11-23-2002

A circumpolar perspective on fluvial sediment flux to the Arctic ocean

Robert M. Holmes
Marine Biological Laboratory, Woods Hole

James W. McClelland
Marine Biological Laboratory, Woods Hole, MA

Bruce J. Peterson
Marine Biological Laboratory, Woods Hole, MA

Recommended Citation

Holmes, R. M., J. W. McClelland, B. J. Peterson, I. A. Shiklomanov, A. I. Shiklomanov, A. V. Zhulidov, V. V. Gordeev, and N. N. Bobrovitskaya, 2002: A circumpolar perspective on fluvial sediment flux to the Arctic Ocean, Global Biogeochemical Cycles, Vol.16(0), XXXX, doi:10.1029/2001GB001849, 2002.

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 16, NO. 4, 1098, doi:10.1029/2001GB001849, 2002

A circumpolar perspective on fluvial sediment flux to the Arctic Ocean

Robert M Holmes,[1] James W. McClelland,[1] Bruce J. Peterson,[1] Igor A. Shiklomanov,[2]
Alexander I. Shiklomanov,[3,4] Alexander V. Zhulidov,[5] Viatcheslav V. Gordeev,[6]
and Nelly N. Bobrovitskaya[2]

Received 12 December 2001; accepted 3 July 2002; published 23 November 2002.

[1] Quantification of sediment fluxes from rivers is fundamental to understanding land-ocean linkages in the Arctic. Numerous publications have focused on this subject over the past century, yet assessments of temporal trends are scarce and consensus on contemporary fluxes is lacking. Published estimates vary widely, but often provide little accessory information needed to interpret the differences. We present a pan-arctic synthesis of sediment flux from 19 arctic rivers, primarily focusing on contributions from the eight largest ones. For this synthesis, historical records and recent unpublished data were compiled from Russian, Canadian, and United States sources. Evaluation of these data revealed no long-term trends in sediment flux, but did show stepwise changes in the historical records of two of the rivers. In some cases, old values that do not reflect contemporary fluxes are still being reported, while in other cases, typographical errors have been propagated into the recent literature. Most of the discrepancy among published estimates, however, can be explained by differences in years of records examined and gauging stations used. Variations in sediment flux from year to year in arctic rivers are large, so estimates based on relatively few years can differ substantially. To determine best contemporary estimates of sediment flux for the eight largest arctic rivers, we used a combination of newly available data, historical records, and literature values. These estimates contribute to our understanding of carbon, nutrient, and contaminant transport to the Arctic Ocean and provide a baseline for detecting future anthropogenic or natural change in the Arctic. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1655 Global Change: Water cycles (1836); 1815 Hydrology: Erosion and sedimentation; 1836 Hydrology: Hydrologic budget (1655); *KEYWORDS:* Arctic rivers, sediment flux, land-ocean interactions, pan-Arctic watershed

Citation: Holmes, R. M., J. W. McClelland, B. J. Peterson, I. A. Shiklomanov, A. I. Shiklomanov, A. V. Zhulidov, V. V. Gordeev, and N. N. Bobrovitskaya, A circumpolar perspective on fluvial sediment flux to the Arctic Ocean, *Global Biogeochem. Cycles*, *16*(4), 1098, doi:10.1029/2001GB001849, 2002.

1. Introduction

[2] Concerns about global warming have stimulated a wide range of polar research. This research is motivated in part because climate change models predict greatest temperature changes in the future in polar regions [*Houghton et al.*, 1996], and because polar systems may be particularly sensitive to change [*Oppenheimer*, 1998; *Serreze et al.*, 2000]. Thus, polar ecosystems should provide early indications of anthropogenic influence on climate.

[3] Examination of inputs from arctic rivers (Figure 1) to the ocean has been proposed as a means for tracking the effects of climate change because fluxes from rivers provide an integrative signal of processes occurring in their watersheds. Most attention has been paid to the flux of fresh water (Table 1), where relatively complete long-term data sets are available and changes in climate are expected to influence annual flux and/or seasonality of inputs [*Aagaard and Carmack*, 1989; *Lammers et al.*, 2001; *Shiklomanov et al.*, 2000]. Constituent fluxes in rivers, including nutrients, organic matter, and suspended sediments may also be sensitive to global change [*Gordeev et al.*, 1996], but in general, constituent data sets have received less attention. In part, this lack of attention is because constituent data sets are relatively sparse compared to water discharge databases, and also because quality control problems have been identified in constituent data sets for some arctic rivers [*Holmes et al.*, 2000, 2001; *Zhulidov et al.*, 2000].

---

[1] Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, USA.

[2] State Hydrological Institute, St. Petersburg, Russia.

[3] Arctic and Antarctic Research Institute, St. Petersburg, Russia.

[4] Also at Water Systems Analysis Group, University of New Hampshire, Durham, New Hampshire, USA.

[5] Centre for Preparation and Implementation of International Projects on Technical Assistance, North-Caucasus Branch, Rostov-on-Don, Russia.

[6] P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia.

0886-6236/02/2001GB001849

Figure 1. Map of pan-arctic watershed showing drainage basins of the eight large rivers that are the focus of this paper and the mouth locations of 11 other arctic rivers that are discussed. The shaded landmass indicates the catchment of the Arctic Ocean including the Yukon River watershed.

[4] Reliable long-term records of constituent fluxes would provide insights into the functioning of the pan-arctic watershed and help to identify ongoing or future changes. The riverine flux of suspended sediments to the Arctic Ocean is one important metric of land-ocean interactions in the Arctic. Although numerous estimates now exist for sediment fluxes in arctic rivers (Table 2), published values for a given river often vary substantially, and the publications provide little information about how the estimates were actually derived. In many cases, it is not specified when the data were collected (Table 3), even though substantial changes in sediment fluxes can result from dam construction, deforestation, agricultural activities, dredging, and/or climate change [*Meade et al.*, 1990]. Propagation of old estimates into the recent literature does not take these changes into account. Moreover, several different methods are used for determining sediment concentrations and calculating sediment fluxes. These methods may yield different results, further confounding comparisons of flux estimates. Given the likelihood of significant temporal changes that are due to recent anthropogenic influences and the potential for differences in estimates depending on methodological approaches, interpretation of sediment flux estimates in the absence of detailed accessory information is tenuous. Nevertheless, accurate estimates of contemporary riverine sediment fluxes in the Arctic are fundamental to understanding land-ocean linkages, carbon, nutrient, and contaminant transport, and coastal processes, and are a prerequisite for detecting future natural or anthropogenic changes.

[5] Our overall objective is to provide a pan-arctic synthesis addressing sediment flux from large rivers toward the Arctic Ocean. We primarily focus on the eight largest rivers (by water discharge) in the pan-arctic watershed, namely the Yenisey, Lena, Ob', Mackenzie, Yukon, Pechora, Kolyma, and Severnaya Dvina rivers (Figure 1 and Table 1). Although the Yukon River does not discharge directly into the Arctic Ocean, it is included here because it makes major contributions of freshwater to the Arctic Ocean via prevailing ocean currents [*Guay and Falkner*, 1997; *Jones et al.*, 1998]. We begin with a review and synthesis of available information on methods of sample collection and approaches to flux calculations that have been used for these rivers, and then present graphically the sediment data sets that we have been able to compile for each river from published and unpublished sources. Using these sediment concentration and flux time series, we investigate the reasons for sometimes conflicting flux estimates in the literature, including the use of different time periods of data and/or data from different sampling locations on a given river. Finally, to the extent that available data allow, we provide best estimates of current sediment transport in the lower reaches of these eight rivers and consider whether there is evidence that sediment flux has changed significantly over the period of record. We also briefly address sediment flux from 10 smaller Russian Arctic rivers.

2. Sediment Sampling and Flux Calculations

[6] Guidelines for suspended sediment sampling and flux calculations prescribed by the major government agencies in Russia, Canada, and the United States that are responsible for monitoring river discharge and water quality are discussed below. The accuracy of sediment flux estimates, of course, depends on a variety of factors from how carefully samples are collected to how well sampling frequency and distribution capture the variability of the system. In most cases, information on these factors is not available for individual arctic rivers. This makes it difficult to retrospectively assess error associated with sediment flux estimates for the different rivers. The descriptions below do, however, allow a broad comparison of similarities and differences between sampling and data handling approaches

Table 1. Average Annual Water Discharge for the Eight Largest Rivers in the Pan-Arctic Watershed[a]

River	Gauging Station	Drainage Area Above Gauging Station, 10^6 km^2	Mean Annual Discharge, km^3/yr
Yenisey	Igarka	2.44	580 (620)
Lena	Kyusyur	2.43	528 (530)
Ob'	Salekhard	2.99	402 (404)
Mackenzie	Arctic Red	1.68	281 (307)
Yukon	pilot station	0.83	203 (205)
Pechora	Ust' Tsil'ma	0.25	108 (141)
Kolyma	Kolymskoye	0.53	103 (132)
Severnaya Dvina	Ust' Pinega	0.35	105 (105)

[a] Values are calculated using monthly discharge data as given in the R-ArcticNet database (www.r-arcticnet.sr.unh.edu) for the listed gauging stations. Values shown parenthetically include estimates of contributions from the entire watershed including nongauged areas.

