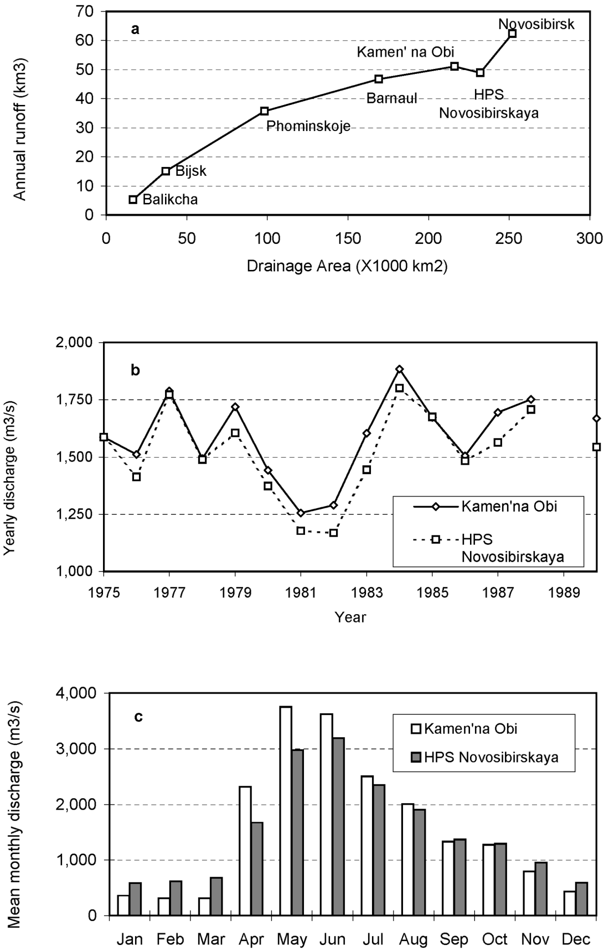


FIG. 4. Potential water losses in the upper Ob regions: (a) yearly discharge (km^3) along the valley, (b) comparison of yearly upstream–downstream streamflow (m^3 s^{-1}), and (c) comparison of mean monthly upstream–downstream discharge (m^3 s^{-1}).

covered over the summer season is likely related to water uses for agricultural activities in this region. To better describe the flow regime and change in these complex regions, monthly and yearly streamflow records collected at seven stations (D–D7 in Fig. 1) along the main upper Ob valley have been examined. The mean yearly discharge amounts during 1975–90 are presented in Fig. 4a. As expected, yearly flows increase (from 5.4 to 51.1 km^3) along the river valley. However, an unexpected decrease in annual flows by about 2.2 km^3 is detected in the midsection of the valley.

Flow reductions along a river valley usually occur over warm and dry climate regions because of evaporation and infiltration. Water withdrawal for irrigation and industrial uses can also cause local streamflow decreases. Cultivated fertile steppe exists in the Novosobirsk regions, with rye, wheat, and sunflowers being the main crops (Stolbovoi et al. 1997). Flow reduction found in the midsection of the upper Ob valley is perhaps associated with agricultural activities. To estimate the potential water uses in this region, calculation of streamflow budget for selected basin intervals is useful. Comparisons of yearly flows between upstream (Kamen'na Obi; D2 in Fig. 1) and downstream (HPS Novosibirkaya; D1 in Fig. 1) stations during 1975–90 show that for most years, flows at downstream station are lower (Fig. 4b), clearly suggesting yearly water losses up to 125 m^3 s^{-1}. It is important to point out that this estimate of water loss is the most conservative (minimal estimate), since we do not take into account intermediate runoff contribution. Our calculation suggests runoff generation of 60–75 mm yr^{-1} (or 1.0 km^3 integrated over this subbasin), which is very similar to Fekete (2001) for this region. Occasionally yearly flows are close to each other between these two stations (Fig. 4b). This interannual variation in yearly upstream-and-downstream flow difference reflects fluctuation in regional water uses over this subbasin.

Monthly flow data can provide detailed information on streamflow changes induced by human impacts and natural variations. Comparisons of mean monthly flows between the same pair of upstream and downstream stations clearly show monthly flow reductions during April to August, with the maximum loss in April and May (Fig. 4c). The summer season water losses, about 14.4 km^3, are partly due to irrigation water uses and reservoir regulations. They coincide with the irrigation season, particularly in April when the irrigation demand is higher during the spring planting season over west Siberia (Romanenko et al. 1999). From September to October, small streamflow differences exist between these two sites. During November through March, strong increases in monthly flows are detected at the downstream station mainly due to reservoir regulation on seasonal flows (Fig. 4c).

A reservoir was constructed above the Novosibirsk station (D in Fig. 1) in 1957 for power production and flood control. The dam is 27 m high and 4382 m long, with the maximum storage capacity of 8.8 km^3, about 7% of the total annual discharge at the Kolpashevo station (C in Fig. 1). A hydropower plant (455 MW yr^{-1}) was also constructed below the dam. The effects of this dam on seasonal streamflow regime are clearly seen in monthly flow records measured at downstream stations. Since the completion of the Novosibirsk reservoir and the power plant in 1957, a gradual increase of winter (November–March) flows by about 200–500 m^3 s^{-1} at the downstream station Novosibirsk is evident (Fig. 5a). This flow increase is the consequence of the reservoir regulation because of the higher demand for electricity and hence more power generation in winter. On the other hand, monthly flows from April to June have been reduced by 200–400 m^3 s^{-1}, or 5%–18%, in order to control snowmelt and rainfall floods, while flows from July to October experience no major changes (Figs. 5a,b). These changes in seasonal streamflow regime are best reflected in the ratio of maximum/minimum monthly flows. The drop of the ratios from 10–20 to 6–10

