[AMERICAN JOURNAL OF SCIENCE, VOL. 296, JUNE, 1996, P. 664–691]

A REASSESSMENT OF THE EURASIAN RIVER INPUT OF WATER, SEDIMENT, MAJOR ELEMENTS, AND NUTRIENTS TO THE ARCTIC OCEAN

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ABSTRACT. A new assessment of water, suspended sediment, major elements, and nutrients discharged by rivers into the Arctic ocean is made. The comparison of this main characteristics of the river basins and water compositions between the two large Eurasian regions located westward and eastward of the Lena River shows some significant differences. Some eastern Siberian rivers such as Yana, Alazcya, Indigirka, Kolyma) . . . are even more similar to the Canadian Arctic rivers than to those located to the west of the Lena river. This river flows at the boundary between the Eurasian and North America tectonic plates. We concluded that tectonic/topographic factors could partly control the composition in suspended sediment of the Eurasian rivers. Tentative mass balances of major elements and silica do not indicate any significant trapping over the Arctic shelf. The river input of nutrients is shown to play a minor role in the primary productivity of this area.

INTRODUCTION

The river discharge from the Eurasian continent plays a key role in maintaining the stratification of the Arctic Ocean and in controlling the ice cover and deep-water formation which represent an important variable in the regulation of the global climate (Aagaard, Swift, and Carmark, 1985; Walsh, 1989). Various attempts have been made to understand better the role of the Arctic region in the global budget of fresh water, dissolved salts, alkalinity, and silicate (Mosby, 1963; Aagaard and Greisman, 1975; Rusanov and Shpaikher, 1979; Anderson and others, 1983; Walsh, 1989; Aagaard and Carmark, 1989; Anderson, Dyssen, and Jones, 1990). Such budgets require a better assessment of the river water discharge and of its chemical composition.

Data from systematic surveys on the regime and resources of surface waters in the framework of the former USSR Goskomgidromet and later of Roskomgidromet system are published in the State Water Cadastre year-books: "Resources of Surface Waters of the USSR," 1966–1973; "Multi-annual data on the regime and resources of surface terrestrial waters," 1982–1989.

Concerning the water and solid discharges from the Russian territory and from the world, several comprehensive textbooks have been considered: Voskresensky, 1962; Karzun, 1974; Lvovich, 1974.

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The total discharge of major ions, nutrients, and organic matter from the Russian territory was first assessed by Alekin and Brazhnikova (1964) and more recently complemented and refined by several authors (Maltseva, 1980; Romankevich and Artemyev, 1985; Maltseva, Tarasov, and Smirnov, 1987; Tarasov and others, 1988; Smirnov and others, 1988).

The aim of this paper is to provide a new evaluation of the discharge of river water and solids, major ions, organic carbon, and nutrients from the Eurasian land mass into the Arctic Ocean. This budget takes into account all the available data, including some unpublished values from the authors. This new budget for the Eurasian rivers is combined with literature data for the North American continent to build a new mass balance for the rivers discharging into the Arctic Ocean as a whole.

THE EURASIAN DRAINAGE BASIN OF THE ARCTIC OCEAN AND THE SPECIFICITY OF ITS CLIMATE AND GEOLOGY

The Eurasian part of the Arctic Ocean drainage basin covers $13.0 * 10^6 km^2$, including the Russian part of the Barents Sea (Ivanov, 1985).

We use in this budget the definition of an "arctic river" given by Pocklington (1987); that is, a "river which drains land within the Arctic climatic zone (10°C July isotherm) to the Arctic Ocean or to marine waters that flow into the Arctic Ocean and which are frozen at least two months of the year." The geographical boundaries considered in this study are shown figure 1. They include all of Greenland and Baffin Island within the Arctic but exclude southern Alaska, northern Scandinavia, and the Kola Peninsula. Water from the rivers draining the Arctic region of Canada into Hudson Bay does not enter the Arctic Ocean but feeds into the Labrador Current system and is carried southward (Pocklington, 1987). Then, the Yukon River, draining indirectly into the Arctic Ocean as a component of the Pacific water that enters the Arctic Ocean via the Bering Strait, is included. Transport through the Bering Strait is also directed to the north with a mean summer flow of $1.6 * 10^6 m^3 s^{-1}$, of which river runoff accounts for 10 percent (Hood, 1983).

The European part of the basin is characterized by the predominance of plains and lowlands, whereas in the eastern Siberian part mountainous landscape prevails (the highest point being the Pobeda Peak on the Chersky Ridge—3147 m above sealevel).

The major part of the Eurasian territory has a strongly pronounced continental climate. Mean January temperatures fall from −15° to −20°C along the coast of the White Sea to −40° to −45°C and even lower in the northeastern part of Yakutia.

The European part of the Arctic basin is under the Atlantic influence. The annual precipitation decreases from 750 to 880 mm in the southwest to 540 to 600 mm in the northeast. The Ural mountains prevent the Atlantic humid air masses from being transported to the eastern part of the Eurasian continent (Zhilg and Alyshinskaya, v. 3,