Table 2. Published Estimates of Suspended Sediment Flux (in Million Metric Tons per Year) for Six of the Largest Arctic Rivers[a]

Reference	Yenisey	Lena	Ob'	Mackenzie	Yukon	Kolyma
1. *Shamov* [1949]	11.0		13.4			
2. *Lopatin* [1952]	^{1}11.0	11.7[b]	^{1}13.4			4.7[b]
3. *Samoilov* [1952]	^{1}11.0	12.0[b]	13.5[b]			4.7[b]
4. *Doronina* [1962]		11.8				
5. *Lisitzin* [1966]					88[c]	
6. *Moore* [1969]				15		
7. *Lisitzin* [1972]	13.2[d]	15.4[d]	15.8[d]	^{6}15[d]	^{5}88	6[d]
8. *Lisitsyna* [1974]	13.2	26.1	15			6.8
9. *Davies* [1974]				57		
10. *Davies* [1975]				199		
11. *Neill and Molland* [1980]				156		
12. *Milliman and Meade* [1983]	^{7}13.2	^{7}12	^{7}15.8	$^{9-11}$100	60	^{7}6
13. *Meade and Parker* [1985]					59[e]	
14. *Thomas et al.* [1986]				218		
15. *Brunskill* [1986]				118		
16. *Hirst et al.* [1987]				92		
17. *Hill et al.* [1991]				125[f]		
18. *Telang et al.* [1991]	14.5[b]	11.7[b]	13.4[b]			
19. *Milliman and Syvitski* [1992]	^{12}13.2	^{12}12	^{12}15.8	42[g]	^{13}60	
20. *Alabyan et al.* [1995]		21[h]				
21. *Ivanov and Piskun* [1995]		16.7–19.4				
22. *Gordeev et al.* [1996]	5.9	17.6	16.5		^{7}88	16.1
23. *Rachold et al.* [1996]		21[h]				
24. *Bobrovitskaya et al.* [1996]	4.2–12.4		15.1–16.6			
25. *AMAP* [1997]	^{22}5.9	^{22}17.6	^{22}16.5	^{19}42	^{19}60	^{22}16.1
26. *Mikhailov* [1997]	4.9–13.0	20.4	13.0			
27. *Carson et al.* [1998]				124[i]		
28. *Macdonald et al.* [1998]				$^{10,14-17,19}$118–230[j]		
29. *Walker* [1998]	13[b]	21[b]	16.5[b]	^{19}42	60[b]	8.2[b]
30. *Are* [1999]		^{4,20,21}11.8–21				
31. *Ivanov and Piskun* [1999]		16.3				10.1[k]
32. *Are and Reimnitz* [2000]		$^{4,20-22}$11.8–21				
33. *Meade et al.* [2000]			^{24}16			
34. *Brabets et al.* [2000]					54[e]	
35. *Gordeev* [2000]	^{22}5.9	^{22}17.6	^{22}16.5			^{22}16.1
36. *Rachold et al.* [2000]		$^{4,20-22}$11.8–21		^{15,17,27}118–128		
37. *Magritsky* [2001]		15.2–20				6.3–12

[a] References are in chronological order, and superscripts indicate relationships among the listed references. Lack of superscript indicates an original estimate calculated using data collected by Roshydromet (Russian rivers), Environment Canada (Mackenzie River), or the USGS (Yukon River), except where indicated by footnote. Where ranges are reported data are from multiple references, gauging stations, or time periods.

[b] Derivation of estimate unclear.

[c] According to A. P. Lisitzin (personal communication.), data from *Russell* [1890], *Lopatin* [1950], and *Samoilov* [1952] were used to derive this estimate.

[d] Although no source information is given by *Lisitzin* [1972], he reports the same sediment flux values in a later publication [*Lisitzin*, 1974], and cites *Zalogin and Radionov* [1969], *Shubaev* [1969], and *Moore* [1969] as the source of the estimates.

[e] Reported in original manuscript in short tons (1 metric ton = 1.102 short tons).

[f] From unpublished manuscript [*Lewis*, 1988].

[g] Was intended to read 142 Mt/yr as reported in an unpublished manuscript by J. P. M. Syvitski, but got mistyped.

[h] Estimate derived using combination of data from Roshydromet and Moscow State University.

[i] Bed load transport adds another 4 Mt/yr of sediment to the Mackenzie delta.

[j] Unpublished manuscripts by Carson (M. A. Carson, Mackenzie Delta sediment regime, unpublished manuscript, 1994a; M.A. Carson, Sediment flux model for the Mackenzie Delta, unpublished manuscript, 1994b) also cited. Value of 230 Mt/yr is incorrectly attributed to *Hirst et al.* [1987]. The origin of this value is unclear.

[k] Sum of model estimates for major delta channels.

that may contribute to differences between sediment flux estimates.

2.1. Russian Arctic Rivers

[7] The vast majority of sediment flux estimates for Russian arctic rivers are derived from data collected by the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). In various papers, data have been attributed to sources such as the Leningrad (St. Petersburg) Hydrometeorological Service, Hydrological Year Books, and State Hydrological Institute (SHI). In each case, however, the database appears to be the same. The different names correspond to different years of the record, and/or identification of the data source with differing degrees of specificity. Sampling programs for suspended sediments were started between 1935 and 1966 for different rivers.

[8] Methods of measurements of sediment concentration and discharge have been developed at the Laboratory of Sediments and Erosion within SHI. Guidelines for sampling from large Russian rivers call for daily collection of a single sample at a specific depth during low flow and twice daily

Table 3. Years of Record for Original Sediment Flux Estimates[a]

Reference	Yenisey	Lena	Ob'	Mackenzie	Yukon	Kolyma
Shamov [1949]	1942–1943		1938–1944			
Doronina [1962]		1936–1944				
Davies [1974]				1973		
Davies [1975]				1974		
Neill and Mollard [1980]				1973–1976		
Thomas et al. [1986]				1974–1976		
Brunskill [1986]				1973–1981		
Hirst et al. [1987]				1973–1984		
Lewis [1988]				1974–1983		
Ivanov and Piskun [1995]		1960–1990[b]				
Gordeev et al. [1996]	1970–1988	through 1990	1971–1988			through 1990
Rachold et al. [1996]		1975–1981				
Bobrovitskaya et al. [1996]	1941–1987[c]		1938–1990[c]			
Mikhailov [1997]	post-1967	1934–1981	1938–1992			
Carson et al. [1998]				1974–1994		
Ivanov and Piskun [1999]		1977–1993				
Brabets et al. [2000]					1975–1996	
Magritsky [2001]		1936–1992[b]				1966–1989[d]

[a] Only references that provide information about years are included. In many cases, data collection was not continuous during the range of years listed, and gaps in the records vary widely among references.

[b] Range represents the combined periods of record for sediment data collected at Kyusyur and several stations downstream for which separate estimates of sediment flux were made.

[c] Sediment flux estimates are given for multiple time frames within the period of record.

[d] Range represents the combined periods of record for sediment data collected at Srednekolymsk, Kolymskoe, and the top of the delta for which separate estimates of sediment flux were made.

collection of a single sample during high flow. During periods when suspended sediment concentrations are less than 100 g/m^3, two samples are combined and processed as one. When sediment concentrations are less than 50 g/m^3, single samples collected daily over a 5–10-day period are combined for processing. If concentrations are below 50 g/m^3 for longer periods of time, sampling is stopped until water discharge begins to increase. From these samples, an average concentration for the river is calculated using an equation that relates the particular sampling location to the river cross section as a whole. The equation is derived and periodically checked by sampling across the river at several depths or using a depth-integrating sampler. We could not obtain date-specific records of sampling at individual rivers, and thus it is difficult to say how the general guidelines described above translate into actual sampling efforts. Nonetheless, presence of data from individual months does put a lower bound on the number of samples collected within a year. The number of months per year that were sampled varies between rivers and over time for individual rivers, but was most consistently done from April through October.

[9] Guidelines for calculation of sediment discharge indicate two approaches. The first approach is a direct calculation of discharge from the cross-section representative concentration data and the corresponding water discharge measurements. This approach is suggested where measurements of suspended sediment have been made frequently. The second approach is indirect, using the relationship between measured sediment discharge and water discharge (sediment rating curves) to estimate sediment discharge on dates when only water discharge was measured. During early years of monitoring at least 15–20 measurements of suspended sediment discharge were made to generate rating curves. These measurements were skewed toward snowmelt and rainfall flood periods when sediment yield was greatest. Later, when relationships between sediment concentration and water discharge were determined to be constant over long time periods, 5–10 samples were used to yearly update the long-term rating curves. Specific information about these methods in relation to individual Russian arctic rivers is sparse, and either one or both methods may have been applied. The information that we do have indicates that sediment rating curves are routinely used on the Ob' River at Salekhard. In addition, estimates for the Lena and Kolyma made by *Magritsky* [2001] used sediment rating curves to fill in large gaps in the historical databases.

2.2. Mackenzie River

[10] Discharge of water and water-borne constituents to the Mackenzie delta have been monitored by Environment Canada since the early 1970s, and nearly all of the published estimates of sediment flux to the delta rely on the Environment Canada database. The monitoring network is maintained through a partnership between the federal and provincial governments. Some references identify Environment Canada directly, whereas others identify specific departments and initiatives of Environment Canada. Published estimates of inputs to the Mackenzie delta were derived using data from stations (1) in the Mackenzie River just above the confluence with the Arctic Red River, (2) in the Arctic Red River below Martin-house, and (3) in the Peel River at Fort McPherson. Where references refer to sediment discharge from the Mackenzie, it sometimes is unclear whether or not contributions from the Peel and/or Arctic Red were considered.