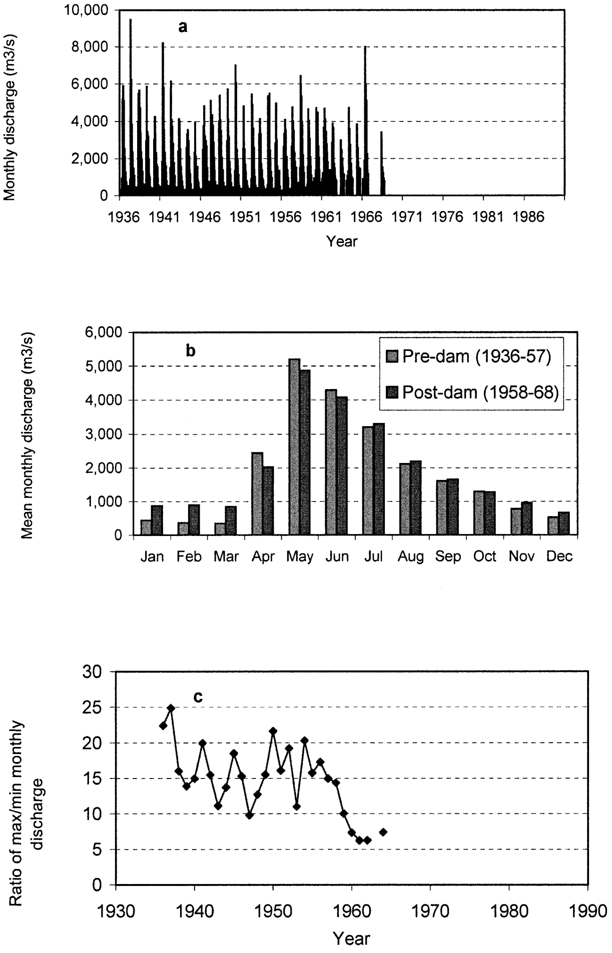


FIG. 5. Dam impacts in the upper Ob regions: (a) monthly discharge (m^3 s^{-1}) time series, (b) comparison between pre- and postdam mean discharge (m^3 s^{-1}), and (c) ratio of max/min monthly discharge, at the Novosibirsk station.

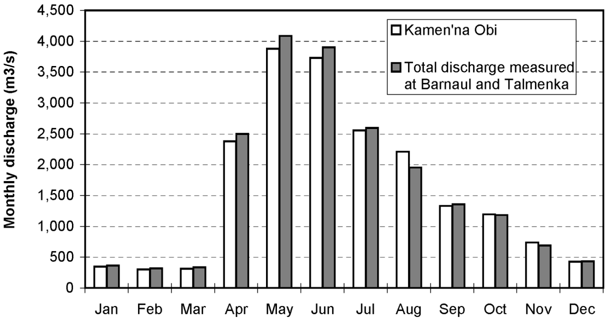


FIG. 6. Potential water losses seen in monthly mean discharge (m^3 s^{-1}) comparison in the upper Ob valley. Data periods are 1936–90 for both the Kamen'na Obi and Barnaul stations and 1943–90 for the Talmenka station, respectively.

(Fig. 5c) due to reservoir regulation is so distinctive that it can be used to detect sudden changes in streamflow characteristics caused by human activities (Vörösmarty et al. 1997; Yang et al. 2004; Ye et al. 2003). Savkin (2000) recently determined the water consumption including evaporation from the Novosibirsk reservoir and reported the yearly total water losses in 2000 being about 2.3 km^3. This result is very similar to the mean yearly discharge difference we found between the Kamen'na Obi and HPS Novosibirskaya stations (Fig. 4a).

Reservoir regulations create uncertainties in determination of streamflow changes and water use patterns. To better detect and determine the potential water uses along the river valley, we carried out a monthly streamflow water-budget calculation for a section of the upper Ob valley without reservoir effect. The segment is the region above station Kamen'na Obi (D2 in Fig. 1) and below stations Barnaul and Talmenka (D3 and D4 in Fig. 1, respectively). Comparisons between mean monthly inflow (total flows measured at stations Barnaul and Talmenka) and outflow (station Kamen'na Obi) during 1936–90 clearly show water losses/uses (up to 200 m^3 s^{-1} in May) from April to July, although the inflows and outflows are similar for other months except for August (Fig. 6). The total water losses during April to July are about 5.2 km^3, mainly due to irrigation water uses in this region.

The source areas of the upper Ob valley are the mountain regions without human activities. Monthly streamflow at station Balikcha (D7 in Fig. 1) during 1936–90 is characterized with low flows from October to April, and high flows from May to September, with the peak flow in June (Fig. 7a). Trend analyses show flow increases during 1936–90 in nearly all months, except in June with a weak decrease. The increasing trends are statistically significant at 90%–99% confidence levels from October to March, and the changes in summer-month flows are less significant. Discharge increases in May and decreases in June suggest an earlier snowmelt associated with climate warming in spring, including May in this region over the last several decades (Fig. 7b). Streamflow increases from July to October are due to summer and fall precipitation increases by about 13 mm from June through September (Fig. 7b). Winter flow increases are the consequence of wetter conditions in the fall season.

b. *The Irtish subbasin/regions*

The Irtish subbasin, 969 000 km^2 (or 39.9% of the Ob watershed) above the Tobolsk station (H in Fig. 1) covers southwest parts of the Ob catchment. Annual discharge at the Tobolsk station is about 2130 m^3 s^{-1} (or 66 km^3), contributing 16.6% of the Ob basin total flow. The Irtish subbasin has three main branches, the upper Irtish, Ishim, and Tobol. The Irtish regions are the major spring-wheat production regions in Russia. Three reservoirs were constructed in the upper Irish regions in the 1950s and 1980s.