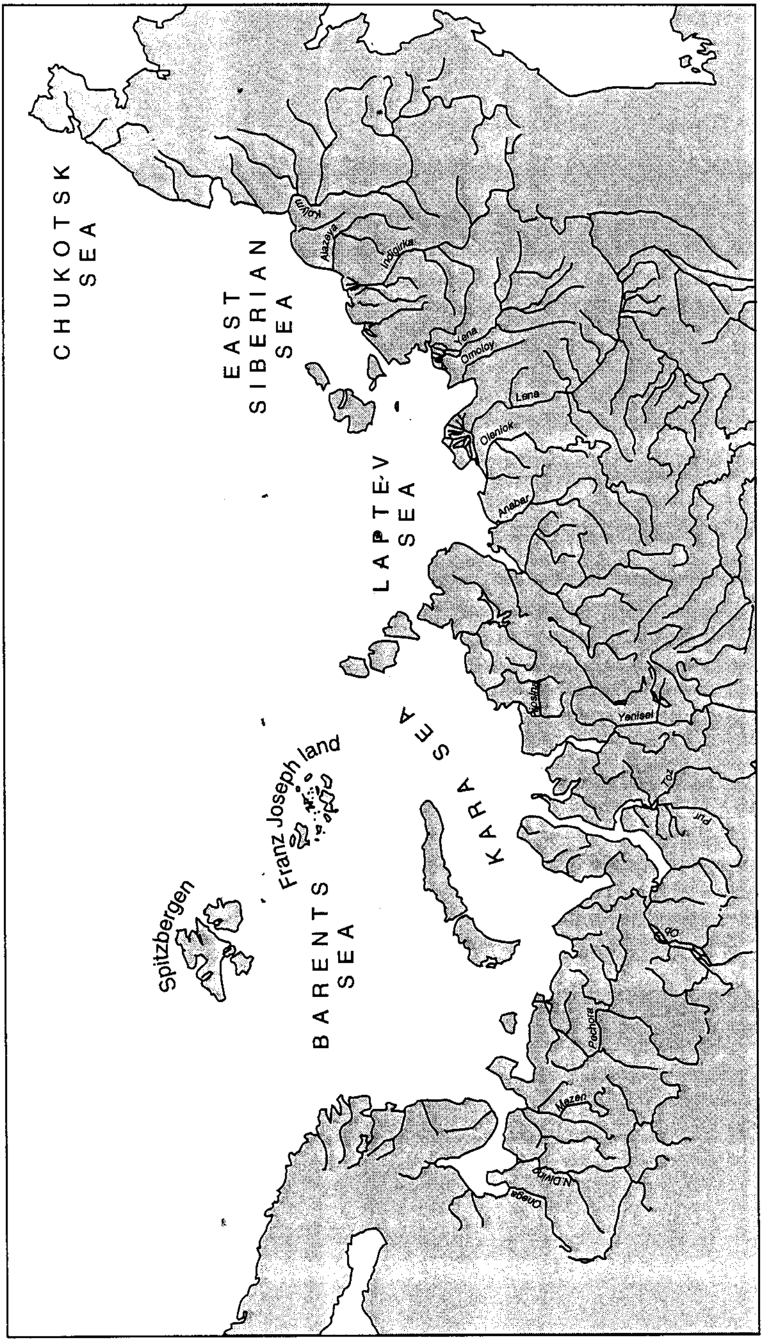

Fig. 1. Map of the Eurasian basin showing the major rivers flowing into the Arctic Ocean.

1972). The minimum annual precipitation occurs over the Siberian area. On the coast of the Kara, Laptev, and East Siberian Seas, the rainfall figures vary between 100 and 300 mm. Eastward, the amount of precipitation increases, reaching 500 mm, in connection with the Pacific influence (Kuprianov, v. 19, 1969). The maximum annual rainfall is over the Western and Eastern Sayan mountains (700-2000 mm) and along the eastern slope of the Putorano Plato in the Middle Siberian flat-mountain region (1200-1600 mm), which encompasses the largest part of the Pyasina River drainage basin. However, the same mountains represent an obstacle to the penetration of humid air masses into the central part of the Yenisei River drainage basin.

The multi-annual permafrost-permeated rocks are very widespread over the Eurasian basin and have a substantial impact on the water balance, playing the role of a water-resistant layer which increases the specific water discharge.

As far as vegetation is concerned, the basin is divided into 4 zones: the tundra, the forest-tundra, the forest (taiga), and the bald rocky terrain, the latter being determined by the elevation above sealevel.

A characteristic feature of the Eurasian Arctic basin is a combination of geological structures of different origin and history: the East-European and Siberian platform and the folded areas, respectively. They are composed of terrigenous, carbonate, chemogenic, and volcanic sedimentary rocks from the Archean to the Quaternary age (Markov, 1985). Also occurring are the easily washed out evaporite deposits (gypsum, anhydrite, halite, salt, rock), which generate highly mineralized ground waters to exert a marked influence on the chemical composition of river water, for example, in the middle reaches of the Lena River (Gordeev and Sidorov, 1993).

The thermal regime of the Arctic basin rivers depends on climate, subsoil water temperatures, areas of permafrost, and on the distribution of lakes and glaciers. The Eurasian Arctic rivers that are meridionally directed have a characteristic flood surge wave moving northward, breaking up ice and causing ice dams and high water levels. The rivers of the European part of the basin have an ice cover during 4 to 6 months. In contrast, the Siberian rivers have a thick ice cover (more than 2 m thickness) during 8 months. The small Siberian rivers are totally frozen in winter (October-May).

MATERIALS AND METHODS

The water runoff and total suspended matter have been calculated using the Roskomgidromet network up to 1985 for the Chukchi Sea basin, up to 1988 for Barents, White, and Kara Sea basins, up to 1990 inclusive for the Laptev and East Siberian Sea basins.

Materials and methods.—TSM was determined by filtering water through paper filters (so-called "blue tape") with a pore size of about 1.0 to 1.5 μm so as to collect a minimum weight sample of 0.1 g (Goskomgidromet, 1977). About 20 samples were collected monthly along several selected cross sections both at surface and at various depthes. Each 10 days at winter time and 5 days during other seasons, one large volume sample was taken. Samples of 1 liter volume were collected and filtered through 0.45 μm poresize membrane filters (SINPORE, Czechoslovakia) for the nutrient elements analysis.

Organic matter in the Laptev and East Siberian Sea basin rivers has been determined in unfiltered river waters by means of bichromate and permanganate oxidations in an acidic medium (Semenov, 1977). The Total Organic Carbon (TOC) was measured by bichromate oxidation and the ratio between bichromate and permanganate oxidations (Skopintsev and Goncharova, 1988).

The flux of TOC for the rivers of the Barents, White, Kara, and Chukchi Seas was calculated for the period 1971 to 1980. To determine the TOC flux into the ocean from these rivers over a period of one year, the multi-year average water discharge for a definite period was multiplied by the multi-year mean values of TOC content for the same period. The average multi-year flux of TOC was obtained by adding the TOC flux during three periods: winter, spring (high water), summer, and autumn. The total delivery of TOC into the ocean was determined by summation for these periods (Maltseva, Tarasov, and Smirnov, 1987). Nutrient fluxes to the Laptev and East Siberian Sea rivers have been computed in a similar way but for the period 1985 to 1990.

The TOC flux to the Laptev and East Siberian Seas by rivers was calculated for the period 1985 to 1990. The long-term monthly fluxes of TOC were computed by averaging the monthly fluxes over six years. The total discharge of TOC into the Arctic Ocean was determined by summation of the long-term monthly fluxes of TOC.

The major ion fluxes were calculated as well as TOC flux for the Laptev and East Siberian Sea basins, 1976 to 1985 for the Barents and White Sea basins, 1971 to 1980 for the Kara Sea basin, and 1980 to 1990 for the Laptev and East Siberian Sea basins.

