Effect of streamflow regulation on mean annual discharge variability of the Yenisei River

SVETLANA STUEFER[1], DAQING YANG[1] & ALEXANDER SHIKLOMANOV[2]

1 *Water and Environmental Research Center, University of Alaska Fairbanks, Fairbanks, Alaska 99775, USA*
sveta.stuefer@alaska.edu

2 *Water System Analyst Group, University of New Hampshire, Durham, NH 03824, USA*

Abstract The magnitude of natural and anthropogenic changes in hydrological systems is one of the major scientific questions yet to be addressed. Relative to climatic effects, dam impacts are much more direct and often cause abrupt changes in the water regimes of rivers. We expect these changes to be evident and detectable in the mean annual discharge (MAD) records and discharge–precipitation relationship of the Yenisei River, Siberia, Russian Federation. We use statistical analysis to compare three periods: (a) natural streamflow (1936–1956), (b) filling of reservoirs (1957–1980), and (c) operation of reservoirs (1981–2006). Comparison of reconstructed and observed MAD suggests that streamflow regulation affects the homogeneity of the MAD between filling of reservoirs and operation periods. We conclude that dam regulation in the Yenisei River is strong enough to modify the MAD response to annual precipitation, particularly during the 1980–2004 period.

Key words discharge; precipitation; Yenisei River; dam; reservoir; streamflow regulation; Arctic

INTRODUCTION

Among the Arctic watersheds, the Yenisei River is most affected by anthropogenic impacts. The total storage of operating and constructed reservoirs in the Yenisei River watershed is 482 km^3 (Shiklomanov *et al.*, 2000). The Yenisei River is referred to as "strongly affected by flow regulation/fragmentation", based on a worldwide classification of fragmentation of the river channels by dams and by water regulation resulting from reservoir operation, interbasin diversion, and irrigation (Dynesius & Nilsson, 1994). Babkina (1988) reported that as of 1986, there were 64 reservoirs in the Angara-Yenisei basin. In addition to the large storage capacity, the cascading reservoirs upstream of the Yenisei and Angara rivers confluence were designed for water redistribution from year to year. The effect of streamflow regulation on seasonal hydrology has been clearly documented for the Siberian Rivers (Shiklomanov, 1978; McClelland *et al.*, 2004; Yang *et al.*, 2004; Berezovskaya *et al.*, 2005; Adam *et al.*, 2007). Seasonal streamflow regulation during spring and early summer reduces the peak discharge, and releases additional water from the reservoirs during the winter months. While it is evident that streamflow regulation has a marked effect on the seasonality of discharge, its effects on the mean annual discharge (MAD) is more complex and often neglected for the large rivers. The primary impacts of water regulation resulting from reservoir operation on MAD include: (a) filling of the reservoirs, and (b) long-term intra-annual streamflow regulation; that is, water is captured in the reservoir and then released in the following years. Such streamflow regulation directly affects the MAD variability.

The magnitude of natural and anthropogenic changes in hydrological systems is one of the major scientific questions yet to be addressed. Our research into this question has been prompted by the fact that, relative to climatic effects, dam impacts are much more direct and often cause abrupt changes in the water regimes of rivers. We expect these changes to be evident and detectable in the mean annual discharge (MAD) records and discharge–precipitation relationship of the Yenisei River. We analyse observed and reconstructed Yenisei River MAD and quantify the effect of streamflow regulation by reservoirs on the MAD and precipitation relationship. The reservoir effect was eliminated in reconstructed MAD using the approach presented by Shiklomanov & Lammers (2009). Our analysis mainly relies on historical measurements from the conventional network. New data on water use and water consumption is also presented.

DATA

Mean annual discharge

Mean annual discharge of the Yenisei River at the Igarka station (67.4°N, 86.5°E) with a drainage area of 2440×10^3 km^2 (Lammers *et al*., 2001) was collected from 1936 to 2006 (Fig. 1). Mean annual discharge is the most accurate observational component of the water balance; its accuracy is 6.1% for the Igarka gauging station (Shiklomanov *et al*., 2006).

