Discharges and yields of suspended sediment in the Ob' and Yenisey Rivers of Siberia

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Abstract The northward-flowing rivers of Siberia deliver immense quantities of water but only relatively small quantities of sediment to the Arctic Ocean. The relatively low delivery of sediment to the ocean by these rivers is explained by the large areas of forest and swamp in their basins. In the Ob' River, sediment yields tend to increase between the headwaters and Kamen' na Obi. Further downstream, sediment yields gradually decrease. Near the mouth of the Ob' River, at Salekhard, sediment yield has remained constant at about 5.3 t km^{-2} $year^{-1}$. In the lower Yenisey River, the already small natural sediment yield of 5.4 t km^{-2} $year^{-1}$ has been decreased several fold by the construction of massive reservoirs on the main stem and on the tributary Angara River, and presently equals 1.8 t km^{-2} $year^{-1}$.

INTRODUCTION

Intensive collection of sediment data in the rivers of the Soviet Union (including Siberia) began during 1935-1938. The stations where sediment discharge is measured presently number about 240 in the Ob' River basin and about 220 in the Yenisey River basin. The rivers are divisible into three parts: the upper reaches where suspended sediment is mobilized; the middle reaches where sediment is transported, deposited, and remobilized downstream; and the lower reaches where sediment accumulates (Polyakov, 1935; Lopatin, 1939; 1952; Shamov, 1954).

During the years since 1935, methods have been developed for computing and estimating erosion, sediment yield, and sediment transport (Makkaveev, 1955; Lopatin, 1952; 1962; Listitsyna & coworkers, 1972; 1974; 1979; Bobrovitskaya, 1972; 1994; Bobrovitskaya & Zubkova, 1991). The very low discharges of river sediment from Siberia to the Arctic Ocean were first described by Lopatin (1952) and later confirmed by Alekseev & Lisitsyna (1974). These data on Siberian rivers were later summarized in a global context by Walling & Webb (1983) and by Milliman & Meade (1983). It is now clear that the great Siberian Rivers Yenisey and Ob', which rank sixth and thirteenth in the world in water discharge, rank among the world's lowest in sediment discharge.

This paper summarizes the sediment discharges in the middle and lower reaches of the Ob' and Yenisey Rivers and assesses their present sediment yields to the Arctic Ocean.

DATA SOURCES

The suspended sediment data discussed in this summary were collected at seven stations in the Ob' River basin and at five stations in the Yenisey River basin during the years 1938-1992. The data were compiled as yearly or monthly totals, and they are displayed here as tonnes per year or tonnes per month. The actual measurements from which these totals were computed were based on samples collected daily.

The daily samples are collected at a representative vertical in the cross section, from a single point at 0.6 depth below the water surface. The representative vertical is usually selected to be in that part of the cross section where water discharge is at a maximum. Its representativeness is established at the outset of sampling by an intensive series of 15-20 comprehensive measurements, each involving five verticals spaced across the section, and five samples (surface, bottom, and at 0.2, 0.6. and 0.8 depths) per vertical. The mean suspended concentration (*Sm*) computed from these 25 measurements is used to calibrate the daily concentration (*Sd*) collected at 0.6 depth at the representative vertical. The curve $Sm = K\,Sd$ is plotted, and used to compute the daily sediment discharge. The curve is reconfirmed every year by 15-20 comprehensive measurements. In some cases, the daily sediment discharge is computed from previously established rating curves of sediment versus water discharge.

The rivers are usually sampled for sediment only during the seven months of the year (April-October) that they are free of ice. Year-round studies have established that only 3-5% of the annual sediment load of these rivers is transported during the other five months, November-March. The histograms shown in the figures have been adjusted to include the sediment discharges during the coldest months.

OB' AND IRTYSH RIVERS

Figure 1 shows yearly sediment and water discharges measured at seven stations on the Ob' and Irtysh Rivers between 1936 and 1992. Whereas the water discharges at these stations increase steadily downstream, and the sequence of wetter and drier years is fairly consistent throughout the Ob' basin, the sediment discharges are significantly more variable, both spatially and temporally. Bobrovitskaya & Zubkova (1991) have shown that the data on water discharges and sediment yields throughout the Ob' and Irtysh basins can be grouped consistently into three periods (Table 1):

(a) Period I, the natural regime, 1938-1956;
(b) Period II, the beginning of intensive human activity in the river channels and basins, 1957-1970; and
(c) Period III, the initiation of environmental protection measures in basins and channels, 1971-1992.