WATER AND SUSPENDED-SEDIMENT DISCHARGE INTO THE EURASIAN ARCTIC SEAS

Our data on the discharge of river water and suspended sediment into the Arctic Seas from the Eurasian land mass are listed in table 1. The largest rivers of the Eurasian Arctic, as regards the annual water discharge (over 100km^3), are the Yenisei (620km^3), Lena (525km^3), Ob (429km^3), Kolyma (132km^3), Pechora (131km^3), Northern Dvina (110km^3) (fig. 1). Together, these 6 rivers provide more than 60 percent of the annual water discharge from the Eurasian territory into the Arctic Ocean. The long-term multi-annual runoff of the largest rivers discharging into the Arctic, as well as their total major ion discharge, generally referred to as TDS (total dissolved solids), solid discharge (TSM), and total organic carbon (TOC) discharge are shown in figure 2.

The specific water discharge into the Arctic Ocean from the Eurasian land mass decreases from west to east, from 9 to 13 l s^{-1} km^{-2} for the Barents and White Sea basin to 4 to 7 l s^{-1} km^{-2} for Laptev and East-Siberian Sea basin, with an average of 7.3 l s^{-1} km^{-2}. The rivers that

TABLE 1

Total water and suspended matter discharge from the Eurasian land mass into the Arctic Ocean

	Area	Discharge			Total suspended matter		
River	$10^6 km^2$	km^3	$m^3.s^{-1}$	$l.s^{-1}.km^{-2}$	$10^6 t.a^{-1}$	$g.m^{-3}$	$t.km^{-2}.a^{-1}$
Barents and White Seas							
Onega	57	15.9	500	8.8	0.3	18	4.9
N. Dvina	357	110	3470	9.7	3.8	35	10.6
Mezen	78	27.2	860	11.0	0.9	32	11.1
Pechora	324	131	4130	12.7	13.5	80	32.4
Other area	570	179	5690	10.0	3.5	20	6.2
Total	1386	463	14600	10.7	22	47	15.9
Kara Sea							
Ob	2545	429	13500	5.4	16.5	38	6.4
Nadym	64	18	570	8.9	0.4	22	6.2
Pyr	112	34.3	1080	9.8	0.6	18	5.5
Taz	150	44.3	1400	9.5	0.9	21	6.1
Yenisei	2594	620	19600	7.6	5.9	10	2.3
Pyasina	182	86	2730	15	3.4	40	18.8
Other area	867	443	7770	9	5.5	12	6.3
Total	6589	1478	46600	7.2	33.2	22	5
Laptev Sea							
Khatanga	364	85.3	2700	7.4	1.7	20	4.6
Anabar	100	17.3	550	5.5	0.4	24	4.1
Olenjok	219	35.8	1140	5.2	1.1	31	5.1
Lena	2486	525	16650	6.7	17.6	34	7.1
Omoloy	39	7	220	5.7	0.13	18	3.2
Yana	238	34.3	1090	4.6	3.5	103	14.8
Other area	197	40.3	1280	6.5	0.65	16	3.3
Total	3643	745	23600	6.5	25.1	34	6.9
East-Siberian Sea							
Indigirka	362	61	1930	5.3	12.9	210	35.6
Alazeya	68	8.8	280	4.1	0.7	80	10.2
Kolyma	660	132	4190	6.3	16.1	120	24.3
Other area	252	48.2	1530	6	3.85	80	15.3
Total	1342	250	7930	5.9	33.6	134	25
Chukchi Sea without Alaska							
Amygyema	29.6	9.2	290	9.7	0.05	6	1.8
Other area	64.6	11.2	2050	5.5	0.65	58	10
Total	94.2	20.4	2340	6.8	0.7	34	7.4
For the entire Eurasian Arctic basin							
Total	13054	2960	95770	7.3	115	40	8.8

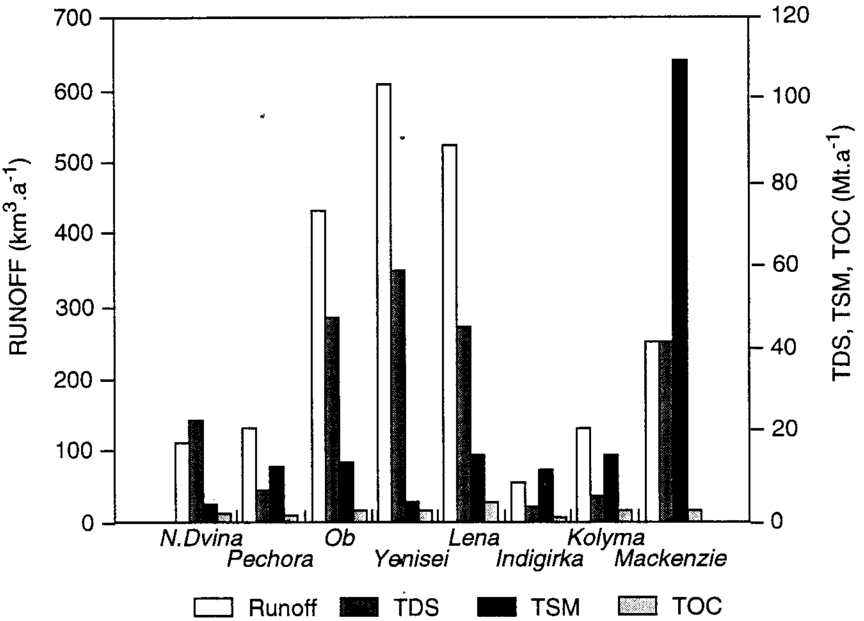

Fig. 2. Multi-annual runoff, total major ions (TDS), total suspended matter (TSM), and total organic carbon (TOC) for the largest Arctic basin rivers.

flow on the west slope of the Urals ridge are characterized by the higher specific water discharges of the European part of the Arctic basin, for example Pechora (table 1). The specific water discharge of the Ob River is relatively small, owing to the climatic and geological conditions. The specific water discharge of the driest part of the Ob drainage basin is related to a flat relief, a negligible connection with groundwater and a multitude of lakes and swamps. The absolute maximum of the specific water discharge is observed for the Pyasina River (15 I s^{-1} km^{-2}) in relation to the maximum precipitation occurring over its basin.