[11] Samples of suspended sediments generally were depth integrated, being taken from a single vertical in the river cross section where flow and depth were maximum. Samples also occasionally were collected from the surface

using 20 l carboys. A limited comparison of surface versus depth integrated samples indicated that surface samples yielded results within 20% of those obtained from depth integrated samples [*Brunskill et al.*, 1975], although studies elsewhere have shown that the difference can be greater. Collections primarily focused on the open water period from May to October each year. During this time period, the goal was to collect at least one sample per month. Difficulties associated with break-up and ice formation periods, however, resulted in less sampling during some months than others. In particular, data for May are scarce. During winter months, sampling through the ice was restricted to once or twice per year.

[12] Data on water discharge are more complete. Daily measurements of water level were generally recorded year-round. Flow was calculated from these data using a stage-discharge rating curve that was verified with direct flow measurements several times per year.

[13] Annual sediment discharge was estimated either directly or with sediment rating curves. Direct estimates involved calculation of monthly sediment discharge from average sediment concentration and water discharge for each month. Annual sediment discharge was then the sum of the monthly sediment discharges. In some instances, a seasonal mean concentration was used for months during which no concentration was measured. For the sediment rating curves, log(concentration) was plotted against log(water discharge) using existing data. From this relationship, daily mean suspended sediment concentrations were derived. These data were then used along with daily water discharge to calculate annual sediment discharge. Most references for the Mackenzie do not give specific information on data analysis, and hence it is difficult to determine if one or both approaches were used. As a general trend, however, it appears that early estimates were derived directly, while later estimates rely more heavily on sediment rating curves. *Carson et al.* [1998] provide a rare example where data handling is clearly described and errors of measurement and calculation are frankly discussed. In their case, estimates are derived from a combination of the two approaches.

2.3. Yukon River

[14] In the upstream Canadian portion of the Yukon basin, suspended sampling began in 1970 by Environment Canada, whereas sampling was initiated by the United States Geological Survey (USGS) at selected sites in the US part of the Yukon in 1953 [*Brabets et al.*, 2000]. However, suspended sediment sampling at the downstream-most sampling station (Pilot Station) did not begin until late in 1975. Periodic sampling by the USGS at Pilot Station continued until 1996, and approximately 70 suspended sediment measurements were made at Pilot Station during this period. The majority of data are from summer months, with few samples being collected during the period when the river is frozen over and none collected during May or November. No discharge or water quality sampling was done at Pilot Station from 1997 to 2000, but in 2001 the USGS NASQAN program resumed sampling at Pilot Station.

[15] According to USGS guidelines, suspended sediment concentration measurements are made by collecting a series of depth-integrated verticals across the stream channel. Mean discharge-weighted suspended sediment concentration in the river cross section was then determined by taking the average concentration of these verticals. Mean suspended sediment concentrations determined in this way, as well as daily water discharge values, are available free of charge from USGS at http://water.usgs.gov/nwis.

3. Data

[16] Our objective here is to present the data used to generate the sediment flux estimates in Table 2 and to provide more recent data where available. In most cases, the data are presented in a far more fundamental form than available in previous publications. Examination of the data at this level of detail is meant to help resolve conflicting flux estimates, allow assessment of interannual variability, aid in the detection of temporal trends, and facilitate estimation of contemporary fluxes.

[17] Water discharge monitoring on downstream reaches of arctic rivers began much earlier in the former Soviet Union than in North America (Figure 2). Gauging began in the 1930s on the Yenisey at Igarka, Lena at Kyusyur, Ob' at Salekhard, Kolyma at Srednekolymsk, and Pechora at Ust' Tsil'ma, and extends all the way back to 1881 for the Severnaya Dvina at Ust' Pinega. For the Mackenzie River, discharge measurements began in 1972 at the village of Arctic Red (Tsiigehtchic). Similarly, discharge measurements on the Yukon River at Pilot Station began in the mid-1970s.

[18] Consistent measurements of sediment flux at the downstream monitoring stations began much later than measurements of water discharge in Russian arctic rivers (Figure 2). The sediment flux record is fairly complete from the late 1960s through the mid 1990s for the Yenisey, Lena, and Kolyma rivers. In addition, there are a few years of coverage in the 1940s and 1950s for the Yenisey River. Coverage for the Ob' River is most complete, extending from 1938 to 1996 with few gaps. Far fewer measurements of sediment are available for the Pechora and Severnaya Dvina rivers. Data for these rivers come from the 1950s and 1980s. Sediment data for Russian rivers cover all months, but summer months were sampled in more years than were low flow months (Figure 3).

[19] Sediment measurements at downstream stations in the Mackenzie and Yukon rivers began simultaneous to water discharge observations and available data extend through the mid-1990s (Figure 2). Annual flux estimates in the Mackenzie River are reported by *Carson et al.* [1998] for the period 1974–1994, and the 1973 estimate comes from *Davies* [1974]. For the Yukon River, flux estimates for individual years have not been previously reported. Thus, sediment flux values for the Yukon River shown in Figure 2 were derived from a rating curve generated using USGS sediment concentration and discharge data and bias corrected using the smearing estimator [*Duan*, 1983].

[20] Sediment sampling was restricted to high discharge months (May through October) on the Mackenzie River (Figure 3), and monthly averages were generally derived

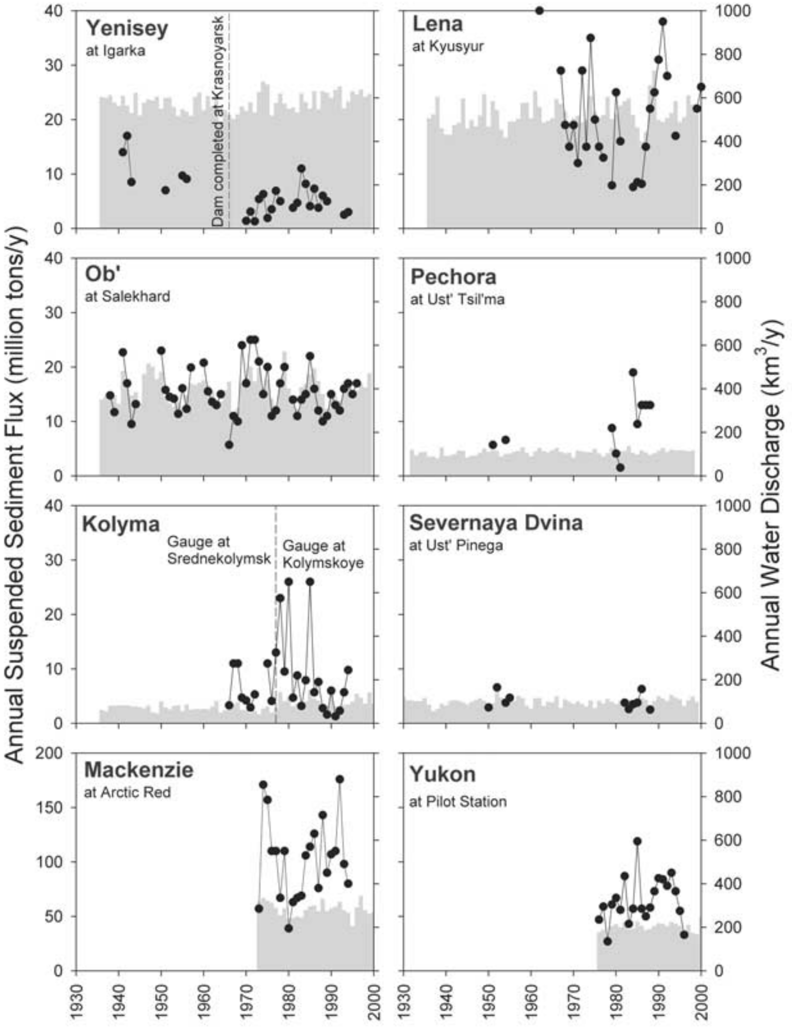

Figure 2. Time series of annual sediment flux (dots) and water discharge (histograms) estimates for the eight largest rivers in the pan-arctic watershed. Lines connect contiguous years within the period of record. Sediment values for Russian rivers are annual averages of monthly flux data provided by SHI. Sediment values for the Mackenzie River are from a compilation of annual values by *Carson et al.* [1998]. Sediment values for the Yukon River were derived from a rating curve generated using USGS sediment concentration and discharge data and bias corrected using the smearing estimator of *Duan* [1983]. In all cases, water discharge is calculated from monthly values available from R-ArcticNet (http://www.r-arcticnet.sr.unh.edu/), with updates provided by UNH. Note that the scales for sediment fluxes in the Mackenzie and Yukon rivers are five times larger than those of the other rivers.

from multiple samples collected throughout these months. However, sampling in May was sparse, presumably owing to complications associated with ice breakup. In fact, May samples were only collected during 4 years, and these samples were all collected in the final few days of the month. Yukon sampling also focused on the high discharge months, although no measurements were made in May, and August was sampled only in 2 years. Sediment measurements were also made during low flow periods of some years, but in contrast to those from the Mackenzie River, samples from the Yukon River at Pilot Station were never collected more frequently than once per month.

[21] Variations in sediment flux from year to year are substantial in most of the arctic rivers, but are more extreme at some rivers than others (Figure 2). The Lena, Ob', Kolyma, Mackenzie, and Yukon show the largest interannual variation, while the Yenisey, Pechora, and Severnaya Dvina have less variable sediment fluxes from year to year. In all cases, changes in annual sediment flux broadly track changes in annual water discharge. Long-term changes are not evident in the sediment flux data, with the exception of the Yenisey and the Kolyma rivers where single stepwise shifts have occurred. In the Yenisey, the shift is associated with construction of the dams, while in the Kolyma the shift is associated with use of data from a new gauge opened closer to the mouth.