Two reaches of the Ob' River and one of the Irtysh River are discussed below in more detail.

Belogor'ye to Salekhard

In the lowermost Ob' River, as measured in the 870 km reach between Belogor'ye and Salekhard, the discharge of water during an average post-1960 year *in*creased by about

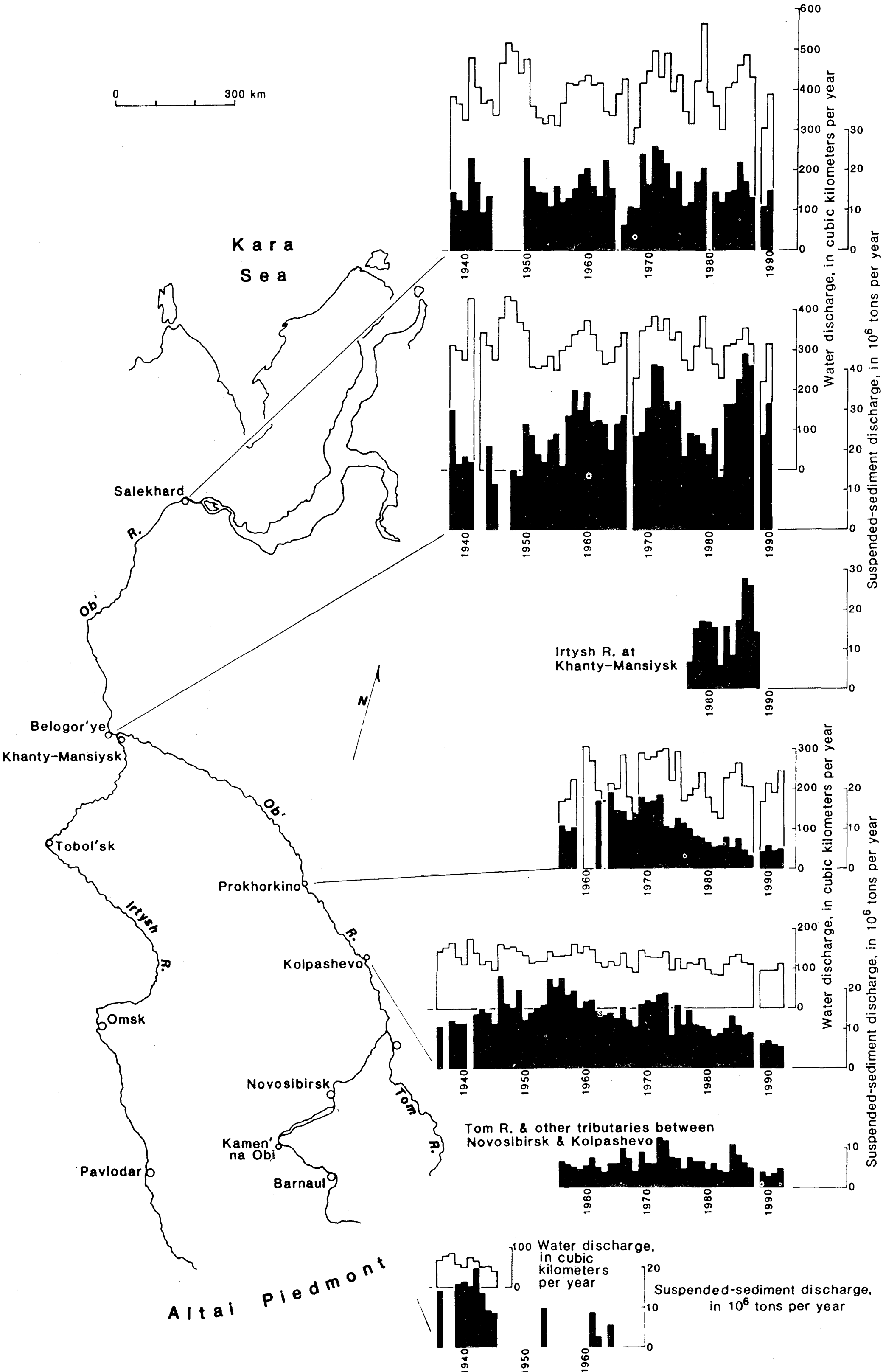

Fig. 1 Suspended sediment and water discharges in the Ob' River and selected tributaries, 1936-1992: annual suspended sediment discharges shown as solid bars; annual water discharges shown as open bars.