The seasonal cycles and trends of subbasin-mean temperature and precipitation during 1936–90 are shown in Fig. 8 for the upper Irtish and Tobol valley. Monthly

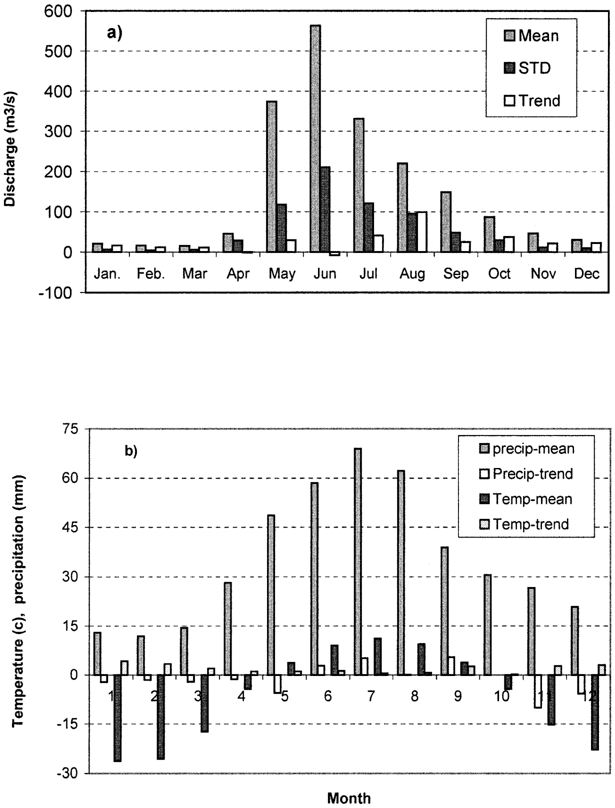


FIG. 7. Long-term mean monthly temperature (°C), precipitation (mm), and discharge ($m^3 s^{-1}$), and their total trends for source area of the upper Ob valley during 1936–90: (a) monthly discharge and its trend at the Balikcha station and (b) basin-mean (above the Balikch station) monthly precipitation and temperature, and their trends.

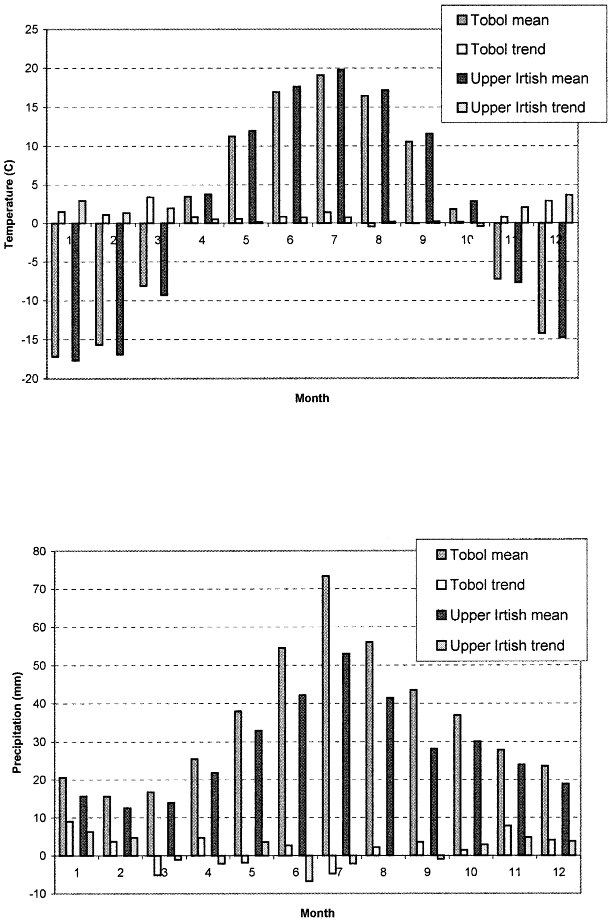


FIG. 8. Long-term subbasin (a) mean temperature (°C) and (b) precipitation (mm), and their total trends during 1936–90 for the Tobol tributary and the upper Irtish valley.

precipitation varies from 15–30 mm in winter to 40–75 mm in summer, while monthly temperatures range from $-10° \sim -20°$C in winter to $10° \sim 20°$C in summer. Temperatures over the subbasins have positive trends during November to July and show very little changes in August, September, and October (Fig. 8a). Precipitation trends in these regions are positive (total increase of 2–9 mm during 1936–90) for most months, and negative (2–6-mm decrease) in March, May, and July (Fig. 8b).

Mean monthly flows and their variation and trends were calculated for several stations along the Tobol valley. The results at three major stations (G4, G1, and G in Fig. 1) show low flows during most months, except April through June with high flows of snowmelt (Figs. 9a–c). Trends in monthly flows are very similar along the valley. During late spring through summer (April to September), strong negative trends, up to 100%–200% decreases, were found in the upper parts of the valley (Figs. 9a,b); the maximum flow decreases occurred in May. In winter months from November to March, relative strong upward trends (up to 50%–70%) were identified at these stations (Figs. 9a–c). These trends are significant (confidence at 95%–99%) in the summer season over the upper parts of the valley and in winter months over the lower parts of the basin.

It is important to note that warming in cold months is significant, and precipitation increases are also strong in the winter season over the Tobol regions (Fig. 8). Strong winter season precipitation increases (total increases of 24.2 mm during November through February) will lead to a thicker snow cover, and consequently a higher snowmelt runoff over the basin. However, streamflow trends over the Tobol valley show very strong decreases during the snowmelt period (April and May), despite increases in winter snow-cover mass and April precipitation. Furthermore, strong discharge decreases were also found over the basin in summer months (June to August), when basin precipitation weakly increased or decreased and temperatures became slightly warmer (Fig. 8). It is not completely unexpected to find the discrepancy in seasonal temperature, precipitation, and discharge trends over large basins, as nonclimate factors such as human activities may also affect regional streamflow regime and change. Water with-