[22] Sediment flux in all the eight largest arctic rivers is highest in late spring/early summer, and increases in sedi-

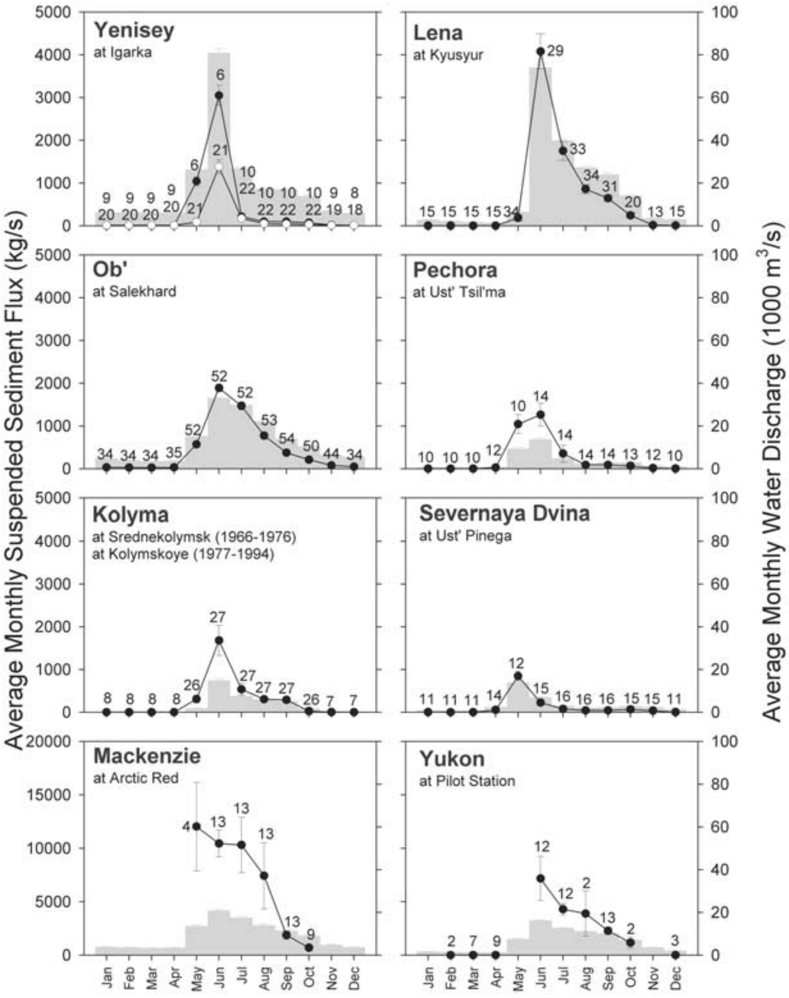

Figure 3. Average monthly sediment flux (dots) and water discharge (histograms) estimates for the eight largest rivers in the pan-Arctic watershed. Sediment values for Russian rivers are averages of monthly flux data provided by SHI. Sediment values for the Mackenzie River are monthly averages of date specific values from the Canadian HYDAT database. Sediment values for the Yukon River are monthly averages calculated using daily sediment concentration and water discharge values from the USGS on-line database. Water discharge values are averages of monthly values available from R-ArcticNet with the addition of more recent data provided by UNH. Numerals above sediment flux data points indicate number of months of data in averages. For the Yenisey River, closed circles represent pre-Krasnoyarsk dam averages whereas open circles represent postdam averages.

ment flux during the spring are generally steeper than declines during the fall (Figure 3). These seasonal changes generally track water discharge. The one clear exception to the pattern is the Yenisey, where sediment flux drops off very rapidly after the summer peak. This is evident in both the predam and postdam data.

[23] Sediment yield varies widely among the eight largest arctic rivers (Table 4). The Mackenzie and Yukon have much greater yields than the other rivers, and the Yenisey stands out with the lowest yield. These differences, at least in part, are linked to differences in sediment concentration among the rivers: plots of sediment concentration relative to water discharge (Figure 4) show that the Mackenzie and Yukon Rivers sort out distinctly from the Yenisey, Lena, and Ob' Rivers. The relatively narrow ranges of discharge in the Kolyma, Pechora, and Severnaya Dvina make these rivers more difficult to categorize in this way. Nonetheless, changes in suspended sediment concentration over their limited ranges of annual water discharge suggest that the Severnaya Dvina should be grouped with the larger Russian rivers, the Kolyma with the North American rivers, and the Pechora somewhere in between.

4. Discussion

[24] Long-term trends and explanations of conflicting sediment flux estimates are discussed for each of the eight largest arctic rivers below, and best contemporary estimates

Table 4. Best Estimates of Contemporary Average Annual Sediment Flux in the Eight Largest Arctic Rivers[a]

River	Station	Best Estimate of Contemporary Sediment Flux, Mt/yr	Confidence in Flux Estimate	Sediment Yield, t/km^2/yr	Source of Flux Estimate
Yenisey	Igarka	4.7	fair	1.9	this paper
Lena	Kyusyur	20.7	good	8.5	this paper
Ob’	Salekhard	15.5	good	6.4	this paper
Mackenzie	multiple sites[b]	124	good	74	*Carson et al.* [1998]
Yukon	pilot station	60	fair	72	R. H. Meade (personal communication)
Kolyma	Top of Delta	10.1	fair	19	*Ivanov and Piskun* [1999]
Pechora	Ust’ Tsil’ma	9.4	poor	38	this paper
Severnaya Dvina	Ust’ Pinega	4.1	fair	12	this paper

[a] Values are accompanied by a qualitative assessment of confidence in the flux estimate based on factors such as amount and consistency of data. For this assessment, we have assumed that sample collection and flux calculations were fundamentally sound.

[b] The Mackenzie estimate is for contributions to the Mackenzie Delta, which includes contributions from the Mackenzie River at Arctic Red (96 Mt/yr), the Arctic Red River at Arctic Red (7 Mt/yr), and the Peel River at Fort McPherson (21 Mt/yr).

are identified. These topics are then addressed in the context of the pan-arctic watershed and global change.

4.1. Yenisey River

[25] At ~620 km^3/yr water discharge and with a catchment area of over 2.5 million km^2, the Yenisey ranks among the largest rivers on Earth. Despite the massive size of the Yenisey River, its suspended sediment flux is low, with published estimates ranging from 4.2 to 14.5 Mt/yr (Table 2). By comparison, the Mississippi River, which has a lower annual water discharge (530 km^3/yr), now transports about 210 Mt/yr suspended sediment [*Meade*, 1996].

[26] Although annual sediment flux in the Yenisey River is remarkably small, there remains a relatively large range of values in the literature (Table 2). A primary cause of these divergent estimates is related to changes associated with dam construction. In 1967, a huge dam was completed on the Yenisey River near Krasnoyarsk (the Krasnoyarsk Dam), and several additional dams were completed on the Angara River (a major tributary of the Yenisey) in the 1970s [*Bobrovitskaya et al.*, 1996; *Meade et al.*, 2000]. Although these dams are more than 2500 km from the mouth of the Yenisey, they trap a significant portion of the Yenisey’s sediment flux. For example, after the construction of the Krasnoyarsk Dam, sediment flux at Divnogorsk (just downstream of the dam) dropped from 6.3 to 0.2 Mt/yr [*Lisitsyna*, 1974]. The impact of these dams is clearly evident in average monthly sediment fluxes far downstream at Igarka, where sediment fluxes during the month of greatest discharge (June) dropped by half after dam construction (Figure 3). As a result, annual flux estimates made using predam data are generally over 10 Mt/yr [*Lisitsyna*, 1974; *Samoilov*, 1952; *Shamov*, 1949], whereas the few published estimates using more recent data (Table 3) are less than 6 Mt/yr. Interestingly, although there is a clear separation between pre- and post-dam annual fluxes, there is a suggestion in the data that postdam fluxes may have increased from the late 1960s through the 1980s (Figure 2). Additional data will be required to determine if this trend has continued.

[27] The mean of the postdam data shown in Figure 2 for the Yenisey River at Igarka is 4.7 Mt/yr. This is the best contemporary estimate of sediment flux available, though our confidence in this estimate is only fair (Table 4), in part because it appears that annual fluxes were gradually increasing from the early 1970s through the 1980s, and also because we have no data after 1994. Our value is close to the postdam mean of 4.2 Mt/yr reported by *Bobrovitskaya et al.* [1996] based on data from 1970 to 1987 (Table 3), but our estimate contains additional data for 1988, 1989, 1993, and 1994.

4.2. Lena River

[28] Annual sediment fluxes in the Lena River at Kyusyur have ranged from 7.6 to 40 Mt/yr between 1962 and 2000, with a mean of 20.7 Mt/yr (Figure 2). Published estimates of average annual sediment flux in the Lena River at this

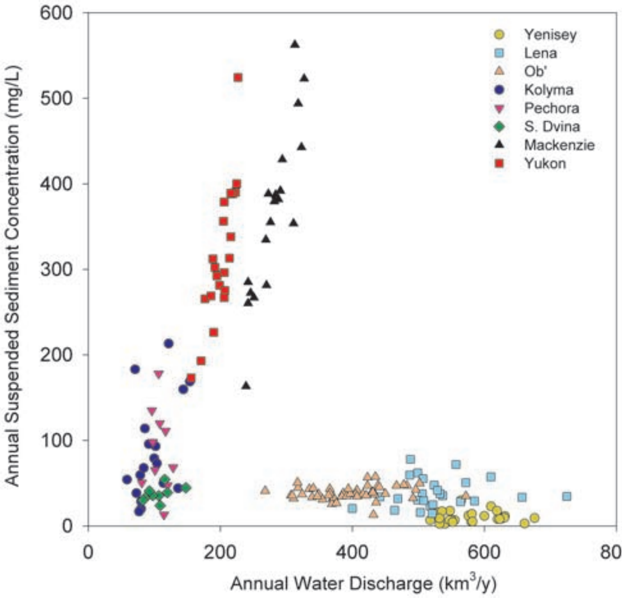

Figure 4. Annual sediment flux as a function of annual water discharge for each year of record in the eight largest Arctic rivers.

station range from 11.7 to 26.1 Mt/yr (Table 2). Interestingly, with the exception of *Lisitsyna* [1974], all pre-1995 publications give estimates of <16 Mt/yr whereas post-1995 estimates generally exceed 16 Mt/yr (Table 2), suggesting that sediment flux in the Lena River might have increased over the past several decades.