Table 1 Mean water discharges, suspended sediment discharges, and suspended sediment yields of the Ob', Irtysh, and Yenisey Rivers for different observation periods.

Station	Drainage area (10^3 km^2)	Period	Water discharge (km^3 year^{-1})	Suspended sediment discharge (10^6 t year^{-1})	Suspended sediment yield (t km^{-2} year^{-1})
Ob' River					
Barnaul	169		46	7.4*	45*
Kamen' na Obi	216		50	21.0*	97*
Kolpashevo	486	I 1943-1956	130	17.2	35.4
		II 1957-1970	127	14.9	30.6
		III 1971-1992	110	10.5	22.0
		Mean post-dam	118	12.7/16.0*	26.3/33*
Prokhorkino	738	II 1962-1970	160	15.6	21.1
		III 1971-1992	158	8.3	11.0
		Mean post-dam	159	12.0/16.0*	16.0/21*
Belogor'ye	2690	I 1938-1956	319	19.2	7.1
		II 1957-1970	324	27.5	10.2
		III 1971-1990	321	29.3	10.9
		Mean post-dam	322	28.4/23*	10.6/11*
Salekhard	2950	I 1938-1956	378	15.1	5.1
		II 1957-1970	388	15.8	5.4
		III 1971-1990	404	16.6	5.6
		Mean post-dam	396	16.2/15.0*	5.5/6.2*
Irtysh River					
Tobol'sk	1490	I 1938-1956	70	10.9	7.3
		II 1957-1970	66	10.3	6.9
		III 1971-1988	66	7.3	4.9
		Mean	67	9.5/11.0**	6.4/11**
Khanty-Mansiysk	1640	III 1977-1987	85	15.7	9.5
Yenisey River					
Kyzyl	115	I 1951-1966	33	1.3*	11*
		II 1967-1975	33	1.2	10
		III 1976-1987	31	1.2	10
Krasnoyarsk (Divnogorsk)	289	I 1955-1966	91	6.3*	22*
		II 1967-1975	82	0.2	0.8
		III 1976-1987	85	0.2	0.8
		Mean post-dam	83	0.2	0.8
Yeniseysk	1400	I 1948-1966	245	13.0*	9.3*
		II 1967-1975	244	4.5	3.2/3.4*
		III 1976-1987	228	3.8	2.7
		Mean post-dam	236	4.2	3.0
Podkamennaya Tunguska	1760	I 1956-1966	334	15.0*	8.5*
		II 1968-1975	348	5.4	3.1/3.4*
		III 1976-1987	332	5.0	2.8
		Mean post-dam	340	5.2	3.0
Igarka	2440	I 1941-1956	546	12.4/13.2*	5.1/5.4*
		II 1970-1975	589	3.2	1.3/2.0*
		III 1976-1987	571	5.3	2.2
		Mean post-dam	580	4.2	1.8

Asterisks mark sediment discharges and yields computed by Lisitsyna (1974): * entire drainage areas above gauging stations; ** drainage areas downstream of dams.

25% (from 322 to 396 km^3 $year^{-1}$) while the discharge of suspended sediment *de*creased by about 40% (from 28.4 $\times$ 10^6 t $year^{-1}$ at Belogor'ye to 16.2 $\times$ 10^6 t $year^{-1}$ at Salekhard). The most likely fate of the 12.2 $\times$ 10^6 t $year^{-1}$ of sediment that left the river during an average post-1960 year was deposition and storage on the 15 000 km^2 of flood plain (up to 50 km wide in some places) that lies between Belogor'ye and Salekhard.