Reconstructed discharge

The reconstruction of MAD for the Yenisei River basin from 1957 to 2006 was implemented using the hydrograph routing model (HRM). The HRM was developed at the University of New Hampshire (USA) in collaboration with the Arctic and Antarctic Research Institute (Russia) (Shiklomanov, 1996; Shiklomanov & Lammers, 2009). The model, based on the genetic formula or Duhamel integral, operates at the sub-basins between gauges. In the HRM, the sub-basin is considered a black box that transforms the inlet hydrograph, $Q'^{(t-\tau)}$, into the outlet hydrograph, $Q_{(t)}$:

$$Q_{(t)} = \int_0^t Q'^{(t-\tau)} P_{(\tau)} \mathrm{d}\tau \quad (1)$$

$P_{(\tau)}$ is the influence function (the travel curve), which is approximated with a two-parameter equation suggested by Nash (1958) and Kalinin *et al*. (1969):

$$P(\tau) = \frac{1}{\tau(n-1)} \left(\frac{t}{\tau}\right)^{n-1} e^{-\left(\frac{t}{\tau}\right)} \quad (2)$$

where n is the number of sub-basins with the same travelling time, τ. The HRM works on a daily time step and uses information from 35 major hydrometric sites across the Yenisei River basin. HRM provides more accurate hydrograph simulations (Shiklomanov & Lammers, 2009) than the approaches based on comparison of mean pre-dam and post-dam hydrographs (e.g. McClelland *et al*., 2004; Yang *et al*., 2004) and it reduces the uncertainty associated with water balance modelling approaches for hydrograph simulation (e.g. Adam *et al*., 2007) as it uses only observed river discharge, which is the most accurately measured component of the hydrological cycle (Shiklomanov *et al*., 2006).

Mean annual reconstructed discharge was calculated from daily data and used to represent MAD from 1957 to 2006 (Fig. 1). The cumulative difference between reconstructed and observed Yenisei MAD from 1957 to 2006 is calculated at 604 km^3. Adam *et al.* (2007) estimated 580 km^3 of runoff reduction due to streamflow regulation from 1956 to 1999. This estimate is comparable with HRM results over the same time period (567 km^3).

Annual precipitation

There are difficulties in using gauge-based precipitation data sets for water budget analyses and predicting streamflow in large Siberian river basins (e.g. Fekete *et al*., 2005). These problems are associated with the construction of precipitation data sets in the northern regions, because of underestimation of solid precipitation by gauges, lack of observations in the mountain regions, and the varying numbers and locations of stations in the networks. On a temporal scale, station networks across Eurasia gave rise to an overestimation of annual precipitation during earlier years (Rawlings *et al*., 2006). For the largest Siberian basins, Adam & Lettenmaier (2007) showed that there is close agreement among five available gauge-based gridded precipitation products. Those products are CRU TS 2.0 (Climate Research Unit of the University of East Anglia); UDel Arctic (University of Delaware; Willmott & Matsuura, 2005); PREC/L (precipitation over the land); Vasclimo (Variability Analyses of Surface Climate Observations at the Global Precipitation Climatology Centre); and UW (University of Washington). Among the five products, the best fit to the length of discharge records is represented by UDel from 1930 to 2004, whereas UW covers the period from 1930 to 1989. Pavelsky & Smith (2006) demonstrate that discrepancies in long-term precipitation variability between UDel and UW are small compared with the discrepancies that exist between river discharge and any of the precipitation products. Working with historical data, we realize that any long-term assessment of precipitation variability depends on conventional gauge observations. We chose to use the original UDel product at the resolution 0.5° × 0.5°, since it yields a similar variability to other products and yet best represents the period of discharge records. The UDel monthly precipitation was summed over the year, and the basin average was calculated (Fig. 1).