[29] However, there are no obvious long-term trends in the data presented in Figure 2, indicating that big changes have not occurred since the early 1960s. It remains possible, though, that sediment flux increased prior to 1962 when our data set begins. The earliest published estimates, such as those of *Lopatin* [1950, 1952] and *Doronina* [1962], use data collected prior to any that we have been able to access (Table 3). With access to these data and detailed information concerning how they were collected, it might be possible to determine if annual sediment flux has increased during the past several decades in the Lena River. However, given the great interannual variability apparent in the available data (Figure 2), such a conclusion in the absence of additional information is probably not warranted. In any case, the higher estimates seem to best represent contemporary conditions, and we consider the mean of annual fluxes shown in Figure 2 (20.7 Mt/yr) to be the best estimate of contemporary sediment flux in the Lena River (Table 4). Our confidence in this estimate is good. Although interannual variability is large, we have data from as recently as 2000 and thus have reasonable confidence that our estimate adequately represents current conditions. Moreover, a recent analysis by *Magritsky* [2001] yielded a similar estimate of average annual sediment flux at Kyusyur of 19.8 Mt/yr. To derive this estimate, Magritsky used a sediment rating curve to fill gaps in the sediment record between 1936 and 1992 (Table 3).

[30] There are conflicting reports in the recent literature concerning how much of the sediment transported by the Lena River reaches the Laptev Sea [*Are and Reimnitz*, 2000]. For example, one recent publication states that only 10–17% of the sediment in the Lena at Kyusyur makes it through the Lena Delta [*Alabyan et al.*, 1995], whereas another paper persuasively argues that essentially all of the Lena's suspended sediment reaches the Laptev Sea [*Rachold et al.*, 2000]. We do not know which of these views is correct, but a clear resolution is needed in order to adequately evaluate the impact of riverine sediment inputs to the Laptev Sea as well as to understand the sediment dynamics of the expansive Lena Delta.

4.3. Ob' River

[31] Although annual sediment flux in the Ob' River at Salekhard varied from 5.7 to 25 Mt/yr between 1938 and 1996 (Figure 2), published estimates of average annual fluxes have all been within a surprisingly narrow range, 13.0–16.6 Mt/yr (Table 2), even though the years of data included in the estimates varied substantially (Figure 3). Similarly, the average of all annual sediment flux data for the Ob' River shown in Figure 2 is 15.5 Mt/yr. The consistency of these estimates and the lack of apparent trend in the annual flux data (Figure 2) indicates that there have been no significant changes in annual sediment flux in the Ob' River since at least the early 1940s. Thus, we consider 15.5 Mt/yr to be a good estimate of contemporary sediment flux in the Ob' River (Table 4).

4.4. Kolyma River

[32] Published average annual flux estimates for the Kolyma River vary by almost 350%, from 4.7 to 16.1 Mt/yr, with the earlier estimates tending to be the lowest (Table 2). Part of the explanation for this wide range of estimates may be that earlier data were collected at Srednekolymsk, whereas later data were collected farther downstream at Kolymskoye. However, according to the data in Figure 2, the average of sediment flux values at Srednekolymsk (1966–1976) are 6.4 Mt/yr, compared to 9.2 Mt/yr at Kolymskoye (1977–1994), not a large enough difference to account for the variation among estimates. Interannual variability at Kolymskoye is large (1.3–26 Mt/yr, Figure 2), and thus differences in estimates are likely due to the specific years that were used to make the estimates. Unfortunately, this cannot be determined for certain because, with the exception of *Magritsky* [2001], none of the published estimates of sediment flux in the Kolyma are accompanied by information on years of data included (Table 3). *Magritsky* [2001] reports a value of 6.23 Mt/yr at Srednekolymsk using data from 1966 to 1976, and a value of 10.8 Mt/yr at Kolymskoye using data from 1977 to 1989. These values are very similar to ours, with the difference in the Kolymskoye values being due to the inclusion of 1990–1994 data in our estimate.

[33] *Ivanov and Piskun* [1999] point out that water and sediment flux measurements made at Kolymskoye do not take into account flow through the Stadukhinskaya branch of the river. Thus they develop a model to estimate sediment flux downstream in the river delta, where gauging is not routinely done. Data on water discharge (collected on expeditions by the All-Union Arctic Institute in 1934, 1935 and 1937, Arktikproject in 1953 and 1954, and Arctic and Antarctic Research Institute (AARI) in 1991) were used to design and regulate an "aerodynamic model" of the Kolyma delta. This model was then used to estimate the distribution of water discharges in the individual branches of the Kolyma delta on an annual basis. Finally, the model estimates of water discharges were used in conjunction with measured data on turbidity (collected on the same expeditions listed above) to derive sediment flux estimates for the individual branches of the Kolyma delta. These branch-specific fluxes were summed to estimate total sediment flux from the Kolyma. The estimate they finally arrived at is 10.1 Mt/yr, slightly higher than the average of annual fluxes measured at Kolymskoye (8.9 Mt/yr). Given that the estimate by *Ivanov and Piskun* [1999] includes contributions from the Stadukhinskaya branch of the river, we consider 10.1 Mt/yr to be the best estimate of contemporary sediment flux in the Kolyma River (Table 4).

4.5. Pechora River

[34] Although the annual water discharge of the Pechora River is only about one-fifth of that of the Yenisey River, it apparently transports a similar amount of sediment (Figure 2). Published estimates of average sediment flux in the Pechora River at Ust' Tsil'ma range from 6.5 Mt/yr [*Lopatin*, 1952] to 13.5 Mt/yr [*Gordeev et al.*, 1996], and the

average of the data presented in Figure 2 is 9.4 Mt/yr. Based on the data we have (Figure 2), it appears that annual sediment flux in the Pechora may have increased in the late 1980s, but data are very limited so it is not possible to determine with any certainty what the actual contemporary average annual sediment flux may be. We consider the mean of data presented in Figure 2 (9.4 Mt/yr) to be the best estimate of contemporary sediment flux in the Pechora River (Table 4), but have poor confidence in this estimate for the reasons discussed above.

4.6. Severnaya Dvina River

[35] As with the Pechora River, only limited annual sediment flux data are available for the Severnaya Dvina River (Figure 2). In contrast to the Pechora, however, the range of annual sediment fluxes in the Severnaya Dvina River at Ust' Pinega is rather low, 2.5–6.6 Mt/yr, with a mean of 4.1 Mt/yr for the data presented in Figure 2. The range of published estimates of average annual sediment flux is also low, ranging from 3.8 Mt/yr [*Gordeev et al.*, 1996] to 5.8 Mt/yr [*Lopatin*, 1952]. We consider 4.1 Mt/yr to be the best estimate of contemporary sediment flux in the Severnaya Dvina River, and although data are limited, have fair confidence in this estimate because interannual variability is relatively low (Table 4).

4.7. Mackenzie River

[36] The literature on sediment flux in the Mackenzie River is the most confusing of any large arctic river but at the same time is also the most complete. The confusion results from several factors. First, the range of published estimates of annual sediment flux in Mackenzie is huge, from 15 to 230 Mt/yr (Table 2). The earliest estimate [*Moore*, 1969] is also by far the lowest (15 Mt/yr), and this estimate was cited later by *Lisitzin* [1972]. According to *Moore* [1969], the original source of this estimate was the Department of Energy, Mines, and Resources, Ottawa, Canada. The highest estimate (230 Mt/yr) comes from *Macdonald et al.* [1998], who cite *Hirst et al.* [1987] as the source of the estimate. However, data given by *Hirst et al.* [1987] indicate that the average annual sediment flux to the Mackenzie Delta (1973–1984) is 92 Mt/yr. It should be noted, however, that Hirst et al. recognize this estimate to be low, and prefer the estimate of 126 Mt/yr reported by Lewis (C. P. Lewis, Mackenzie Delta sedimentary environments and processes, unpublished manuscript, 1988).

[37] A second source of confusion comes from a typographical error by *Milliman and Syvtiski* [1992], where sediment flux in the Mackenzie was printed as 42 Mt/yr instead of 142 Mt/yr as they intended (J. P. M. Syvitski, personal communication, 2001). Although this typographical error has been identified and noted in some subsequent publications [*Macdonald et al.*, 1998], other manuscripts have propagated the erroneous figure [*Arctic Monitoring and Assessment Program* (*AMAP*), 1997; *Meybeck and Ragu*, 1995; *Walker*, 1998].

[38] A third source of considerable variation in Mackenzie River sediment flux estimates results from different years of data used to derive the estimates (Table 3). This is particularly true for the earlier estimates, which often used only a few years of data. For example, estimates by *Davies* [1974, 1975], *Neill and Mollard* [1980], and *Thomas et al.* [1986] all use four or fewer years of data, which given the high interannual variability, leads to considerable differences in estimated fluxes.