The specific water discharge for the rivers of the North American part of the Arctic basin is very similar: 7.0 I s^{-1} km^{-2} (Ivanov, 1985). The specific water discharge of the Yukon River is 7.8 I s^{-1} km^{-2} (Telang and others, 1991). Accordingly, the specific water discharge for the whole of the Arctic basin is lower than the world average (11 I s^{-1} km^{-2}) (Milliman, 1989). These rather low values of the specific water discharge are related to the low annual precipitation over the Arctic basin. The long-term monthly average discharges of the largest Eurasian Arctic basin rivers are shown in figure 3A. According to these data, the maximum discharges for North Dvina, Onega, and Mezen (last 2 rivers are not shown on fig. 3 because of their small scale) are observed in May. For the Pechora and Siberian rivers, Ob, Yenisei, Lena, Indigika, et cetera, the maximum

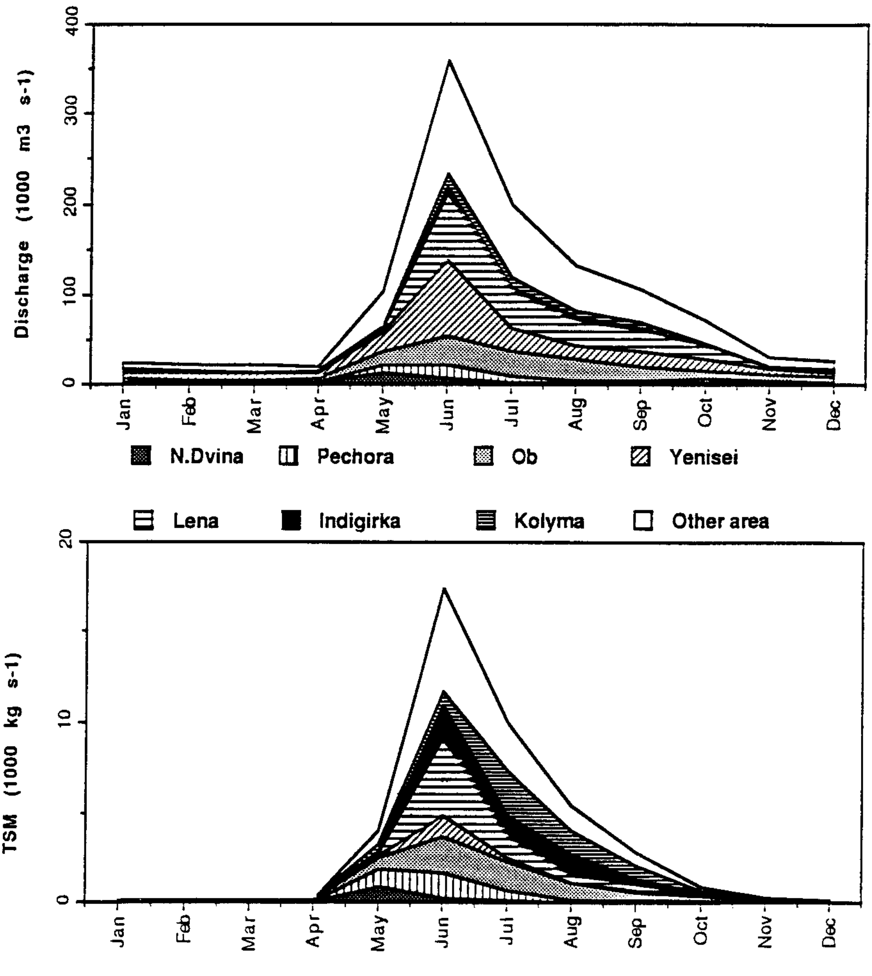

Fig. 3. Seasonal variations of the water discharge (A) and total suspended matter (B) by the largest Eurasian rivers.

discharge is observed in June. The Eurasian Arctic rivers discharge 60 percent of their total annual water discharge into the Arctic Ocean during the flood period (May-July) (See table 1). This percentage varies from 45 to 55 percent (Onega, Mezen, Pechora, Ob) to 60 to 65 percent (North Dvina, Yenisei, Lena, Yana, Indigirka, Kolyma), to a maximum of 80 percent (Olenjok). During the winter period (November-April), the total discharge into the Arctic Ocean does not exceed 15 percent of the annual water discharge.

The turbidity of the Eurasian Arctic basin river waters ranges from 6 to 210g m^{-3}, with an average of 38g m^{-3}. The maximum average turbidity of waters is observed for the Indigirka (210g m^{-3}), Kolyma (120g m^{-3}), and Yana (103g m^{-3}) Rivers. This can be related to the geology of the drainage basins, where interstratified ice layers make the Quaternary sediments easily erodable (Protasiev, v. 17, 1972). The Barents, White and Kara Sea basin rivers are characterized by a low average turbidity (19–65g m^{-3}). The lower courses of these rivers flow through broad, swampy lowlands where the suspended material eroded in the upper reaches is deposited, especially during the spring season, when the extensive upstream flooding reaches the coastal ice-barrier. The low average turbidity observed in the Laptev Sea basin rivers, except the Yana River, can be related to the wide spread permafrost and the small thickness of the active layer (0.5–3.0m) on the drainage basins of these rivers (North Yakutiya, 1962) and to the very short duration of the positive air temperatures.

The long-term monthly average TSM discharge of the largest Eurasian Arctic rivers is shown in figure 3B. According to these data, the maximum TSM is discharged in the Onega, North Dvina, and Mezen in July, as well as the water discharge. For the other largest Eurasian Arctic rivers, the maximum SM discharges are observed in June.

For the Barents, White, Kara, and Laptev Sea basin rivers, there is a good correlation between the specific water discharge and the suspended matter discharge (fig. 4). The East Siberian rivers (Yana, Alazeya, Indigirka, and Kolyma) show a different slope, characterized by a specific SM discharge more similar to the North American rivers than to the other Siberian rivers.

The Mackenzie and Yukon Rivers have a suspended load many times greater than the Eurasian Arctic rivers (110 and 88 $* 10^6$t per yr, respectively). This difference is a consequence of the differences in the superficial geology of the river courses: the Mackenzie and Yukon flow through sandy, terraced banks and alluvial strata intensively eroded by the swift-flowing waters (Pocklington, 1987).

The total suspended matter (TSM) flux from the Eurasian territory into the Arctic Ocean averages 112 $* 10^6$t per yr, which is somewhat higher than the figures given by Milliman and Meade (1983); that is 84 $* 10^6$t per yr, but these authors considered a smaller drainage basin. The largest amount of TSM is transported by the Lena (17.6 $* 10^6$t per yr), Ob (16.5 $* 10^6$t per yr), Kolyma (16.1 $* 10^6$t per yr), Pechora (13.5 $* 10^6$t per yr), and Indigirka (12.9 $* 10^6$t per yr) rivers. These 5 rivers account for about 70 percent of the annual TSM export from the Eurasian land mass into the Arctic Ocean. They all have a very low suspended sediment yield (Mass/area) compared to the world average (Milliman and Meade, 1983).