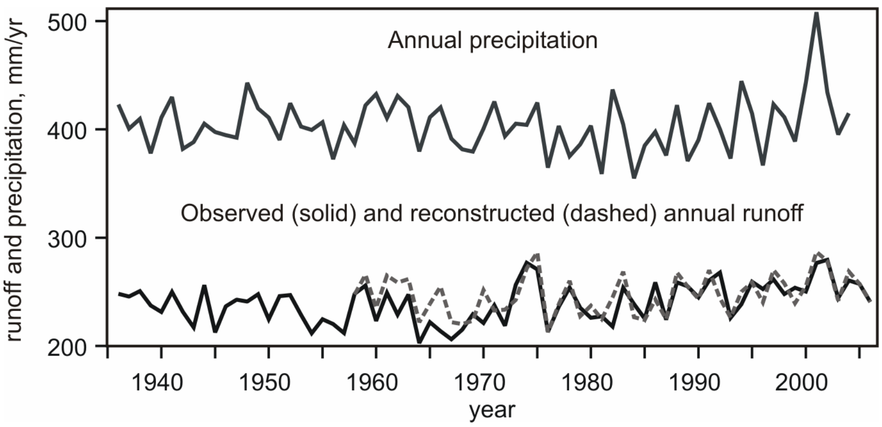

Fig. 1 Observed and reconstructed mean annual runoff and annual precipitation (mm/year).

METHODS

Assessment of reservoir impact on MAD

There are seven large (with capacity greater than 1 km^3) operational reservoirs in the Yenisei River watershed: Bratskoe (169.3 km^3), Irkutskoe (48.1 km^3), Krasnoyarskoe (73.3 km^3), Ust'-Ilimskoe (59.4 km^3), Sayano-Shushenskoe (31.3 km^3), Ust-Khantaiskoe (23.5 km^3) and Kureiskoe (9.9 km^3) (Malik *et al.*, 2000). After reviewing extensive Russian literature on streamflow regulation effects, we highlight a study by Shiklomanov & Veretennikova (1978), where decrease in the Yenisei River MAD was quantified based on reservoir parameters, the hydrological budget of each reservoir, and maps of mean evaporation. Evaporation increase was attributed to the additional evaporation from the reservoir's flooding zone and assumed no climate change. Shiklomanov & Veretennikova (1978) calculated actual MAD decrease from 1936 through 1970 and projected MAD decrease from 1971 through 2000 (Table 1). Their analysis was performed for all reservoirs with a volume greater than 0.05 km^3. Future projections were exaggerated; they assumed that total useful reservoir storage in the Yenisei and Lena River watersheds would increase by 900 km^3 by the end of the 20th century. In reality, only two large reservoirs in the Yenisei basin were filled after 1975: the Sayano-Shushenskoe (capacity 31 km^3) and Kureiskoje (capacity 10 km^3) (Malik *et al.*, 2000). The Bogucharskoe reservoir (58.6 km^3) is still under construction.

Table 1 Reduction in mean annual discharge (km^3/year) under the effect of economic activity (Shiklomanov & Veretennikova, 1978). Long-term (1936–2006) average MAD is 585 km^3/year.

Period of averaging	1936–1940	1941–1950	1951–1955	1956–1960	1961–1965	1966–1970	1971–1975	1976–1980	1981–1985	1986–1990	1991–2000
Evaporation	0	0	0	0.01	0.20	0.51	0.90	1.05	1.19	1.62	3.30
Storage	0	0	0	0.36	19.5	19.7	4.03	15.7	11.9	16.5	39.3
Total	0	0	0	0.37	19.7	20.2	4.93	16.7	13.1	18.1	42.6

RESULTS

Examination of mean annual discharge

Long-term MAD data from 1936 to 2006 allow us to separate the records into three similar periods in length, so as to represent different stages of streamflow regulation by reservoirs in the Yenisei River watershed. We examine the homogeneity of the mean, variance, and distribution function of MAD during these three periods: (1) natural regime (no streamflow regulation) from 1936 to 1956, (2) reservoir filling and initial operation (most of the dead volume was filled during this period) from 1957 to 1980, and (3) operation of reservoirs from 1981 to 2006 (Table 2). We assume that filling and operation of reservoirs with a capacity less than 1 km^3 cannot be detected in the annual discharge of the Yenisei River outlet because of its extremely large watershed area. The period of filling and initial operation in the Yenisei basin refers to 1957–1980, because six reservoirs with a total capacity of 404.9 km^3 were constructed and filled during this period. Afterward, only the Kureiskoje reservoir (9.9 km^3) was filled (from 1986 to 1990).

Table 2 Consistency analysis of mean, variance and distribution functions for natural streamflow regime, reservoir filling and operation periods.