[39] A final source of confusion relates to sampling stations. Sometimes estimates of Mackenzie River sediment discharge include contributions from the Arctic Red River (a tributary of the Mackenzie River which enters just downstream of the gauging station at the village of Arctic Red), and/or the Peel River (not technically a Mackenzie tributary but it does discharge into the Mackenzie Delta). Given the relatively large contributions of these two rivers (sediment transport is ~7 and 21 Mt/yr in the Arctic Red and Peel rivers, respectively), it is important to be clear whether their sediment fluxes are included in a Mackenzie River annual flux estimate.

[40] Although all of these sources of confusion are significant for the Mackenzie River, the paper by *Carson et al.* [1998] does an exemplary job of clearly describing the available data and documenting how sediment flux calculations were made. Moreover, sources of error and estimates of uncertainty are highlighted. *Carson et al.* [1998] estimate average annual sediment flux to be 103 Mt/yr for the Mackenzie River. This estimate includes ~7 Mt/yr from the Arctic Red River. The Mackenzie Delta also receives 21 Mt/yr from the Peel River. Thus, total average suspended sediment flux to the Mackenzie Delta is estimated to be 124 Mt/yr. We consider the estimates of *Carson et al.* [1998] to best represent contemporary sediment flux in the Mackenzie River (Table 4), and most other papers published since the mid-1990s report similar estimates (Table 2).

4.8. Yukon River

[41] Relatively few sediment flux estimates have been published for the Yukon River. The earliest estimate comes from *Lisitzin* [1966], who reported annual sediment flux to be 88 Mt/yr. According to A. P. Lisitzin (personal communication, 2001), data from *Russell* [1890], *Lopatin* [1950], and *Samoilov* [1952] were used to derive this estimate. The same value is later reported by *Lisitzin* [1972, 1974], *Gordeev et al.* [1996], and *Gordeev* [2000].

[42] The most commonly cited annual suspended sediment flux value for the Yukon River is 60 Mt/yr. *Milliman and Meade* [1983] were the first to publish this estimate, which they derived using data from Eagle (far upstream from the mouth of the Yukon) and from estimates of contributions from a major tributary, the Tanana River. *Meade and Parker* [1985] report a value of 65 million tons per year, but since this number comes from a USGS publication, the units are short tons, not metric tons as are more commonly used. To convert from short tons to metric tons, multiply by 0.907; thus, the estimate of annual sediment flux in the Yukon River by *Meade and Parker* [1985] is essentially identical to that reported by *Milliman and Meade* [1983] and in fact the difference is simply due to rounding (R. H. Meade, personal communication, 2001).

[43] The first estimate of Yukon River sediment flux made using sediment data collected at a downstream station was

Table 5. Summary of Sediment Flux Data for Additional Russian Arctic Rivers[a]

River	Station	Average Annual Discharge, km^3/yr	Period of Sediment Record	Years in Sediment Record	Average Annual Sediment Flux, Mt/yr	Sediment Yield, t/km^2/yr
Indigirka	Vorontsovo	50.4	1956–86	26	11.1	36.4
Taz	Sidorovsk	33.1	1969–75	4	0.7	7.0
Yana	Yubileynaya	32.2	1973–94	19	4.0	17.9
Olenek	71.8°N, 123.6°E	31.5	1968–94	21	1.1	5.6
Pur	Samburg	28.3	1941–81	26	0.7	7.4
Mezen	Malonisogorskaya	20.4	1949–87	5	0.6	10.7
Onega	Porog	15.7	1979–88	9	0.3	5.4
Anabar	Saskylakh	13.3	1967–90	23	0.4	5.1
Alezeya	Andryushkino	1.5	1980–92	12	0.1	3.4
Omoloy	Namy	1.1	1979–84	4	0.04	3.7

[a] Annual discharge estimates are derived using the R-ArcticNet database, and water discharge stations correspond to sediment observation stations.

also made by Meade and published by *Brabets et al.* [2000]. The estimate was derived using data from about 70 sediment samples that were collected at Pilot Station between 1975 and 1996. According to R. H. Meade (personal communication), he calculated an annual sediment flux at Pilot Station of 62.8 million short tons per year (56.9 million Mt/yr). Due to uncertainties related to limited data availability, he then rounded the estimate to 60 million short tons per year (54 million metric tons per year) as reported by *Brabets et al.* [2000]. Thus, Yukon River sediment flux estimates made in the early 1980s by Meade using upstream data, as well as more recent estimates made by Meade using data from Pilot Station, all are in the neighborhood of 60 Mt/yr. This value (60 Mt/yr) is probably the best estimate of contemporary sediment flux in the Yukon River at Pilot Station, although confidence in the estimate is only fair because of limited data.

4.9. Other Rivers

[44] In addition to the eight largest arctic rivers that we have emphasized in this paper, sediment inputs from smaller arctic rivers can also be substantial. We calculated average annual sediment flux from 10 of the smaller rivers in the Roshydromet network from historical records. These data are summarized in Table 5. Of the 10 rivers examined, the Indigirka, and Yana (Figure 1) stand out as having sediment fluxes comparable to those of the largest Russian rivers. *Gordeev et al.* [1996] give similar sediment flux estimates for the rivers listed in Table 5, though his values for water discharge are consistently higher than ours. This difference is due to estimates of additional inputs of water in downstream reaches of the rivers. These additional inputs of water do not appear to have been translated into greater sediment fluxes, possibly with the exception of the Alezeya and Omoloy Rivers.

[45] Historical sediment flux data for smaller North American arctic rivers is more scarce than for the Russian rivers, but the Colville River in Alaska (average annual water discharge 16 km^3/y according to *Meybeck and Ragu* [1995]) does provide one example (Figure 1). Sediment transport in this river was estimated to be 5.8 Mt/yr for 1963 [*Arnborg et al.*, 1967] and 4.1 Mt/yr for 1977 (calculated from data on USGS website). Although these values only represent 2 years, they nonetheless show the potential of the Colville to transport substantial amounts of sediment.

5. Synthesis

[46] According to the estimates given in Table 4, the combined average annual sediment flux of the eight largest arctic rivers is 249 Mt/yr. By comparison, estimates provided in other papers for these eight rivers yield combined flux estimates of 165 Mt/yr [*Lisitzin*, 1972], 175 Mt/yr [*AMAP*, 1997], and 178 Mt/yr [*Walker*, 1998]. In all cases, the majority of the difference between our estimate and the others comes from the Mackenzie River. In work by *AMAP* [1997] and *Walker* [1998], the Mackenzie values are erroneously low due to propagation of a typographical error from *Milliman and Syvitski* [1992]. The Mackenzie value given by *Lisitzin* [1972] is also unrealistically low.

[47] The eight rivers that have been the focus of this paper contribute ~65% of riverine freshwater inputs to the Arctic Ocean, but are they equally significant in terms of sediment flux? This is a difficult question to answer, largely because there is only limited data for smaller arctic rivers which may contribute disproportionally large amounts of sediment [*Milliman and Syvitski*, 1992]. *Gordeev et al.* [1996] provide the most complete list of estimates, with values presented for 20 Eurasian arctic rivers. In addition, they give flux estimates for other, presumably ungauged, areas in the Eurasian arctic. Their estimate of total sediment flux in Eurasian arctic rivers is 115 Mt/yr, whereas our estimate from the sum of the 16 Eurasian arctic rivers presented in Tables 4 and 5 is 84 Mt/yr. Ungauged areas and extra rivers included in the *Gordeev et al.* [1996] compilation account for over half of the difference between our estimate and theirs. The remaining difference is due to higher estimates for some rivers given by *Gordeev et al.* [1996] as compared to our new estimates. Regardless of this difference, it is clear that many rivers make substantial contributions to the total sediment flux from Eurasia to the Arctic Ocean. In contrast, it is highly likely that the Yukon and Mackenzie rivers carry most of the river sediment from the North American Arctic because they drain the areas of tectonism and active alpine glaciation that are the great generators of

fluvial sediment. Data from smaller rivers in North America are needed to confirm this.

[48] Although sediment yields vary greatly among arctic rivers (Tables 4 and 5), distinct geographical patterns are evident. The Yukon and Mackenzie rivers contribute only 21% of the combined annual water discharge of the eight largest arctic rivers (Table 1), but transport 73% of the suspended sediments. In contrast, the Yenisey, Lena, and Ob contribute 65% of the combined annual water discharge of the eight largest arctic rivers while transporting only 17% of the suspended sediments. Sediment yields in these three rivers have sometimes been considered anomalously low [*Milliman and Meade*, 1983], but in fact their yields are generally in line with what has been observed in other lowland rivers [*Milliman and Syvitski*, 1992].

[49] Variations in sediment concentration as a function of water discharge among the eight largest arctic rivers (Figure 4) also reflect geographical patterns. The drainage basins of the Mackenzie, Yukon, and Kolyma rivers share features of geology and climate that set them apart from the drainage basins of the Yenisey, Lena, Ob', Pechora, and S. Dvina rivers [*Gordeev et al.*, 1996; *Semiletov et al.*, 2000]. This division is broadly reflected in Figure 4, although the Pechora is an obvious exception. In any case, the distribution of rivers in Figure 4 reminds us that simply grouping rivers according to their continental affiliations can disguise functional differences.