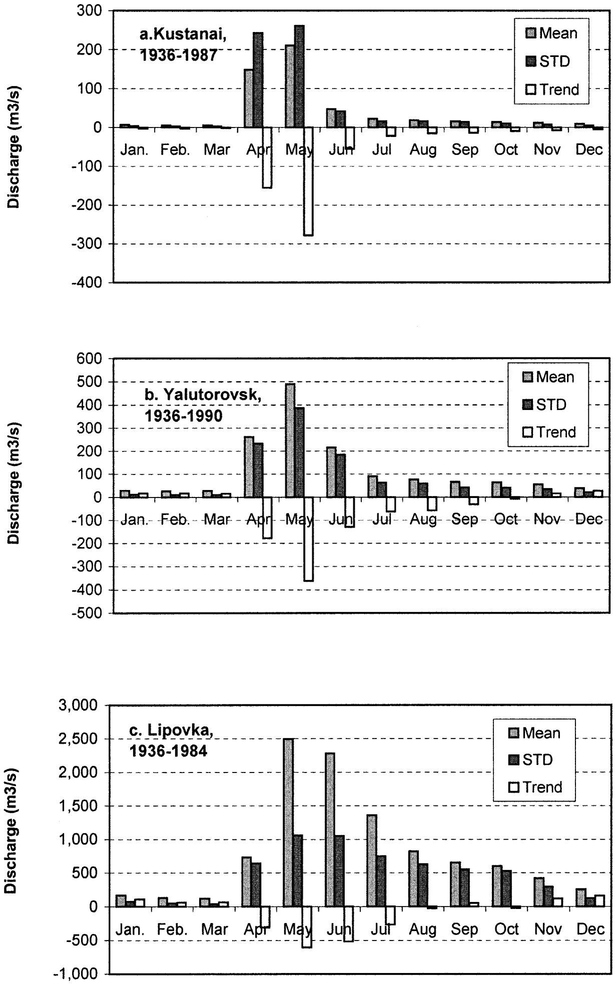


FIG. 9. Long-term mean monthly discharge (m^3 s^{-1}), standard deviation (STD), and total trend during the observations periods at the selected stations in the Tobol valley.

drawal for irrigated cropland of 50 204 km^2 in the Irtish basin has been reported around 2.6–3.1 km^3 yr^{-1} during the recent decade (State Hydrological Institute 2001). Annual flow data collected at six sites along the Tobol valley generally show streamflow increases with basin area, except decreases by about 2.8 km^3 in the upper part of the valley (Fig. 10). These decreases in annual flow are generally consistent with the published water withdrawal records (State Hydrological Institute 2001). Therefore, irrigation water uses in summer are responsible for the consistent flow decreases along the Tobol valley.

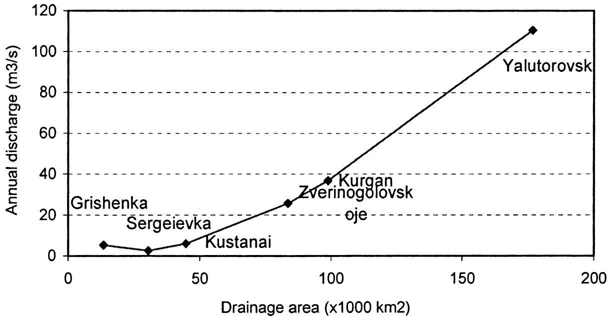


FIG. 10. Comparison of yearly mean discharge (m^3 s^{-1}) along the Tobol valley. Data periods cover 1936–90 (see Table 1 for details).

Relative to the Tobol tributary, the Ishim valley is small in size and generates less flow, about 80 m^3 s^{-1}, or 38 km^3 yr^{-1}. Short flow records show that over the upper parts of the valley, flows are low during July to March and high from April to June, with the maximum in April. In the lower parts of the valley, flows are low from July to March and high from April to June, with the peak flow in May (Fig. 11). The delay of peak flow from April to May in the lower portions of the valley is owing to a late snowmelt in the northern regions. Flow trends cannot be objectively determined in this valley because of the short records.

In the source areas of the upper Irtish basin, monthly flows show no abrupt changes over the past six decades, and the ratios of maximum/minimum monthly flows are stable (Fig. 12a). Three reservoirs were constructed in the 1950s and 1980s in the upper and middle sections of the Irtish basin (Fig. 1). Their effects on seasonal streamflow regime are clearly seen in monthly flow records along the upper Irtish valley. For instance, since the completion of the Bukhtarma reservoir (dam height 90 m, maximum storage capacity 49.8 km^3) and a power plant (capacity 675 MW yr^{-1}) in 1960, an abrupt increase of winter (November to March) flows by 200–500 m^3 s^{-1} is evident at the station Shul'ba (E3 in Fig. 1). A reduction in summer peak flows from 3500–4000 m^3 s^{-1} to 2000–3000 m^3 s^{-1} is also very clear (Fig. 12b). As a result, the monthly hydrograph changed very significantly: Monthly flows became lower in summer and higher during winter, reducing seasonal differences. These changes in seasonal flow regime are best reflected in the ratio of maximum/minimum monthly flows (Fig. 12b). The drop of the ratios from 6–18 to 3–10 because of reservoir regulation is very distinctive. Another reservoir, the Ust-Kamenogorsky, was constructed in 1952,

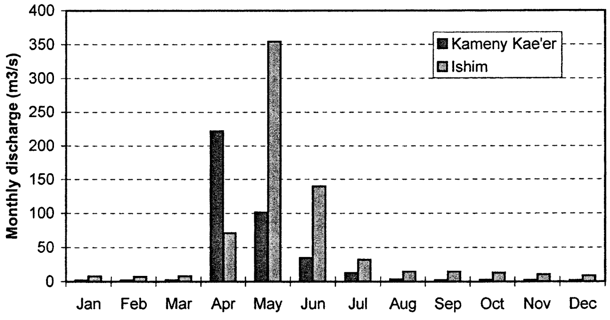


FIG. 11. Comparison of monthly mean discharge (m^3 s^{-1}) between the upper (the Kameny Ka'er station) and lower (the Ishim station) parts of the Ishim valley. Data periods are 1955–90 for the Kameny Ka'er station and 1947–81 for the Ishim station, respectively.