Test	Natural	Filling and initial operation		Operation
Yenisei River	1936–1956	1957–1980		1981–2006
Length (years)	21	24		26
Mean (cubic km per year)	575	569		608
Coefficient of variation	0.06	0.09		0.06
Chi-square to normal distribution	h=0	h=0		h=0
F test	h=0 (p=0.066)		h=0 (p=0.251)	
T test	h=0 (p=0.636)		h=1 (p=0.003)	
Kolmogorov-Smirnov	h=0 (p=0.558)		h=1 (p=0.004)	
Yenisei River Reconstructed	1936–1956	1957–1980		1981–2006
Length (years)	21	24		26
Mean (cubic km per year)	575	592		611
Coefficient of variation	0.06	0.08		0.07
Chi-square to normal distribution	h=0	h=0		h=0
F test	h=0 (p=0.088)		h=0 (p=0.601)	
T test	h=0 (p=0.181)		h=0 (p=0.156)	
Kolmogorov-Smirnov	h=0 (p=0.145)		h=0 (p=0.073)	

The result h is 1 if the test rejects the null hypothesis at the 5% significance level (two-tailed tests); 0 otherwise. The p-value of a test is given in parentheses.

Hypothesis tests on equal mean (T test), variance (F test) and distribution function show that the biggest difference (23 km^3) between the reconstructed and observed mean MAD was detected during the second period "Filling and initial operation". Results show that streamflow regulation affected homogeneity of the mean in Yenisei MAD, causing lower observed MAD as if it would be without construction of reservoirs. Two tests (equal means and the same distribution functions) reject the null hypothesis at less than 5% significance level between "Filling and initial operation" (period 2) and "Operation" (period 3). Once the same hypothesis is tested on the reconstructed MAD, no tests are rejected (Table 2). This implies that the streamflow regulation does affect homogeneity of mean MAD and could influence trends detected in the observed MAD. Detailed trend analysis of the Yenisei River discharge (Shiklomanov & Lammers, 2009) showed that Sayano–Shushenskoe and Krasnoyarskoe reservoirs exert a considerable influence on MAD trend over the upper part of the river. Among others, Sayno-Shushenskoe and Krasnoyarskoe reservoirs are designed for long-term intra-annual streamflow regulation. These reservoirs are located upstream of confluence of the Yenisei and Angara rivers, in the upper part of the Yenisei River watershed.

Mean annual discharge and precipitation relationship

A linear fit between discharge and precipitation can explain 10 to 11% of the variability in the observed MAD (Fig. 2(a) and (b)) and 33 to 49% variability in the reconstructed MAD (Fig. 2(c) and (d)). The relationship between annual precipitation and MAD improves significantly for the reconstructed discharge, especially during the 1981–2004 period. Hydrological interpretations of discharge–precipitation scatter plots suggest that streamflow regulation in the Yenisei River watershed is strong enough to affect MAD response to precipitation. The reconstructed MAD reveals much higher R-squared in relation to precipitation, whereas observed records exhibit a weak linkage during reservoir operation. This shows that reconstruction is useful for describing river system response to the climatic forcing, particularly precipitation, in the Yenisei River watershed.