THE DISCHARGE OF MAJOR IONS

The chemical composition of waters of the Arctic Ocean basin rivers, including the Mackenzie and the Alaskan rivers, is given in table 2. The maximum total dissolved ionic salts (TDS) are observed in the White Sea

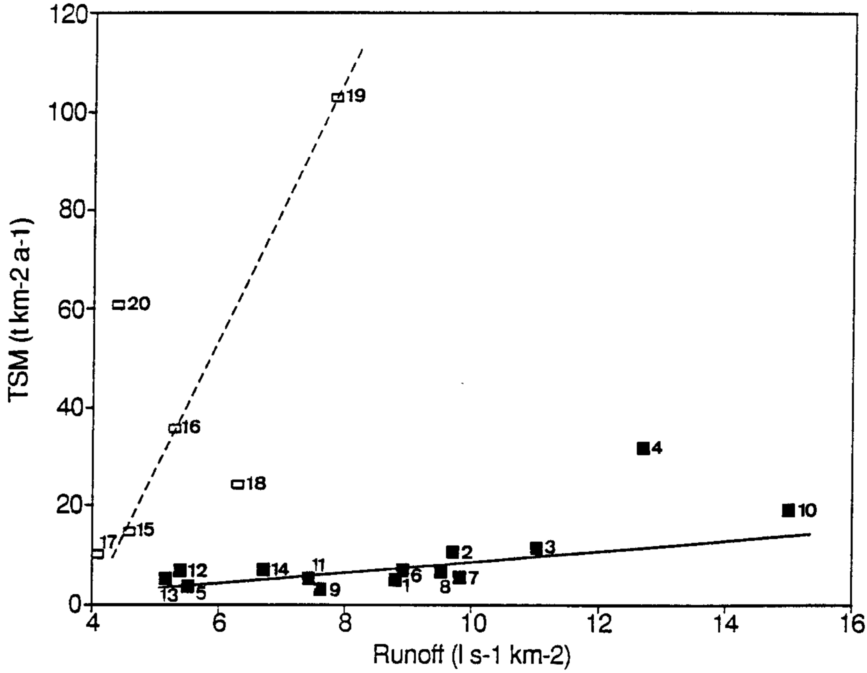

Fig. 4. Mean specific annual TSM export by the largest Arctic rivers versus their respective runoff. 1-Onega, 2-North Dvina, 3-Mezen, 4-Pechora, 5-Ob, 6-Nadym, 7-Pyr, 8-Taz, 9-Yenisei, 10-Pyasina, 11-Khatanga, 12-Anabar, 13-Olenjok, 14-Lena, 15-Yana, 16-Indigirka, 17-Alazeya, 18-Kolyma, 19-Mackenzie, 20-Yukon.

basin rivers that drain mainly quaternary glacial deposits (clays and sands). The average concentration (172mg l^{-1}) for the rivers discharging to the White sea is similar to the TDS of the Mackenzie River. The absolute maximum of TS (225 mg l^{-1}) is observed in the North Dvina River. The largest rivers of the Kara and Laptev Sea basins (Ob, Yenisei, Lena, Khatanga, and Olenjok) are characterized by a higher TDS (100–123mg l^{-1}) than the world average value. The minimum TDS (18.4–50.8 mg l^{-1}) is observed for the small and medium tundra and forest-tundra rivers (Anabar, Yana, Omoloy, Alazeya, Ebitem, and Amguema) of the Laptev, East Siberian, and Chukchi Sea basins.

Regarding the chemical composition of the Eurasian rivers, the waters of the Arctic basin contain mostly bicarbonates (55-80 percent of the total anions). As for the tundra zone of the Laptev, East Siberian, and Chukchi Seas, the most abundant anion in the river water is sulphate (55-60 percent of the total anions), bicarbonate ion constituting only 30 to 35 percent of the total anions. This is clearly shown in figure 5, featuring a triangular plot of the interrelations Ca–Mg–(Na + K) and HCO_3–(Cl + SO_4)–SiO_2. For the calcium-carbonate waters, silicate weathering

TABLE 2

Major-ion concentrations for the Arctic rivers (mg.l⁻¹)

River, area	Cl^- mg.l⁻¹	SO_4^{--} mg.l⁻¹	HCO_3^- mg.l⁻¹	Mg^{++} mg.l⁻¹	Ca^{++} mg.l⁻¹	Na^+ mg.l⁻¹	K^+ mg.l⁻¹	Sum of ions mg.l⁻¹	Sum of ions µeq.l⁻¹
Barents and White Seas									
Onega (1)	5.1	37.3	102	9.1	32.4	4.6	1.0	192	5180
N. Dvina (1)	8.1	52.0	106	8.8	39.0	9.5	1.3	225	6170
Mezen (1)	6.0	8.9	87.3	5.2	18.8	10.0	1.0	137	3610
Pechora (2)	3.5	7.7	39.5	3.1	10.0	3.2	0.5	67.5	1800
Kara Sea									
Ob (3)	9.9	4.8	76.3	5.1	19.0	4.2	3.8	123.0	3040
Yenisei (2)	9.9	8.4	55.2	3.3	15.9	6.3	1.0	100.0	2700
Pyr (3)	2.5	1.9	25.6	2.0	4.5	2.9	0.5	39.9	1050
Taz (3)	3.2	5.7	64.9	5.0	12.2	5.3	0.9	97.2	2640
Laptev Sea (3)									
Khatanga	17.0	4.7	60.1	4.6	15.1	10.0	4.0	116.0	3140
Anabar	1.5	1.6	34.1	2.2	10.7	0.6	0.1	50.8	1380
Olenjek	5.0	4.0	79.5	4.4	21.8	3.8	0.6	119.0	3230
Lena	17.1	12.3	52.0	4.4	16.0	10.0	1.7	114.0	3230
Yana	2.4	8.4	20.4	1.4	6.1	3.3	0.6	42.6	1160
Omoloy	2.1	17.2	13.1	1.8	7.5	2.7	0.5	44.9	1290
Ebitem	1.4	6.0	18.6	1.4	4.4	2.7	0.5	35.0	930
Tundra	2.0	18.2	13.8	1.9	8.2	2.7	0.4	47.2	1360
East-Siberian Sea (3)									
Indigirka	1.8	12.3	31.3	2.6	11.9	0.4	0.1	60.4	1650
Alazeya	1.6	5.6	8.9	1.0	3.6	1.2	0.2	22.1	630
Kolyma	2.3	10.2	28.5	1.8	10.5	1.3	0.2	54.8	1480
Tundra	2.3	6.0	12.9	1.2	4.0	2.1	0.3	28.8	780
Chukchi Sea without Alaska (3)									
Amgyema	1.3	3.9	8.0	0.3	3.0	1.6	0.3	18.4	500
Tundra	1.4	5.2	7.7	0.7	3.0	1.4	0.2	19.6	550
Eurasian Arctic rivers (3)									
Average	7.6	9.9	48.2	3.6	15.4	4.6	0.8	90	2450
NORTH AMERICAN ARCTIC BASIN (4)									
Beaufort Sea									
Mackenzie	10.5	32.6	96.5	9.3	36.5	9.2	1.1	196	5560
Chukchi Sea, Alaska									
Colvilll	1.1	19.4	53.5	4.3	16.4	2.6	0.8	97	2610
Kobuk	0.6	13.7	32.7	3.7	21.6	0.9	0.4	73.6	2260
Kuparuk	1.5	4.8	51.6	1.6	16.4	1.3	0.6	77.7	2010
WORLD RIVER AVERAGE (5)									
Average	5.8	8.25	52	3.35	13.4	5.15	1.3	89.2	2360

(1) Zatuchnaya and Gershanovich (1991), (2) Tsirkunov (1985), (3) Authors' estimates, (4) Telang and others (1991), (5) Meybeck (1979).