The amount of sediment deposited annually on this flood plain has changed with time during the decades since 1938. Whereas water discharges at Belogor'ye have remained relatively constant during the full period of record, 1938-1990, the mean annual suspended sediment discharge has increased from 19.2 $\times$ 10^6 t $year^{-1}$ during the natural regime (1938-1956) to 28.4 $\times$ 10^6 t $year^{-1}$ during periods II and III (1957-1990). Meanwhile, the mean suspended sediment discharge at Salekhard increased only slightly: from 15.1 to 16.6 $\times$ 10^6 t $year^{-1}$. The increase at Belogor'ye is probably attributable to an increasing sediment yield to the Ob' River from the Irtysh River, but the record of sediment discharge of the Irtysh River at Khanty-Mansiysk is not long enough to confirm this supposition (Fig. 1, Table 1). Consequently, the quantity of sediment deposited on the flood plain increased from 4.1 $\times$ 10^6 t $year^{-1}$ under the natural regime (period I) to 12.7 $\times$ 10^6 t $year^{-1}$ under the more recent anthropogenic influence (period III).

Kolpashevo to Prokhorkino

A more complicated pattern of sediment storage seems to have prevailed in the reach of Ob' River between Kolpashevo and Prokhorkino. Sediment discharges in this reach have been influenced by the dam completed in 1957 at Novosibirsk, the capacity of which is sufficiently large to trap as much as 90% of the inflowing sediment (Avakyan, 1988; Brune, 1953). According to data obtained by Tkacheva (Laboratory of Sediments, State Hydrological Institute, 1974), about 70% of the sediment input from the Ob' River was trapped by the reservoir during 1961-1964. Offsetting some of the losses of sediment trapped in the reservoir are inputs from tributaries, such as the Tom and Chulym River, that enter the Ob' River between Novosibirsk and Kolpashevo. Lisitsyna (1974) listed the sediment discharge of the Tom River at Tomsk as 3.5 $\times$ 10^6 t $year^{-1}$. We estimate the total sediment discharge to the Ob' River from tributaries in this reach to equal 6.6 $\times$ 10^6 t $year^{-1}$ during a year of average water discharge.

Water discharge measured in the Ob' River at Prokhorkino during 1957-1992 was always 25-40% greater than that at Kolpashevo (Fig. 1). The suspended sediment discharge at Prokhorkino during the same years, however, has changed markedly. During 1957-1970, the suspended sediment discharge was slightly greater at Prokhorkino (15.6 $\times$ 10^6 t $year^{-1}$) than at Kolpashevo (14.9 $\times$ 10^6 t $year^{-1}$). During the 20-year period of record since 1970, the quantity of suspended sediment passing Prokhorkino (8.3 $\times$ 10^6 t $year^{-1}$) averaged about 20% less than that at Kolpashevo (10.5 $\times$ 10^6 t $year^{-1}$).

Tobol'sk to Khanty-Mansiysk

In the lowermost 600 km of the Irtysh River, in the reach between Tobol'sk and Khanty-Mansiysk, the suspended sediment discharge actually *in*creases downstream. During the

7 years in which suspended sediment data were available for both stations (1977-1979, 1984-1986, 1988), the water discharge between the two stations increased by about 30%, the suspended sediment discharge more than doubled, and the sediment yield increased by 60%. These increases in sediment are due largely to intensive bank erosion processes in this reach (Rossomakhin, 1963; Hendelman, 1994; Bobrovitskaya, 1994).

YENISEY RIVER

The Yenisey River (Fig. 2) discharges more fresh water to the sea than all but five of the world's major rivers. It discharges an average of 630 km^3 $year^{-1}$ into the Arctic Ocean (Vladimir I. Babkin, oral communication, 1994). For comparison, the seventh-ranked Mississippi discharges 580 km^3 $year^{-1}$, and the eighth-ranked Lena discharges 530 km^3 $year^{-1}$.

A remarkable feature of this great river is that it carries very little sediment. Even before the closure of the large dams at Krasnoyarsk and on the tributary Angara River, the mean annual sediment discharge measured in the Yenisey at the Podkamennaya Tunguska gauging station was only 15×10^6 t $year^{-1}$ (Lisitsyna, 1974, p. 69). This can be compared with the $400\text{-}500 \times 10^6$ t $year^{-1}$ of suspended sediment carried by the Mississippi River before so many reservoirs were built on its tributaries. The already low natural sediment discharge of the Yenisey was further decreased by large reservoirs. The Krasnoyarsk hydroelectric dam, whose reservoir is large enough to hold the water inflow of an average year, was completed in 1966. Lisitsyna (1974, p. 69) reported average sediment discharges at Divnogorsk (just downstream of the dam) to have been 6.3×10^6 t $year^{-1}$ before the dam was closed and 0.2×10^6 t $year^{-1}$ subsequently. The sediment records at Yeniseysk and Podkamennaya Tunguska shown in Fig. 2 clearly reflect the closure of the Krasnoyarsk dam in 1966. The second phase of large dam construction in the Yenisey River basin culminated during the 1970s with the completion on the Angara River of the massive reservoir at Bratsk and another just down river at Ust' Ilim.