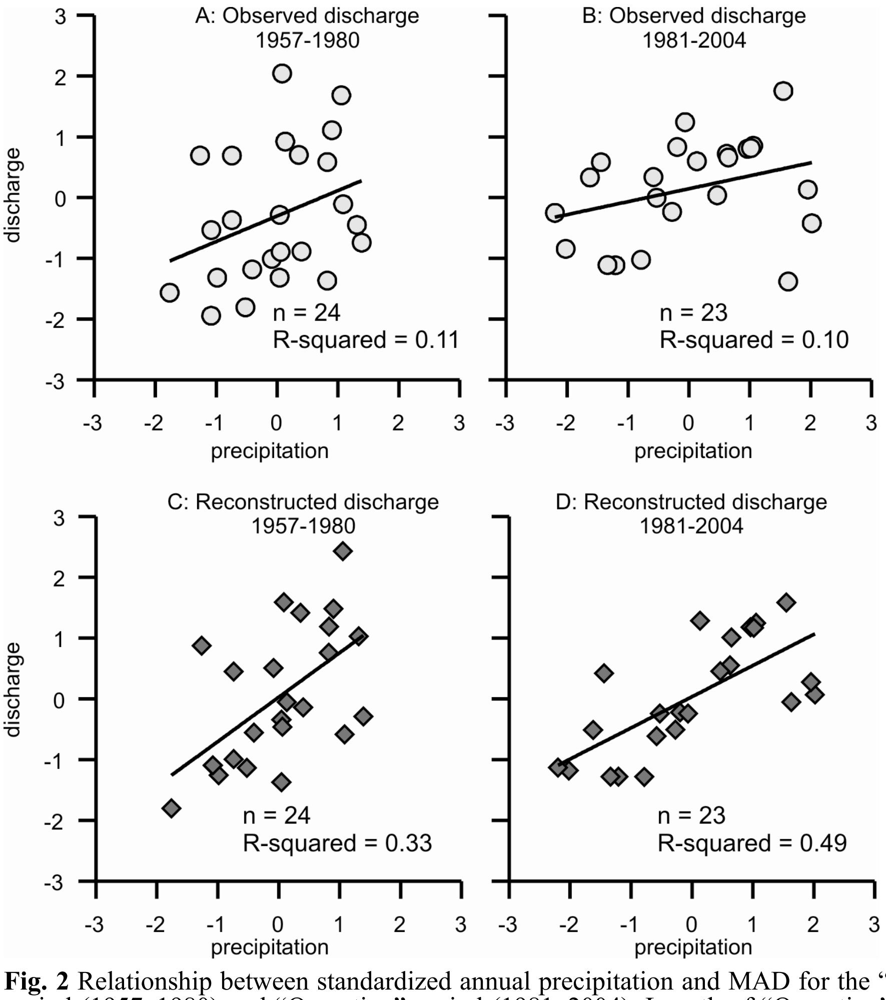

Fig. 2 Relationship between standardized annual precipitation and MAD for the "Filling & Operation" period (1957–1980) and "Operation" period (1981–2004). Length of "Operation" period is limited by precipitation data availability (1936–2004). We use the de-trended and standardized discharge and precipitation data (zero mean, unit standard deviation) so that they can be compared with each other.

CONCLUSIONS

Climate change and human activities affect watershed hydrology. We used reconstructed and observed discharge data to segregate climatic effects and the effect of streamflow regulation by reservoirs in the Yenisei River watershed. We demonstrate clear and visible changes in discharge records and in the discharge–precipitation relationship during three periods: (a) natural streamflow

(1936–1956), (b) filling of reservoirs (1957–1980), and (c) operation of reservoirs (1981–2006). Results show that the relationship between annual precipitation and mean annual discharge is distorted after 1957 due to construction and operation of large reservoirs. The interesting result is that long-term intra-annual streamflow regulation in the upper part of the Yenisei River watershed significantly affects mean annual discharge, even downstream at the outlet station Igarka, and distorts the relationship between discharge and basin-wide precipitation. We conclude that streamflow regulation resulting from construction and operation of reservoirs limits use of the observed Yenisei River discharge for climate change analysis not only at seasonal, but also at intra-annual time scale.

Acknowledgements The study was supported by the National Science Foundation grant ARC-0612334. Data support from the Arctic RIMS project is greatly appreciated.

REFERENCES

Adam, J. C. & Lettenmaier, D. P. (2007) Exploring the roles of precipitation and temperature changes on the variability of Eurasian arctic river discharge. *J. Geophys. Res*. **112**, D24114, doi:10.1029/2007JD008525.

Adam, J. C., I. Haddeland, F. Su & Lettenmaier, D. P. (2007) Simulation of reservoir influences on annual and seasonal streamflow changes for the Lena, Yenisei, and Ob' Rivers. *J. Geophys. Res.* **112**, D24114, doi:10.1029/2007JD008525.

Babkina, I. V. (1988) Economical use of reservoirs in the Angaro-Yenisei basin. In: *Siberian Water Resources: Study, Management and Control* (ed. by A. V. Petenkov), 94–99, Krasnoyarsk (in Russian).

Berezovskaya, S., Yang, D. & Kane, D. (2004) Compatibility of precipitation and runoff trends over the large Siberian watersheds. *Geophys. Res. Lett.* **31**, L21502, doi:10.1029/2004GL021277.