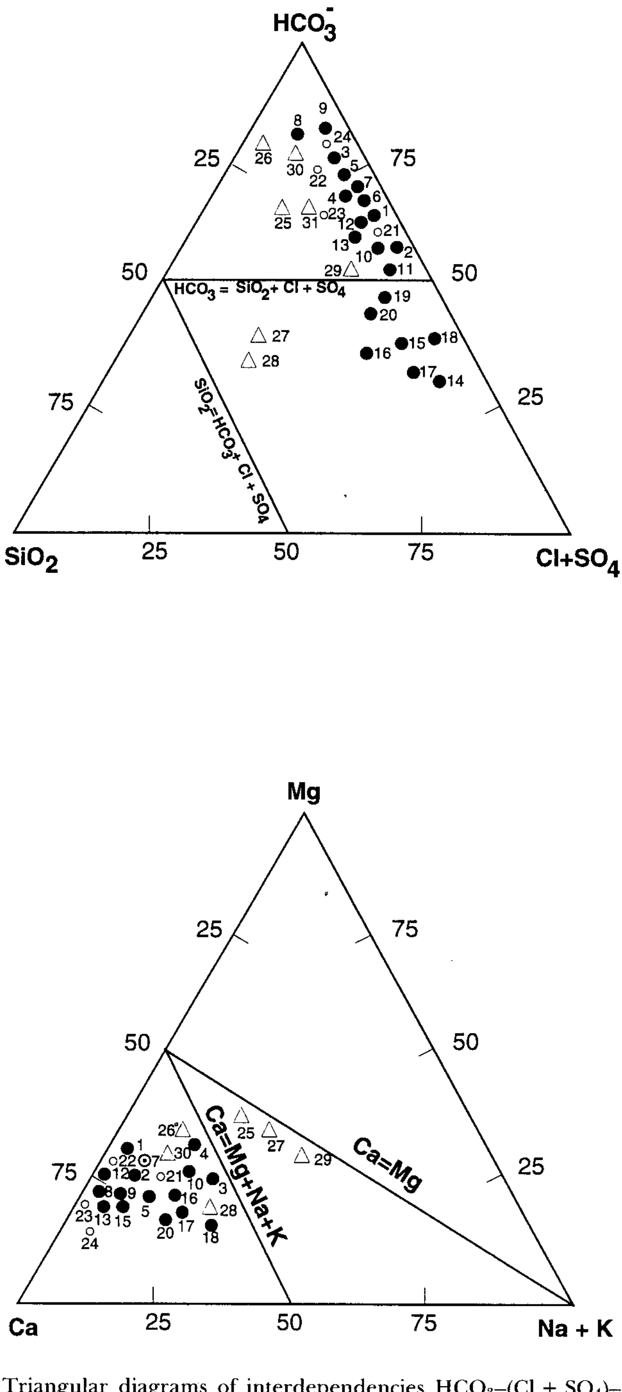

Fig. 5. Triangular diagrams of interdependencies HCO_3–(Cl + SO_4)–SiO_2 (A) and Ca–Mg–(K + Na) (B) for river waters of the Arctic basin and the largest rivers of other climatic zones. Eurasian Arctic rivers: 1-Onega, 2-North Dvina, 3-Mezen, 4-Pechora, 5-Ob, 6-Yenisei, 7-Khatanga, 8-Anabar, 9-Olenjok, 10-Lena, 11-Yana, 12-Indigirka, 13-Kolyma, average and small Eurasian tundra rivers, 14-Laptev Sea basin, 15-East Siberian Sea basin, 15-Chukchi Sea basin, 17-Omoloy, 18-Ebitem, 19-Alazeya, 20-Amguema; North American Arctic rivers, 21-Mackenzie, 22-Yukon, small Alaskan rivers, 23-Kobuk, 24-Kuparuk. Largest world rivers: 25-Amazon, 26-Ganges-Brahmaputra, 27-Zaïre, 28-Orinoco, 29-Huanghe, 30-Changjiang, 31-average for world rivers (all concentrations are expressed in meq/l. ● Eurasian rivers (1-20); ○ North American rivers (21-24); Δ Largest world rivers (25-31).

TABLE 3

Concentrations of major ions in precipitation of the different areas of the Lena River drainage basin and neashore territory of the Laptev and East-Siberian seas (mg.l^{-1})

Station	Mg^{++}	Na^{+}	K^{+}	Ca^{++}	NH_4^{+}	HCO_3^{-}	Cl^{-}	SO_4^{--}	$NO3^{-}$	TDS
Upper reaches of the Lena River (rain, snow), 1981-1985										
Kirensk	0.4	0.8	0.6	0.7	0.4	3.7	1.2	1.5	0.6	9.9
Middle reaches of the Lena River (rain, snow), 1981-1985										
Yakustsk	0.7	1.1	0.7	0.8	0.7	4.7	2.1	2.5	0.6	13.9
Lower reaches of the Lena River, 1981-1985										
Kusur (rain)	0.8	0.9	0.4	1.0	0.4	2.5	2.5	3.5	0.2	12.2
Tiksi (rain)	1.0	0.9	0.3	1.2	0.7	3.2	3.2	2.0	0.4	12.9
Kusur (snow)	0.7	1.4	0.6	1.5	0.4	4.2	4.2	2.0	2.0	15.2
Tiksi (snow)	0.9	2.1	0.8	2.0	0.8	3.7	6.5	1.9	0.5	19.2
Laptev and East-Siberian Seas basins (snow), 1989-1991										
Forest-tundra territory										
Tumeti	0.8	1.4	0.4	1.0	0.7	3.7	3.9	1.2	0.3	13.4
Kusur	0.7	1.4	0.6	1.5	0.4	4.2	4.2	2.0	0.2	15.2
Chokurdah	0.6	2.2	0.9	0.5	0.6	3.7	4.5	1.3	0.2	14.5
Andrushkino	0.6	1.4	0.4	1.7	0.4	2.4	4.2	1.2	0.1	12.4
Average	0.7	1.6	0.6	1.2	0.5	3.5	4.2	1.4	0.2	13.9
Tundra territory										
Kigiliach	0.7	2.1	1.5	2.0	0.2	3.2	7.7	1.6	0.2	19.2
Tiksi	0.9	2.1	0.8	2.0	0.8	3.7	6.5	1.9	0.5	19.2
Ubileynaya	0.6	2.4	1.2	1.2	0.3	6.0	4.8	1.1	0.2	17.8
Alazeya	0.6	1.7	1.5	2.8	0.5	2.1	9.5	1.5	0.1	20.3
Cherski	0.7	1.4	1.3	2.8	0.4	3.5	7.9	1.2	0.3	19.5
Average	0.7	1.9	1.3	2.0	0.4	3.7	7.3	1.5	0.3	19.1
New Siberian Islands (snow), 1989-1991 (3)										
Shalaurova	1.0	3.0	0.8	2.8	0.7	4.1	11.0	1.1	0.2	24.6
Zhohova	0.9	3.1	1.0	2.8	0.5	5.1	9.4	1.3	0.1	23.8