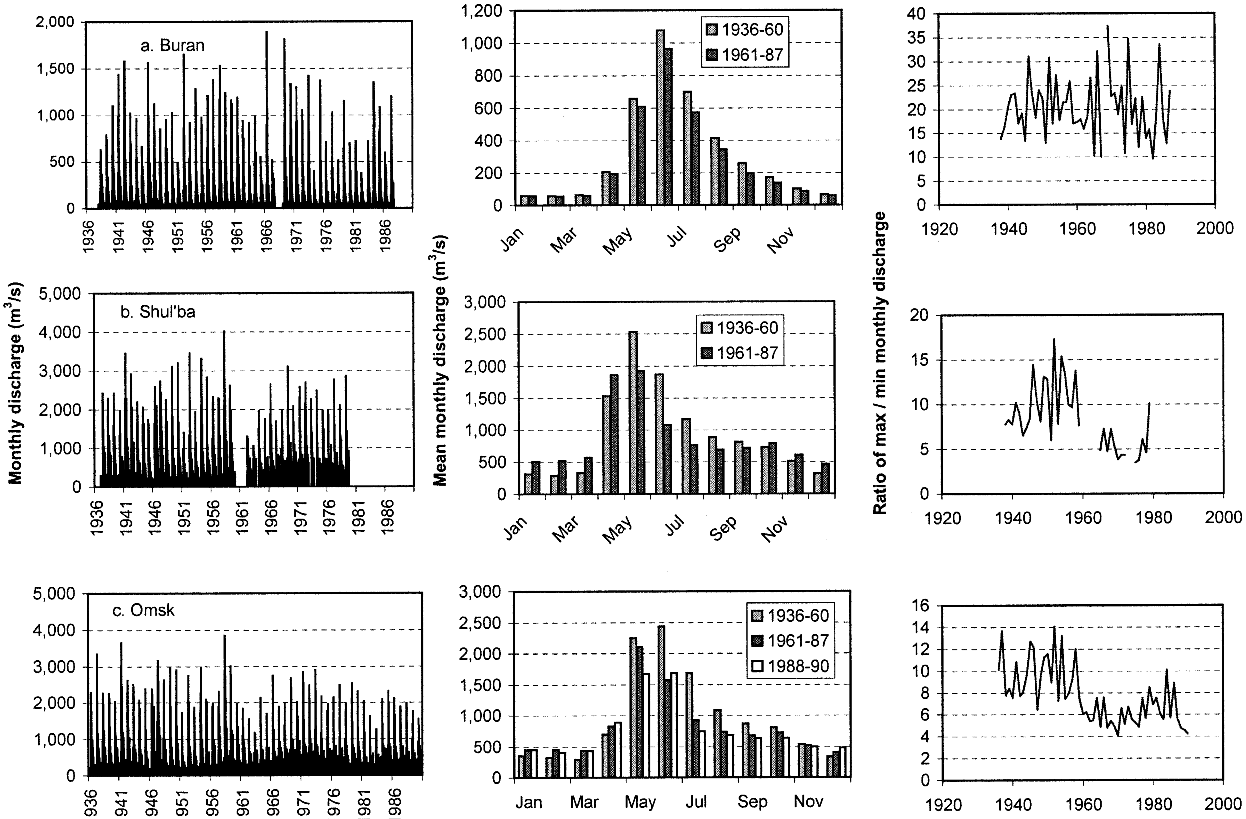


FIG. 12. Dam impacts on streamflow ($m^3 s^{-1}$) regime in the upper Irtish regions: (left) monthly discharge time series during 1936–90, (middle) seasonal regimes are compared between the pre- and postdam periods, and (right) ratios of max/min monthly discharge are displayed for each year.

with dam height 65 m, maximum storage capacity 0.63 km^3, and power plant production 331 MW yr^{-1}. The regulation effect of this small reservoir is not strong and cannot be detected in discharge records at the Shul'ba station, about 200 km downstream of the dam. The third reservoir (the Shul'binsk) was built at the middle stream of the upper Irtish in 1987. The dam is 36 m high and 570 m long. The reservoir capacity and power plant production are 2.4 km^3 and 702 MW yr^{-1}, respectively. Remarkable changes in monthly flows at the Omsk station (E1 in Fig. 1) located about 260 km below the Shul'binsk dam have been detected because of regulations of upstream reservoirs (Fig. 12c). Comparisons of the long-term mean monthly flows at the Omsk station show that during December to March, mean monthly discharge gradually increased from 400 to 500 $m^3 s^{-1}$, and flows in April were also enhanced by about 200–300 $m^3 s^{-1}$. On the other hand, monthly flows were strongly reduced by 160–940 $m^3 s^{-1}$ during summer and fall seasons. For instance, the summer peak discharge in June was reduced from 2700–3800 to 1700–2500 $m^3 s^{-1}$ over the past seven decades, and the ratio of high/low flows decreased from 8–14 for the predam period to 4–7 during the postdam years (Fig. 12c). These changes in monthly flow characteristics, that is, a general flow increase in winter and a decrease in summer, are consistent with those identified by Yang et al. (2004) and Ye et al. (2003) for other regulated subbasins in the Yenisei and Lena watersheds. In addition to monthly flow, reservoir operations may also affect yearly flow characteristics. Ye et al. (2003) and Yang et al. (2004) found consecutive lower flow years in the west Lena and upper Yenisei basins during the times of reservoir filling after the dam constructions.

Monthly flows at the Irtish basin outlet (the Tobolsk station; H in Fig. 1) show a low-flow period from November to April, and a high-flow season from May through October, with May and June having the highest peaks (Fig. 13a). The twin-peak feature of the monthly hydrograph has been discovered over major tributaries within the Irtish basin (Figs. 13b,c). This indicates a different hydrologic regime over the Irtish basin. The 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 southwest parts of the Ob basin. The interannual variation of Irtish basin monthly flow is similar to the upper Ob regions, with low variations in winter and high fluctuations during summer (Figs. 13a–c). Because of human activities in the Irtish regions, it is difficult to determine hydrologic