Yeniseysk

The effects of these three large reservoirs on the down river discharges of sediment and water are best demonstrated by the data collected at the gauging station at Yeniseysk, which is about 50 km downstream of the Angara-Yenisey confluence. Data in the left column of Fig. 3 show the seasonal distributions of suspended sediment and water discharge before the completion of the reservoirs. These data are compatible with those reported by Lopatin (1952). Data in the middle and right columns of Fig. 3 show the reduced suspended sediment discharges after the construction of dams on the Yenisey (at Krasnoyarsk) and Angara Rivers. The mean annual water discharges were not reduced, but the seasonal distribution of water discharge was significantly modified (lower row, Fig. 3). Less water is now discharged during the peak months of May-July; more water is discharged during the cold months of November-April.

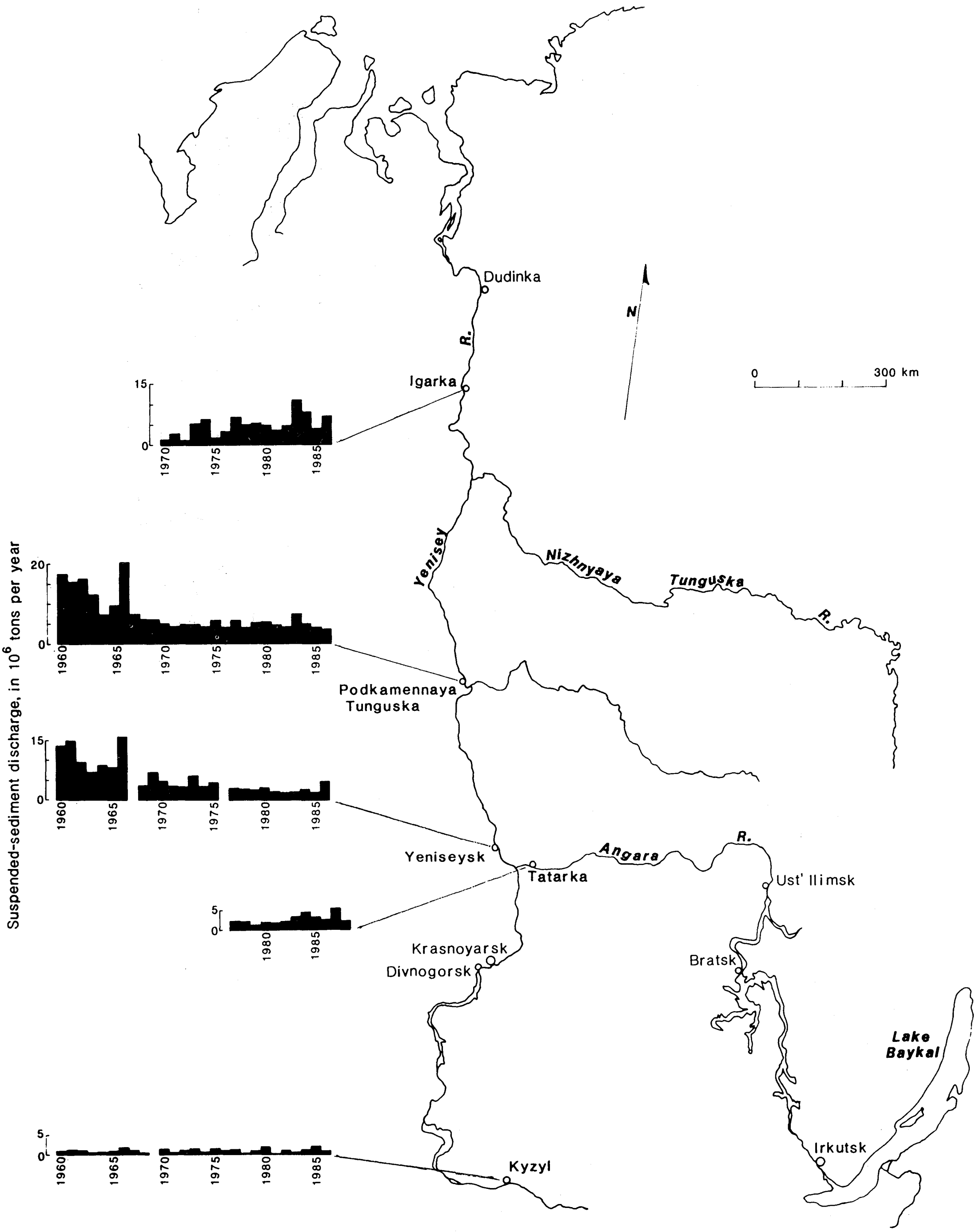

Fig. 2 Annual suspended sediment discharges measured at five gauging stations on the Yenisey and Angara Rivers during 1960-1988 (records were missing or incomplete at Yeniseysk during 1967 and 1976, and at Kyzyl during 1969).

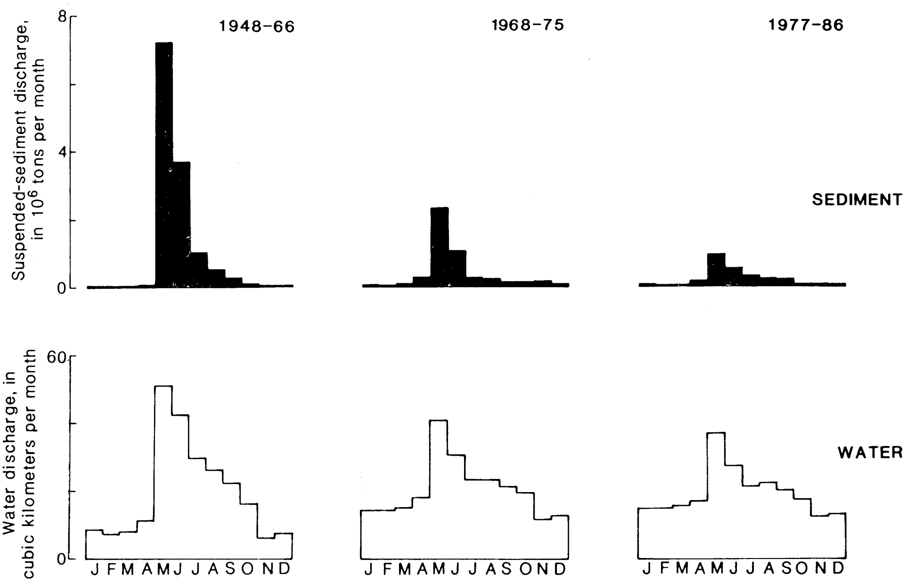

Fig. 3 Mean monthly discharges of suspended sediment (upper) and water (lower), for the Yenisey River at Yeniseysk. Data were grouped to represent conditions before construction of the dam at Krasnoyarsk (1948-1966), after the completion of the dam at Krasnoyarsk but before completion of the dam on Angara River at Ust' Ilim (1968-1975), and after completion of all major dams (1977-1986).