in the drainage basin is rather low. The typical features in these basins are the predominance of Ca and Mg cations and high (Ca + Mg)/(Na + K) ratios; the relation $HCO_3 > SiO_2 + Cl + SO_4$ is also observed. As can be seen in table 2 and figure 5, these conditions are fulfilled for all the largest Eurasian Arctic rivers, except for the small and medium tundra rivers of the Laptev, East Siberian, and Chukchi Sea basins (Omoloy, Ebitem, Alazeya, Amguema). The points, corresponding to these rivers, shift in the diagram (in fig. 5A) toward the enhanced $Cl + SO_4$. This can be related to the composition of the precipitation which represents the only source for these rivers and which are characterized by the predominance Cl and SO_4 ions over the HCO_3 ion (table 3).

Data on total dissolved ionic salts discharged into the Arctic Ocean by rivers from the Eurasian land mass are listed in table 4. According to our estimate, TIS from the Eurasian Land mass into the Arctic Ocean is

TABLE 4

Multiannual average major-ion export into the Arctic Ocean with the river runoff ($10^6t.a^{-1}$) TDS: Total dissolved salts; DT: dissolved transport

River, area	Area 10^3km^2	Disch. $km^3.a^{-1}$	Cl^- $10^6t.a^{-1}$	SO_4^{--} $10^6t.a^{-1}$	HCO_3^- $10^6t.a^{-1}$	Mg^{++} $10^6t.a^{-1}$	Ca^{++} $10^6t.a^{-1}$	Na^+ $10^6t.a^{-1}$	K^+ $10^6t.a^{-1}$	TDS $10^6t.a^{-1}$	TD $t.km^{-2}$
Barents and White Seas											
Onega	57	15.9	0.08	0.6	1.5	0.14	0.51	0.07	0.02	3	52.7
N. Dvina	357	110	0.88	5.6	11.5	0.95	4.23	1.01	0.16	24.4	68.2
Mezen	78	27.2	0.16	0.3	2.19	0.13	0.51	0.23	0.03	3.54	45.3
Pechora	324	131	0.50	0.4	5.68	0.1	1.52	0.45	0.07	8.71	26.9
Other area	570	179	0.98	2.9	10.9	0.74	3.38	0.78	0.13	19.8	34.7
Total	1386	463	2.60	9.8	31.9	2.05	10.2	2.54	0.41	59.4	42.9
Kara Sea											
Ob	2545	429	4.25	2.06	28.9	2.00	7.37	2.29	0.38	47.2	18.5
Yenisei	2594	620	5.93	5.11	32.8	2.03	9.71	3.77	0.63	59.9	23.1
Pyr	112	34.3	0.09	0.07	0.88	0.07	0.15	0.10	0.02	1.32	11.8
Taz	150	44.3	0.14	0.25	2.88	0.22	0.54	0.23	0.04	4.30	28.7
Other area	867	443	1.66	2.01	7.02	0.97	4.17	1.21	0.20	17.2	14.5
Total	6589	1478	12.1	9.5	72.4	5.29	21.9	7.60	1.27	130	19.7
Laptev Sea											
Khatanga	364	85.3	1.07	0.48	4.09	0.31	1.07	0.66	0.25	7.93	21.8
Anabar	100	17.3	0.03	0.07	0.54	0.04	0.17	0.02	0.003	0.87	8.7
Olenjok	219	35.8	0.17	0.17	2.6	0.15	0.72	0.13	0.02	3.97	18.1
Lena	2486	525	8.98	6.46	27.3	2.32	8.42	5.26	0.88	59.6	23.4
Yana	238	34.3	0.08	0.31	0.71	0.05	0.21	0.11	0.02	1.49	6.3
Other area	197	40.3	0.09	0.52	1.1	0.09	0.39	0.13	0.02	2.34	9.9
Total	3643	745	10.4	8.01	36.3	2.96	11	6.31	1.19	76.2	20.9
East-Siberian Sea											
Indigirka	362	61.00	0.11	0.83	1.73	0.14	0.70	0.05	0.01	3.57	9.90
Kolyma	660	132.00	0.30	0.94	3.43	0.25	1.35	0.21	0.03	6.51	9.90
Other area	252	48.20	0.13	0.34	0,79	0.07	0.23	0.12	0.02	1.70	5.30
Total	1342	250.00	0.54	2.11	5.95	0.46	2.28	0.38	0.06	11.80	8.90
Chukchi Sea without Alaska											
Amygyema	29.6	9.20	0.01	0.03	0.07	0.00	0.03	0.02	0.00	0.16	5.40
Other area	64.6	11.20	0.02	0.06	0.09	0.01	0.04	0.02	0.00	0.24	3.70
Total	94.2	20.40	0.03	0.09	0.16	0.01	0.07	0.04	0.01	0.40	4.20
For the entire Eurasian Arctic basin											
Total	13054	2960	21.5	29.8	143.5	10.7	45.5	13.8	2.3	267.1	20.5
NORTH AMERICAN ARCTIC BASIN (1)											
Mackenzie	18.05	249	2.08	6.15	22.00	8.2	0.26	2.1	1.88	42.7	23.7

(1) Telang and others (1991).