[50] Although we have stated that we are addressing sediment flux to the Arctic Ocean, in fact we are using this phrase rather loosely. Instead, we are evaluating sediment flux in the downstream reaches of major arctic rivers, much of which may be retained in the marginal filter [*Lisitzin*, 1995]. The distribution of this sediment in deltas, estuaries, and the broad shelf of the Arctic Ocean is often unclear [*Bauch et al.*, 2001]. As pointed out earlier, there is considerable disagreement about the proportion of Lena River sediment that reaches the Laptev Sea, with estimates ranging from 10 to nearly 100% [*Alabyan et al.*, 1995; *Are and Reimnitz*, 2000; *Rachold et al.*, 2000]. For the Mackenzie, it has been estimated that about half of the river's suspended sediment is transported through the extensive Mackenzie Delta [*Macdonald et al.*, 1998], but it seems unlikely that a significant portion of the suspended sediment from the Yenisey and Ob' rivers is transported through their lengthy estuaries on annual timescales [*Meade et al.*, 2000]. Still less likely is a significant contribution of sediment from the Yukon River to the Arctic Shelf. Thus, whereas the flux estimates provided in this paper allow assessment of sediment flux from a large percentage of the pan-arctic watershed, further research will be needed to determine how much of this sediment actually reaches the sea.

[51] Variation among published sediment flux estimates for individual rivers (Table 2) can largely be attributed to differences in the years of record included or use of data from different sampling stations. Because sediment flux is highly variable from year to year, establishing reliable average annual values requires integration over at least decadal time frames. Trends in sediment flux over time are not evident, and thus in most cases long-term averages of sediment flux provide best contemporary estimates. Notable exceptions are the Yenisey and Kolyma Rivers, where stepwise shifts accompanying dam construction and a change in sampling location, respectively, make it necessary to use only more recent flux data to represent present conditions.

[52] Long-term increases in water discharge have already been detected at the pan-arctic scale [*Semiletov et al.*, 2000]. Given the dependence of sediment flux on water discharge, we would suspect that sediment flux might be increasing as well. The absence of identifiable long-term trends in sediment flux is likely linked to the variability in the data. Records of sediment flux are much shorter than those of water discharge, and frequently lack values for winter months when changes in water discharge are most evident. Longer-term data sets, and reduction in variation induced by sampling and data handling, will be needed to determine if long-term changes are indeed occurring.

[53] At present, it is unclear to what extent inconsistencies in sampling and data handling contribute to variations in the sediment data. A unique feature of arctic rivers that greatly complicates accurate determination of sediment flux is ice breakup. During the breakup period, suspended sediment sampling is very dangerous if not impossible, yet sediment fluxes may be substantial during these periods. We must somehow figure out a way to reasonably account for sediment fluxes during the breakup period. In the meantime, we must acknowledge this deficiency in current sediment flux estimates for large arctic rivers. A further confounding factor is that sample collection and flux calculation methods often vary among rivers and perhaps over time. Ideally, standard methods would be used throughout the pan-arctic catchment. Perhaps the closer cooperation emerging among arctic nations will facilitate standardization of sediment methods as well as protocols for other hydrologic and water quality parameters. At any rate, for sediment flux to be a useful metric of global change in the future, monitoring must continue and artifacts introduced by sampling and data handling must be minimized.

[54] Fluxes of water and waterborne constituents from arctic rivers to the ocean provide an integrative signal of processes occurring in their watersheds. Shifts in these fluxes over time give clues about natural and anthropogenic changes in the Arctic. Increases in water discharge may be linked to anthropogenic increases in greenhouse gases and associated climate change [*Miller and Rusell.*, 2000]. Waterborne constituents, such as nutrients and suspended sediments, provide information about alterations in biogeochemical processes accompanying climate and land-use changes. Compared to water discharge, however, analytical challenges and shorter time series of constituent data have made interpretation of long-term trends more difficult [*Holmes et al.*, 2000, 2001; *Zhulidov et al.*, 2000]. Thus, for many of these constituents our current challenge is not so much to identify historical trends but instead to establish a reliable contemporary baseline against which to evaluate future changes. In this paper, we have established contemporary sediment flux estimates for the eight largest arctic rivers. Together these values provide a baseline for sediment flux at the pan-arctic scale. This large-scale perspec-

tive is essential for understanding the effects of global change on the Arctic System as a whole.

[55] **Acknowledgments.** This research was funded by the Arctic System Science Program of the National Science Foundation (grants NSF-OPP-9524740, NSF-OPP-9818199, and NSF-OPP-0229302). We thank an anonymous reviewer and Bob Meade for their thoughtful reviews of the manuscript.

References

Aagaard, K., and E. C. Carmack, The role of sea ice and other fresh water in the arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498, 1989.

Alabyan, A. M., R. S. Chalov, V. N. Korotaev, A. Y. Sidorchuk, and A. A. Zaitsev, Natural and technogenic water and sediment supply to the Laptev Sea, *Rep. Polar Res.*, *176*, 265–271, 1995.

Arctic Monitoring and Assessment Program, Arctic pollution issues: A state of the Arctic environmental report, report, 188 pp., Oslo, 1997.

Are, F. E., The role of coastal retreat for sedimentation in the Laptev Sea, in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens et al., pp. 287–295, Springer-Verlag, New York, 1999.

Are, F., and E. Reimnitz, An overview of the Lena River Delta setting: Geology, tectonics, geomorphology, and hydrology, *J. Coastal Res.*, *16*, 1083–1093, 2000.

Arnborg, L., H. J. Walker, and J. Peippo, Suspended load in the Colville River, Alaska, 1962, *Geogr. Ann.*, *49*, 131–144, 1967.

Bauch, H. A., H. Kassens, O. D. Naidina, M. Kunz-Pirrung, and J. Thiede, Composition and flux of Holocene sediments on the eastern Laptev Sea shelf, Arctic Siberia, *Quat. Res.*, *55*, 344–351, 2001.

Bobrovitskaya, N. N., C. Zubkova, and R. H. Meade, Discharges and yields of suspended sediment in the Ob' and Yenisey Rivers of Siberia, in *Erosion and Sediment Yield: Global and Regional Perspectives, IAHS Publ.*, vol. 236, edited by D. E. Walling and B. W. Webb, pp. 115–123, Int. Assoc. Hydrol. Sci., Gentbrugge, Belgium, 1996.

Brabets, T. P., B. Wang, and R. H. Meade, Environmental and hydrologic overview of the Yukon River basin, Alaska and Canada, *Water Res. Invest. Rep. 99-4204*, 106 pp., U.S. Geol, Surv., Anchorage, 2000.

Brunskill, G. J., Environmental features of the Mackenzie system, in *The Ecology of River Systems*, edited by B. R. Davies and K. F. Walker, pp. 435–471, Dr. W. Junk, Dordrecht, Netherlands, 1986.

Brunskill, G. J., P. Campbell, S. E. M. Elliott, B. W. Graham, W. J. Dentry, and R. Wagemann, The chemistry, mineralogy, and rates of transport of sediments in the MacKenzie and Porcupine river watersheds, N.W.T. and Yukon, 1971–73, *Tech. Rep. 546*, 69 pp., Environ. Canada, Winnipeg, 1975.

Carson, M. A., J. N. Jasper, and F. M. Conly, Magnitude and sources of sediment input to the Mackenzie Delta, Northwest Territories, 1974–94, *Arctic*, *51*, 116–124, 1998.

Davies, K. F., Hydrometric data summary: Mackenzie River basin, 1973, *Environ. Soc. Comm. Rep. 74-8, Inf. Canada Cat. R57-6/1973*, 84 pp., Can. Task Force N. Oil Dev., Ottawa, Ont., 1974.

Davies, K. F., Mackenzie River input to the Beaufort Sea, *Tech. Rep. 15*, 72 pp., Can. Dep. of Environ., Beaufort Sea Project, Whitehorse, Yukon Territory, 1975.

Doronina, N. A., The rivers–Severnaya Yakutia (in Russian), *Trans. ARRI*, *236*, 193–222, 1962.

Duan, N., Smearing estimate–a nonparametric retransformation method, *J. Am. Stat. Soc.*, *78*, 605–610, 1983.

Gordeev, V. V., River input of water, sediment, major ions, nutrients and trace metals from Russian territory to the Arctic Ocean, in *The Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis, pp. 297–322, Kluwer Acad., Norwell, Mass., 2000.

Gordeev, V. V., J. M. Martin, I. S. Sidorov, and M. V. Sidorova, A reassessment of the Eurasian river input of water, sediment, major elements, and nutrients to the Arctic Ocean, *Am. J. Sci.*, *296*, 664–691, 1996.

Guay, C. K., and K. K. Falkner, Barium as a tracer of Arctic halocline and river waters, *Deep Sea Res., Part II*, *44*, 1543–1569, 1997.

Hill, P. R., S. M. Blasco, J. R. Harper, and D. B. Fissel, Sedimentation on the Canadian Beaufort Shelf, *Cont. Shelf Res.*, *11*, 821–842, 1991.

Hirst, S. M., M. Miles, S. P. Blachut, L. A. Goulet, and R. E. Taylor, Quantitative synthesis of the Mackenzie Delta ecosystem, in *Report to Inland Waters Directorate*, 23 pp., Environ. Canada, Yellowknife, Northwest Territories, 1987.

Holmes, R. M., B. J. Peterson, V. V. Gordeev, A. V. Zhulidov, M. Meybeck, R. B. Lammers, and C. J. Vörösmarty, Flux of nutrients from Russian rivers to the Arctic Ocean: Can we establish a baseline against which to judge future changes?, *Water Resour. Res.*, *36*, 2309–2320, 2000.

Holmes, R. M., B. J. Peterson, A. V. Zhulidov, V. V. Gordeev, P. N. Makkaveev, P. A. Stunzas, L. S. Kosmenko, G. H. Kohler, and A. I. Shiklomanov, Nutrient chemistry of the Ob' and Yenisey rivers, Siberia: Results from June 2000 expedition and evaluation of long-term data sets, *Mar. Chem.*, *75*, 219–227, 2001.