SEDIMENT YIELDS THE IN OB' AND YENISEY BASINS

In the Ob' River basin, sediment yields are greatest in the Altai Piedmont area. The specific sediment yield from the tributaries amounts to 320 t km^{-2} year^{-1}. In small basins drained by ephemeral streams, sediment yields range up to 7000 t km^{-2} year^{-1} (Bobrovitskaya & Zubkova, 1991). Along the main stem of the Ob' River itself, however, sediment yields do not exceed the maximum of 97 t km^{-2} year^{-1} that is observed at Kamen' na Obi (Lisitsyna, 1974).

As shown in Table 1, sediment yields measured in the Ob' River main stem decrease progressively down river of Kamen' na Obi, as the river collects the runoff from areas of low lying forest and swamp (Lopatin, 1952; Shamov, 1954). At the mouth of the river at Salekhard, in the zone of stable sediment accumulation, the sediment yield has remained virtually unchanged for the last 60 years.

The Yenisey River flows along the boundary between the West Siberian Lowland and the Middle Siberian Highland, making its way through erosion resistant rocks. Before the construction of the Krasnoyarsk Reservoir, sediment yields in the upper reaches of the river near Krasnoyarsk were 22-24 t km^{-2} year^{-1} while those in the middle and lower reaches were 5-9 t km^{-2} year^{-1}. After the construction of the reservoir in 1966, sediment yields decreased to 0.8 t km^{-2} year^{-1} in the upper reaches and 2-3 t km^{-2} year^{-1} in the middle and lower reaches. The zone of sediment accumulation is observed at Igarka.