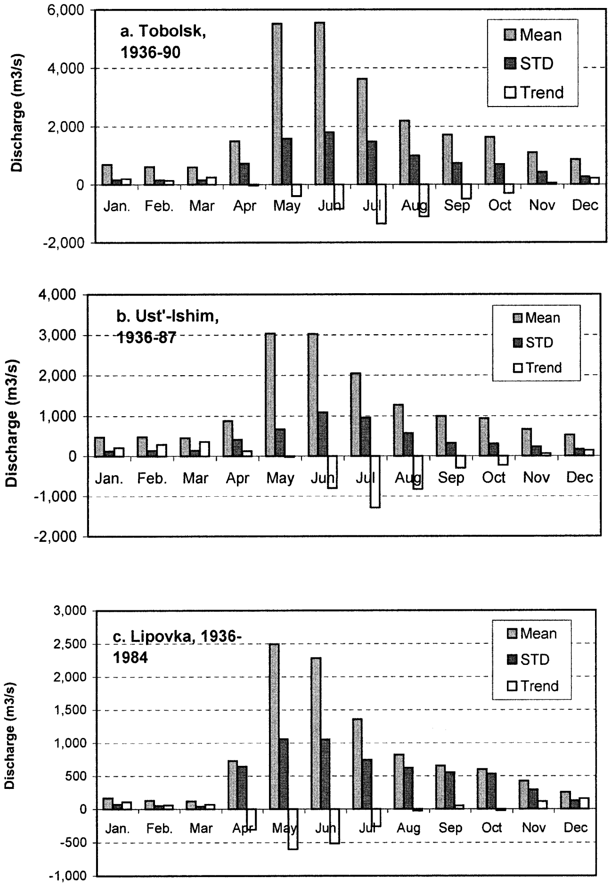


FIG. 13. Monthly mean flows (m³ s⁻¹), standard deviation, and total trends during the observation periods at Irtish basin mouth and major subbasins. Data periods are shown in the figure.

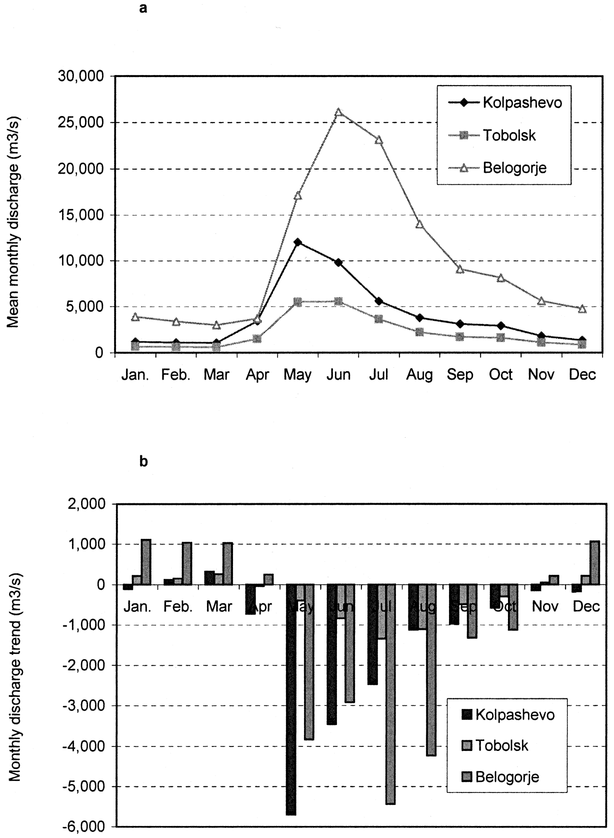


FIG. 14. (a) Mean monthly flows (m³ s⁻¹) and (b) their total trends during 1936–90 in the mid-Ob regions.

response to climate change and variation. Monthly streamflow trends observed at the subbasin outlet reflect the combined impacts of reservoir regulation and water withdrawal/use mainly for irrigation. Weak increasing trends are seen at the basin outlet (station H in Fig. 1) during December to March (Fig. 13a) due to upward trends found in the upper Irtish regions, particularly in the Tobol tributary (Fig. 13c) and the upper Irtish valley (Fig. 13b). On the other hand, discharge decreases (by about 400–1300 m³ s⁻¹) are found at the Irtish basin mouth from May to October, owing to reservoir regulations in the upper Irtish valley (Fig. 13b) and irrigation water uses over the Tobol tributary (Figs. 9a–c). Annual flows at the Irtish basin outlet also have a downward trend (−14%) during 1936–90 mainly because of summer flow decreases in the major tributaries.

c. The mid-Ob regions

The mid-Ob region is defined as the regions above Belogorje station (B in Fig. 1) and below stations Kolpashev (C in Fig. 1) and Tobolsk (H in Fig. 1) in the upper Ob and Irtish subbasins. The drainage area of this section is about 705 000 km², or 29.0% of the Ob basin. Annual discharge is 4068 m³ s⁻¹, or 31.7% of Ob River total flow. Monthly discharge data collected at the Belogorje station show lower flows from November to April, high flow from May to August, and recession from September and October (Fig. 14a). As expected, the peak flows at the Belogorje station (representing the mid-Ob regions) are higher than those for the upper Ob (the Kolpashev station) and Irtish (the Tobolsk station) subbasin, and they occur (late) in June because of runoff routing through the basin and late onset of snowmelt in the northern parts of the mid Ob regions (Fig. 14a).

Trends in monthly flows at the Belogorje station during 1936–90 reveal little changes in November, strong increases from December to April, and very strong decreases from May to October (Fig. 14b). It is important to point out that similar decreasing flow trends over summer and early fall seasons have been observed for both the upper Ob and the Irtish tributaries. Weak winter flow increases have also been found over the Irtish subbasin due to reservoir impacts, while the upper Ob with relatively weak reservoir regulations has weak downward or no trends. The increases in winter flow identified at the Belogorje station are due to runoff increases associated with winter warming and increases in precipitation (Wang and Cho 1997) and snow cover (Ye et al. 1998). The overall similarities in streamflow trends among the upper Ob, the Irtish tributary, and the mid-Ob region (Fig. 14b) indicate a transfer of streamflow trends from upstream to downstream through basin integration.