Houghton, J. T., L. J. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, *Climate Change 1995: The Science of Climate Change*, 584 pp., Cambridge Univ. Press, New York, 1996.

Ivanov, V. V., and A. A. Piskun, Distribution of river water and suspended sediments in the river deltas of the Laptev Sea, *Rep. Polar Res.*, *176*, 142–153, 1995.

Ivanov, V. V., and A. A. Piskun, Distribution of river water and suspended sediment loads in the deltas of rivers in the basins of the Laptev and East-Siberian Seas, in *Land-Ocean Systems in the Siberian Arctic: Dynamics and History*, edited by H. Kassens et al., pp. 239–250, Springer-Verlag, New York, 1999.

Jones, E. P., L. G. Anderson, and J. H. Swift, Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation, *Geophys. Res. Lett.*, *25*, 765–768, 1998.

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, and B. J. Peterson, Assessment of contemporary arctic river runoff based on observational discharge records, *J. Geophys. Res.*, *106*, 3321–3334, 2001.

Lisitsyna, K. N., Discharge of suspended sediments by rivers of Siberia (in Russian), *Trudy Gosudarstvennyi Gidrol. Inst.*, *210*, 48–72, 1974.

Lisitzin, A. P., *Processes of Modern Sedimentation in the Bering Sea* (in Russian), 574 pp., Nauka, Moscow, 1966.

Lisitzin, A. P., *Sedimentation in the World Ocean*, 218 pp., Soc. of Econ. Paleontol. Mineral., Tulsa, Okla., 1972.

Lisitzin, A. P., *Sedimentation in the Ocean: Quantitative Distribution of Sedimentary Material* (in Russian), 438 pp., Nauka, Moscow, 1974.

Lisitzin, A. P., The marginal filter of the ocean, *Oceanology*, *34*, 671–682, 1995.

Lopatin, G. V., Erosion and runoff of alluvia (in Russian), *Prioda*, *7*, 1950.

Lopatin, G. V., *Suspended Loads of the USSR Rivers–Formation and Transport* (in Russian), 368 pp., Publ. House of Geogr. Lit., Moscow, 1952.

Macdonald, R. W., S. M. Solomon, R. E. Cranston, H. E. Welch, M. B. Yunker, and C. Gobeil, A sediment and organic carbon budget for the Canadian Beaufort Shelf, *Mar. Geol.*, *144*, 255–273, 1998.

Magritsky, D. N., Natural and anthropogenic changes of hydrological regime in the lower streams and mouth of the biggest rivers of East Siberia (in Russian), Ph.D. thesis, Moscow State Univ., Moscow, 2001.

Meade, R. H., River-sediment inputs to major deltas, in *Sea-Level Rise and Coastal Subsidence*, edited by J. D. Milliman and B. U. Haq, pp. 63–85, Kluwer Acad., Norwell, Mass., 1996.

Meade, R. H., and R. S. Parker, Sediment in rivers of the United States, in *National Water Summary 1984*, pp. 49–60, U.S. Geol. Surv., Reston, Va., 1985.

Meade, R. H., T. R. Yuzyk, and T. J. Day, Movement and storage of sediment in rivers of the United States and Canada, in *Surface Water Hydrology*, edited by M. G. Wolman, and H. C. Riggs, pp. 255–280, Geol. Soc. of Am., Boulder, Colo., 1990.

Meade, R. H., N. N. Bobrovitskaya, and V. I. Babkin, Suspended-sediment and fresh-water discharges in the Ob and Yenisey rivers, 1960–1988, *Int. J. Earth Sci.*, *89*, 578–591, 2000.

Meybeck, M., and A. Ragu, *River Discharges to the Oceans: An Assessment of Suspended Solids, Major Ions and Nutrients*, 245 pp., U.N. Environ. Programme, Paris, 1995.

Mikhailov, V. N., *River Mouths of Russia and Adjacent Countries: Past, Present and Future* (in Russian), 412 pp., GEOS, Moscow, 1997.

Miller, J. R., and G. L. Russell, Projected impact of climate change on the Freshwater and salt budgets of the Arctic Ocean by a global climate model, *Geophys. Res. Lett.*, *27*, 1183–1186, 2000.

Milliman, J. D., and R. H. Meade, World-wide delivery of river sediment to the oceans, *J. Geol.*, *91*, 1–21, 1983.

Milliman, J. D., and J. P. M. Syvitski, Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers, *J. Geol.*, *100*, 524–544, 1992.

Moore, G. T., Interaction of rivers and oceans–Pleistocene petroleum potential, *Am. Assoc. Pet. Geol. Bull.*, *53*(12), 2421–2430, 1969.

Neill, C. R., and J. D. Mollard, Examples of erosion and sedimentation along some northern Canadian rivers, paper presented at International Symposium on River Sedimentation, Chin. Soc. of Hydraul. Eng., Beijing, China, 1980.

Oppenheimer, M., Global warming and the stability of the West Antarctic Ice Sheet, *Nature*, *393*, 325–332, 1998.

Rachold, V., A. Alabyan, H. W. Hubberten, V. N. Korotaev, and A. A. Zaitsev, Sediment transport to the Laptev Sea–hydrology and geochemistry of the Lena River, *Polar Res.*, *15*, 183–196, 1996.

Rachold, V., M. N. Grigoriev, F. E. Are, S. Solomon, E. Reimnitz, H. Kassens, and M. Antonow, Coastal erosion vs riverine sediment discharge in the Arctic Shelf seas, *Int. J. Earth Sci.*, *89*, 450–460, 2000.

Russell, I. C., Notes on the surface geology of Alaska, *Bull. Geol. Soc. Am.*, *1*, 99–162, 1890.

Samoilov, N. V., *River Mouths* (in Russian), 526 pp., Geographizadat, Moscow, 1952.

Semiletov, I. P., N. I. Savelieva, G. E. Weller, I. I. Pipko, S. P. Pugach, A. Y. Gukov, and L. N. Vasilevskaya, The dispersion of Siberian river flows into coastal waters: meteorological, hydrological and hydrochemical aspects, in *The Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis, pp. 323–366, Kluwer Acad., Norwell, Mass., 2000.

Serreze, M. C., J. E. Walsh, F. S. Chapin, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry, Observational evidence of recent change in the northern high-latitude environment, *Clim. Change*, *46*, 159–207, 2000.

Shamov, G. I., *Suspended Sediment Discharge of the USSR Rivers* (in Russian), *Proc. State Hydrol. Inst.*, vol. 20, 120 pp., State Hydrol. Inst., St. Petersburg, 1949.

Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, B. J. Peterson, and C. J. Vörösmarty, The dynamics of river water inflow to the Arctic Ocean, in *The Freshwater Budget of the Arctic Ocean*, edited by E. L. Lewis, pp. 281–296, Kluwer Acad., Norwell, Mass., 2000.

Shubaev, L. M., *General Physical Geography* (*Principles of Landuse*) (in Russian), 348 pp., Publ. House High School, Moscow, 1969.

Telang, S. A., R. Pocklington, A. S. Naidu, E. A. Romankevich, I. I. Gitelson, and M. I. Gladyshev, Carbon and mineral transport in major North American, Russian arctic, and Siberian rivers: The St. Lawrence, the Mackenzie, the Yukon, the arctic Alaskan rivers, the arctic basin rivers in the Soviet Union, and the Yenisei, in *Biogeochemistry of Major World Rivers*, edited by E. T. Degens, S. Kempe, and J. E. Richey, pp. 75–104, John Wiley, New York, 1991.

Thomas, D. J., R. W. Macdonald, and A. B. Cornford, Geochemical mass-balance calculations for the coastal Beaufort Sea, N.W.T., Canada, *Rapp. P. V. Reun. Comm. Int. Explor. Sci. Mer. Mediterr.*, *186*, 165–184, 1986.

Walker, H. J., Arctic deltas, *J. Coastal Res*, *14*, 718–738, 1998.

Zalogin, B. S., and N. A. Radionov, *The Mouth Areas of the USSR Rivers* (in Russian), 312 pp., Mysl', Moscow, 1969.

Zhulidov, A. V., V. V. Khlobystov, R. D. Robarts, and D. F. Pavlov, Critical analysis of water quality monitoring in the Russian Federation and former Soviet Union, *Can. J. Fish. Aquat. Sci.*, *57*, 1932–1939, 2000.

V. V. Gordeev, P. P. Shirshov Institute of Oceanology, Russian Academy of Sciences, 23 Krasikova, Moscow 117218, Russia. (gordeev@geo.sio.rssi.ru)

R. M. Holmes, J. W. McClelland, and B. J. Peterson, Ecosystems Center, Marine Biological Laboratory, 7 MBL Street, Woods Hole, MA 02543, USA. (rholmes@mbl.edu; jmcclelland@mbl.edu; Peterson@mbl.edu)

A. I. Shiklomanov, Water Systems Analysis Group, University of New Hampshire, Durham, NH 03824, USA. (sasha@eos.sr.unh.edu)

I. A. Shiklomanov and N. N. Bobrovitskaya, State Hydrological Institute, 23 Second Line, V.O., St. Petersburg 199053, Russia. (ishiklom@zb3627.spb.edu)

A. V. Zhulidov, Centre for Preparation and Implementation of International Projects on Technical Assistance, North-Caucasus Branch, 200/1 Stachki Avenue, #301, Rostov-on-Don 344104, Russia. (zhulidov@ncbcppi.rnd.runnet.ru)