Berezovskaya, S., Yang, D. & Hinzman, L. (2005) Long-term annual water balance analysis of the Lena River. *Global Planet. Change* **48**, 84–95.

Dynesius, M. & Nilsson, C. (1994) Fragmentation and flow regulation of river system in the northern third of the world. *Science* **266**, 753–761.

Fekete, B. M., Vörösmarty, C. J., Roads, J. O. & Willmott, C. J. (2004) Uncertainties in precipitation and their impacts on runoff estimates. *J. Clim.* **17**, 294–304.

Kalinin, G. P., Kuchment, L. S. & Koren, V. I. (1969) Principles for elaboration of mathematical runoff models. In: *Floods and their Computation: Proceedings of the Leningrad Symposium*, vol.1, 60–65. UNESCO publication.

Malik, L. K., Koronkevich, N. I., Zaitseva, I. S. & Barabanova, E. A. (2000) Development of dams in the Russian Federation and NIS countries. A WCD briefing paper prepared as an input to the World Commission on Dams, Cape Town, www.dams.org.

McClelland, J. W., Holmes, R. M., Peterson, B. J. & Stieglitz, M. (2004) Increasing river discharge in the Eurasian Arctic: Consideration of dams, permafrost thaw, and fires as potential agents of change. *J. Geophys. Res,* **109**(D18), 10.1029/2004JD004583.

Nash, J. E. (1958) The form of the instantaneous unit hydrograph. In: *IAHS Darcy Symposium*, vol. 3, *Crues/Floods*, 114–118. Available at: www.iahs.info/redbooks/042.htm.

Pavelsky, T. M. & Smith, L. C. (2006) Intercomparison of four global precipitation data sets and their correlation with increased Eurasian river discharge to the Arctic Ocean. *J. Geophys. Res.* **111**, D21112, doi:10.1029/2006JD007230.

Rawlins, M. A., Willmott, C. J., Shiklomanov, A., Linder, E., Frolking, S., Lammers, R. B. & Vörösmarty, C. J. (2006) Evaluation of trends in derived snowfall and rainfall across Eurasia and linkages with discharge to the Arctic Ocean. *Geophys. Res. Lett.* **33**, L07403, doi:10.1029/2005GL025231.

Shiklomanov, A. I. (1996) Influence of human activity and climate change on runoff in the Yenisei River basin. PhD Thesis, Arctic and Antarctic Research Institute, St Petersburg, Russia.

Shiklomanov, A. I., Yakovleva, T. I., Lammers, R. B., Karasev, I. Ph., Vörösmarty, C. J. & Linder, E. (2006) Cold region river discharge uncertainty – estimates from large Russian rivers. *J. Hydrol.* **326**, 231–256.

Shiklomanov, A. I. & Lammers, R. B. (2009) Record Russian river discharge in 2007 and the limits of analysis. *Environ. Res. Lett.* **4**, 1–9.

Shiklomanov, I. A. (1978) Dynamics of anthropogenic changes in annual river runoff in the USSR. *Trudy GGI* **239**, 3–26.

Shiklomanov, I. A. & Veretennikova, G. M. (1978) Effect of reservoirs on the annual runoff of the rivers in the USSR. *Soviet Hydrology: Selected papers* **17**(1), 23–32.

Shiklomanov, I. A., Shiklomanov, A. I., Lammers, R. B., Peterson, B. J. & Vörösmarty, C. J. (2000) The dynamics of river water inflow to the Arctic Ocean. In: *The Freshwater Budget of the Arctic Ocean* (ed. by E. L. Lewis, E. P. Jones, P. Lemke, T. D. Prowse & P. Wadhamns), 281–296. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Willmott, C. J. & Matsuura, K. (2005) Arctic land-surface precipitation: 1930–2004 gridded monthly time series (v. 1.03). Center for Climatic Research, University of Delaware, Newark.

Yang, D., Ye, B. & Kane, D. (2004) Streamflow changes over Siberian Yenisey River basin. *J. Hydrol.* **296**, 59–80.

Yang, D., Kane, D., Zhang, Z., Legates, D. & Goodison, B. (2005) Bias-corrections of long-term (1973–2004) daily precipitation data over the northern regions. *Geophys. Res. Lett*. **32**, L19501, doi:10.1029.