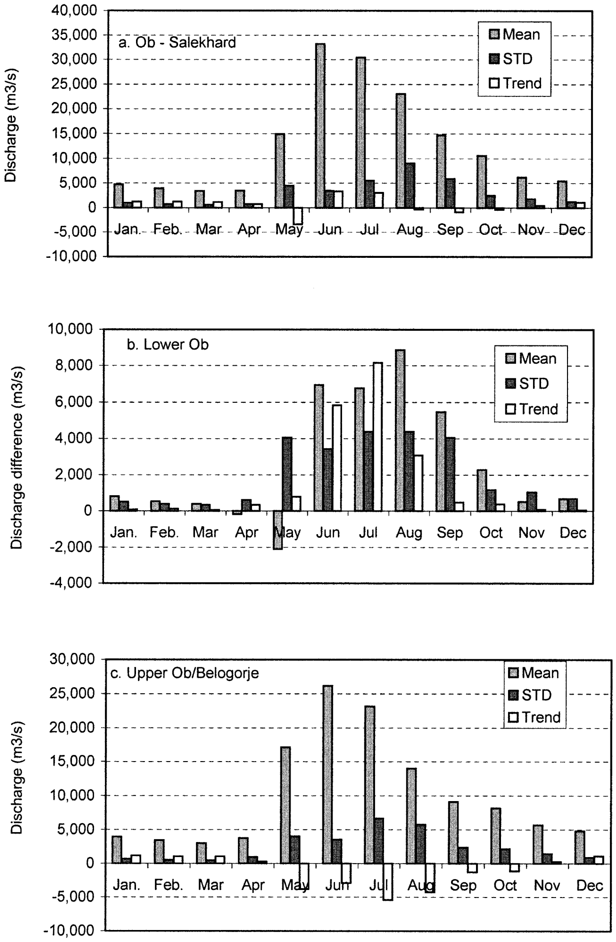


FIG. 15. Monthly mean flow ($m^3 s^{-1}$), standard deviation, and total trend during 1936–90 at the (a) Ob basin outlet, (b) the lower Ob, and (c) the upper Ob.

d. The lower Ob regions and basin as a whole

Streamflow records observed at the watershed outlet reflect basin integration of both natural variations and human-induced changes, such as changes of land cover/land use and regulations of large dams within the watersheds. Discharge data collected at the river mouth are particularly important as they represent freshwater input to the ocean and are often used for basin-scale water balance calculations, climate change analysis, and validations of land surface schemes and GCMs over large spatial scales (Bonan 1998; Arora 2001; Nijssen et al. 2001a,b; Dai and Trenberth 2002). It is therefore important to understand the fundamental characteristics, including temporal variations and changes, of monthly and yearly streamflow at the basin outlet.

The long-term monthly discharge during 1936–90 at the Salekhard station (A in Fig. 1) is presented in Fig. 15a. It generally shows a low-flow period from November to April and a high runoff season from June to October, with the maximum discharge occurring usually in June because of snowmelt floods. Monthly streamflow variation at the Ob basin outlet is usually small (500–1200 $m^3 s^{-1}$, or 17%–22%) in the cold season and large (3500–9000, about 10%–40%) in summer months owing to snowmelt and heavy rainfall floods. The lower Ob regions, partly underlain by discontinuous permafrost (Zhang et al. 1999) and dominated by snow cover, are expected to be more sensitive to regional climate changes particularly during the snowmelt periods (Nijssen et al. 2001a,b). There were no large dams or agricultural activities in the northern Ob regions. To understand the streamflow characteristics and its change in the lower Ob regions, a monthly discharge difference time series during 1936–90 has been generated by subtracting flow contribution of the mid Ob region (station B in Fig. 1) from the measured discharge at the mouth of the Ob watershed (station A in Fig. 1). These data, defined as discharge difference (DD), primarily represent changes in storage amount that is dominated by runoff generation in this part of the Ob basin. Based on these data, we determined the long-term mean DD and carried out a trend analysis. Results show low DD (1700–3200 $m^3 s^{-1}$) during the cold months from November to April, negative DD in May (about 2000 $m^3 s^{-1}$), and high DD during June to October, with a peak about 9000 $m^3 s^{-1}$ in August (Fig. 15b). Streamflow usually increases along the river valley. The negative DD found in May is likely related to the Ob River ice conditions. Vuglinsky (2002) reported that river ice thickness can reach up to 2 m in normal winters over the northern Siberian coastal regions. Similar to other northern-flowing rivers, the Ob River breaks up during late April to May in the upper parts of the basin, and around late May to early June in the lower regions. This delay of river ice breakup from south to north allows the lower Ob basin to receive upstream runoff contribution and store the flow in the main river valley above its mouth, resulting in widespread flooding (negative discharge difference) in May over the northern parts of the Ob basin.

Trend analyses of the monthly discharge during 1936–90 at the Salekhard station show noticeable changes in streamflow characteristics (Fig. 15a). Since the mid-1930s, discharge at this site has increased by 20%–30% in the low-flow season from November to April. The flow increases in winter months at the basin outlet are mainly due to increased contribution from upstream (Fig. 15c) and, to a small extent, associated with runoff increase over the lower Ob regions (Fig. 15b). Summer months are an important season, since both snow-cover melt during early summer and heavy rainfall in midsummer can generate peak flows through-out the watershed. A downward trend (−4%), or close to 3400 m³ s⁻¹, was found in May at the Ob basin mouth (Fig. 15a). This trend is associated with flow reductions in May over both the upper Ob and the Irtish subbasin because of reservoir regulations to hold water to reduce snowmelt floods by up to 50%–70% during the spring season. Flows in June and July decreased in the two major subbasins, particularly from the upper Ob regions by about 35%–45% (Fig. 15c). However, DD in June and July increased very strongly by 35%–50% in the lower Ob regions (Fig. 15b) because of increases in winter precipitation and snow-cover depth (Ye et al. 1998). Discharge difference increases in June and July over the lower Ob regions outweigh runoff decreases in the upper basins, leading to an increasing flow trend (10%) at the Ob basin outlet. From August to October, little (less than 10%–20%) changes in monthly flows have been found at the Ob basin outlet, although the two main subbasins have decreasing trends and the lower Ob region shows a weak increasing tendency (Figs. 15b,c).