REFERENCES

Alekseev, V. V. & Lisitsyna, K. N. (1974) Stok vzveshennyk nanosov (Discharge of suspended sediment). In: *Mirovoi Vodnyi Balans i Vodnye Resursy Zemli*, 510-516. Gidrometeoizdat, Leningrad.

Avakyan, A. B. (1988) Reservoirs of the USSR and tasks of their investigation. *Wat. Resour.* **6**, 538-549.

Bobrovitskaya, N. N. (1994) Assessment of trends to sediment discharge variations in the rivers of the Former Soviet Union (FSU). In: *Proc. Int. Symp., East-West, North-South Encounter on the State-of-the-Art in River Engineering and Design Philosophies*, 32-39. State Hydrological Institute, St Petersburg.

Bobrovitskaya, N. N. (1972) Zavisimost srednego mnogoletnego stoka bvzveshennykh nanosov rek ETS ot fiziko-geograficheskikh factorov. *Trudy Gosudarstvennyi Gidrol. Inst.* **191**, 68-84.

Bobrovitskaya, N. N. & Zubkova, K. M. (1991) Vodnoerosionnye prozessy na sklonakh i stok nanosov rek Altaiskogo raiya (Erosion of slopes and sediment discharge in rivers of the Altai region). In: *Doklady Sektsii Ruslovykh Protsessov Nauchnogo Soveta GKNT*, vol. 2, 104-127.

Brune, G. M. (1953) Trap efficiency of reservoirs. *Trans. AGU* **34**(3), 407-418.

Hendelman, M. M. (1994) The laws of meandering of the Irtysh River. In: *Proc. Int. Symp., East-West, North-South Encounter on the State-of-the-Art in River Engineering and Design Philosophies*, 140-149. State Hydrological Institute, St Petersburg.

Lisitsyna, K. N. (1974) Stok vzveshennikh nanosov rek sibiri (Discharge of suspended sediment by rivers of Siberia). *Trudy Gosudarstvennyi Gidrol. Inst.* **210**, 48-72.

Lisitsyna, K. N. & Aleksandrova, V. I. (1972) Sediment load of rivers in the European USSR. *Sov. Hydrol. Selected Pap.* **11**(2), 79-100.

Lisitsyna, K. N., Radionova, N. N. & Tkacheva, L. G. (1979) Variability of the annual suspended sediment discharge of rivers in the European USSR, Siberia and Soviet Central Asia. *Sov. Hydrol. Selected Pap.* **18**(4), 275-284.

Lopatin, G. V. (1939) K voprosu izuchenia tverdogo stoka rek SSSR (On the problem of solid discharge from the rivers of USSR). *Met. Gidrol.* **1**, 106-108.

Lopatin, G. V. (1952) *Nanosy Rek SSSR* (Sediment in Rivers of USSR). Zapiski vsesoyuznogo geogr. obshchestva, n. s., **14**, 1-366.

Lopatin, G. V. (1962) Intensität der Wassererosion auf dem Gebiet der Ud. SSR, 43-51. IASH Publ. no. 59.

Makkaveev, N. I. (1955) *Ruslo Reki i Erosia v ee Basseine* (River channel and erosion in its basin). Akad. Nauk SSSR, Moscow.

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

Polyakov, B. V. (1935) *Issledovanie Stoka Vzveshennych i Donnych Nanosov* (Investigations of yields of suspended and bedload sediments). Gidrometeoizdat, Leningrad.

Rossomakhin, M. V. (1963) Investigations of the shape of the valley of the Irtysh River in relation to the sediment and water stage regimes. *Sov. Hydrol. Selected Pap.* **2**(4), 336-355.

Shamov, G. I. (1954) *Rechnye Nanosy. Rezhim, Raschety i Metody Izmerenii* (River sediment. Regime, computation and the method of measurement). Gidrometeoizdat, Leningrad.

Walling, D. E. & Webb, B. W. (1983) Patterns of sediment yield. In: *Background to Palaeohydrology* (ed. by K. J. Gregory), 69-100. John Wiley, New York.