Determinations of annual streamflow trends are important for climate change analysis. Serreze et al. (2003) recently reported an increase trend in yearly total runoff over large Siberian watersheds including the Ob basin. Over the period 1935–99, annual flow increases were found by 6% in the Lena River (Yang et al. 2002; Ye et al. 2003) and 3% in the Yenisei basin (Yang et al. 2004). Figure 16 presents the trends of yearly discharge for the major subbasins and at the Ob watershed outlet. It shows a significant (90% confidence) downward trend in the upper Ob regions (Fig. 16a), a slight downward trend in the Irtish subbasin (Fig. 16b), a weak negative trend in the mid Ob region (Fig. 16c), and a very strong increase in the lower Ob region (Fig. 16d). The decrease in annual streamflow over the upper parts of the Ob basin is partly associated with agriculture and urban water consumptions in the southern regions, while the rise of yearly flow over the lower Ob regions is mainly associated with increases in snowmelt floods due to increases in winter precipitation (Wang and Cho 1997) and snow-cover depth (Ye et al. 1998). As result of strong flow increases over the lower Ob regions that overcome the flow decreases in the southern parts of the watershed, the Ob basin (as a whole) has a weak increase (about 5%) in annual flow (Fig. 16e).

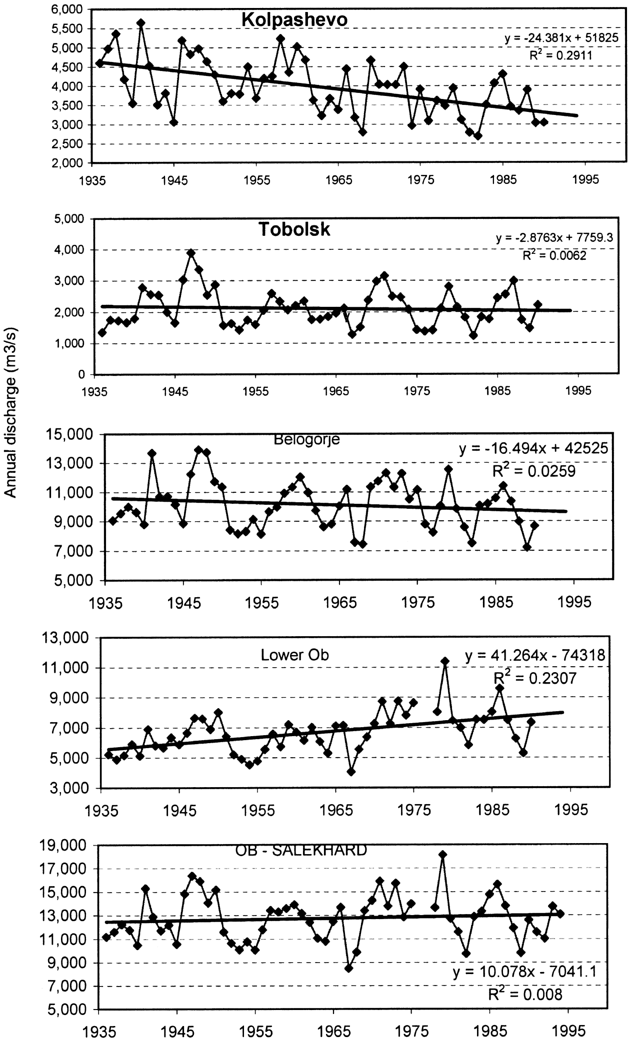


FIG. 16. Yearly streamflow time series and their trends during 1936–90 over the Ob basin.

4. Conclusions

Based on systematical analyses of long-term monthly discharge records for the major subbasins within the Ob River watershed, this study found that changes in streamflow are different between the upper and lower parts of the Ob watershed. Over the upper Ob basin, streamflow decreased in summer months and increased over the winter season during 1936–90. The decreases in summer are mainly due to increased water uses along the river valley for agricultural and industrial purposes during recent decades and to reservoir regulations to reduce the summer peak flows. The increases in winter streamflow are caused by reservoir impacts to release water for power generation during winter months. In the lower Ob regions, however, streamflow increased during midsummer and winter months and decreased slightly in autumn. The increases in summer streamflow were associated with increases in summer precipitation and winter snow cover over the northern Ob basin.

This study quantified the minimal water uses/losses along the river valleys in the upper parts of the Ob watershed. We found that the water losses by up to 2.8–5.2 km³ yr⁻¹ along the upper valleys mainly occur in summer months when the irrigation demands are the highest. Given the large magnitude of the water losses identified in the Ob catchment, it is important to emphasize that the water losses seen in the Ob basin monthly and yearly flow records will significantly impact large-scale hydrological investigations, such as development of gridded runoff datasets and analyses of streamflow trends over large regions (Grabs et al. 2000; Lammers et al. 2001). These water losses will introduce negative biases in monthly and yearly runoff estimates and create uncertainties in determinations of regional discharge trends. Future efforts are certainly necessary to better quantify the amounts of water losses in large watersheds and to develop and apply appropriate monthly/yearly adjustment methods to both regional and basin-scale runoff analyses.

Similar to recent analyses for the Lena and Yenisei basins (Ye et al. 2003; Yang et al. 2004), this study also demonstrated that the reservoir regulation has significantly altered the monthly discharge regimes in the upper portions of the Ob River basin. Operations of four reservoirs in the upper Ob regions enhanced the winter flows by 25%–45% and reduced the summer flows by 10%–50%. These alterations lead to a streamflow regime change toward less seasonal variation over mid- and upper portions of the Ob basin. It seems clear that, due to reservoir regulations and water uses in the upper parts of the basin, discharge records observed at the Ob watershed 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.

The results of this study clearly demonstrate that, because of human activities and impacts, it is not easy, using streamflow data alone, to detect and quantify basin-scale hydrologic response to climate changes and variations. Regional or subbasin scale analyses of climatic, hydrologic, and human activity data/information are important and useful to understand climate–hydrology–human interaction and its change due to natural causes and human influences. This study illustrates that, relative to climate factor, human activities are sometimes more important and direct in altering regional hydrologic regimes and affecting their long-term changes at both seasonal and regional scales. It is therefore necessary to consider human activities in regional and global environment change analyses and further examine their impacts in other large northern watersheds.

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