slightly higher than the earlier estimates of Alekin and Brazhnikova (1964) (267 * 10^6 instead of 247 * 10^6t per yr). The greatest disparity in the estimates exists for the Barents and White Seas basin (59.4 * 10^6 against 34.7 * 10^6 t per yr). This can be attributed primarily to the larger number of rivers that have been considered, the use of data covering a more recent period, and possibly to the way the average was calculated. In the previous estimate, the annual average value was obtained from the annual mean concentration and annual water discharge. In our estimation, because of the very different characteristics of the water in different seasons, mean monthly concentrations were multiplied by the water discharge of the same month, and all data were averaged for the year. It is generally accepted that the role played by man may significantly increase the TDS of the rivers draining the territory of the former USSR, during the first half of this century. This influence is still negligible for the arctic rivers Lena, Ob, Yenisei, Yana, Penjina, Kamchatka, Indigirka (Nikanozov and Tsirkunov, 1984, 1991). This conclusion is based on the comparison between natural and anthropogenic interannual variations of water discharges and dissolved salt fluxes. The TDS exported by the Yenisei ($59.9 * 10^6$t per yr), Lena ($59.6 * 10^6$t per yr), Ob ($47.2 * 10^6$t per yr), and North Dvina ($24.4 * 10^6$t per yr) provide about 70 percent of the annual TIS discharged from the Eurasian land mass into the Arctic Ocean (fig. 2).

The specific erosion for Eurasian Arctic rivers, as well as specific discharge, decreases from west to east from 10 to 30 t km^{-2} per yr for the White Sea basin rivers to 2 to 5 t km^{-2} per yr for the Chukchi Sea basin rivers and small tundra rivers of the Laptev, East Siberian, and Chukchi Seas.

For the Barents, White, Kara, and Laptev Sea basins, the TDS exported is considerably greater than over the TSM export. The ratios of TSM to TDS are very low and range between 0.1 and 0.5, except for the Pechora River (1.5). For rivers of the East Siberian Sea basin, the TSM export is greater than over the TIS export, with a TSM/TIS ratio of 1.6 to 3.6.

THE DISCHARGE OF ORGANIC CARBON, NUTRIENTS AND SILICA

The average concentration and export of TOC for the largest rivers of the Eurasian and North American land mass into the Arctic basin are given in table 5. According to our estimate, the total export of TOC from the Eurasian land mass into the Arctic Ocean is $28.7 * 10^6$t per yr. This is higher than the value given by Smirnov and others (1988), $21 * 10^6$t per yr but very similar to the estimation of Romankevich and Artemyev (1985), $28.4 * 10^6$t per yr.

The annual TOC loss per unit area of catchment basin correlates significantly with runoff, as shown in figure 6. The rivers of the Barents and White Sea basin, except the Mezen River, flow through forest and swamps and have the highest TOC yield (5.2–7.2t km^{-2} per yr). For Siberian rivers, the TOC yield is lower and rather uniform (0.9–2.1t km^{-2} per yr). Nevertheless, the concentration of TOC in Siberian rivers is relatively high (5–10 mg l^{-1}). For the tundra zone of the Laptev, East Siberian, and Chukchi Sea basins, the TOC yield is very low (0.5–0.8t km^{-2} per yr). The amount of TOC transported by the Lena ($5.30 * 10^6$t per yr), Yenisei ($4.59 * 10^6$t per yr), Ob ($3.05 * 10^6$t per yr), North Dvina ($2.57 * 10^6$t per yr), Pechora ($1.70 * 10^6$t per yr), and Kolyma ($1.07 * 10^6$t per yr) rivers (fig. 1) provides about 80 percent of the annual export of TOC from the Russian territory into the Arctic Ocean.

TABLE 5

Average TOC concentrations and fluxes for the largest Arctic rivers

		Area	Discharge		TOC	TOC fluxes	
	River, area	$10^3 km^2$	km^3	$l.s^{-1}.km^{-2}$	$mg.l^{-1}$	$10^6 t.a^{-1}$	$t.km^{-2}.a^{-1}$
	EURASIAN ARCTIC BASIN						
1	Onega (1)	57	15.9	8.8	20.7	0.33	5.8
2	N. Dvina (2)	357	110.0	9.7	23.4	2.57	7.2
3	Mezen (1)	78	27.2	11.0	7.0	0.19	2.4
4	Pechora (2)	324	131.0	12.7	13.0	1.70	5.2
5	Ob (1)	2545	429.0	5.4	7.1	3.05	1.2
6	Nadym (1)	64	18.0	8.9	5.0	0.09	1.4
7	Pyr (1)	112	44.3	9.8	6.7	0.23	2.1
8	Yenisei (2)	2594	620.0	7.6	7.4	4.59	1.8
9	Khatanga (3)	364	85.3	7.4	6.3	0.54	1.5
10	Anabar (3)	100	17.3	5.5	5.1	0.09	0.9
11	Olenjok (3)	219	35.8	5.2	7.2	0.26	1.2
12	Lena (3)	2486	525.0	6.7	10.1	5.30	2.1
13	Yana (3)	238	34.3	4.6	6.7	0.23	1.0
14	Indigirka (3)	362	61.0	5.3	7.7	0.47	1.3
15	Kolyma (3)	660	132.0	6.3	8.1	1.07	1.6
16	Amygyema (4)	30	9.2	9.7	6.7	0.06	2.1
	NORTH AMERICAN ARCTIC BASIN						
17	Mackenzie (5)	1805	249	4.4	12.6	3.12	1.7

(1) Smirnov and others (1988); (2) Artemiev and Romankevich (1988); (3) Authors' estimates; (4) Maltseva, Tarasov, and Smirnov (1987); (5) Telang (1985).

According to the data in table 6, the Arctic rivers are characterized by high DOC concentrations (0.3–3.2 mg l^{-1}) and relatively low POC concentrations (0.7–3.2mg l^{-1}), except the Mackenzie River. The percentage of particulate matter (dry wt), constituted of POC in the European Arctic rivers, is relatively high (16.0–23.3 percent). In contrast, lower values are measured in the Siberian and North American Arctic rivers (0.2–3.8 percent). In general, DOC contributes 86 to 91 percent of TOC export, except in the Mackenzie River (42 percent).

Tables 7 and 8 show the average annual concentrations and fluxes of dissolved nutrients by the largest Arctic rivers. According to our estimate, the total export of PO_4, NO_3, and SiO_2 from the Eurasian land mass into the Arctic Ocean makes up 47 * 10^3, 470 * 10^3, and 16.9 * 10^6t per yr, respectively. This is smaller than the estimate of Tarasov and others (1988) for the period 1970 to 1980 for nitrate (631.10^3t per yr) but very close for phosphate (52.10^3t per yr) and silica (18.8.10^6t per yr).

The Barents, White, and Kara Sea basin rivers are characterized by higher nutrient concentrations than the Laptev, East Siberian, and Chukchi Sea basin rivers.

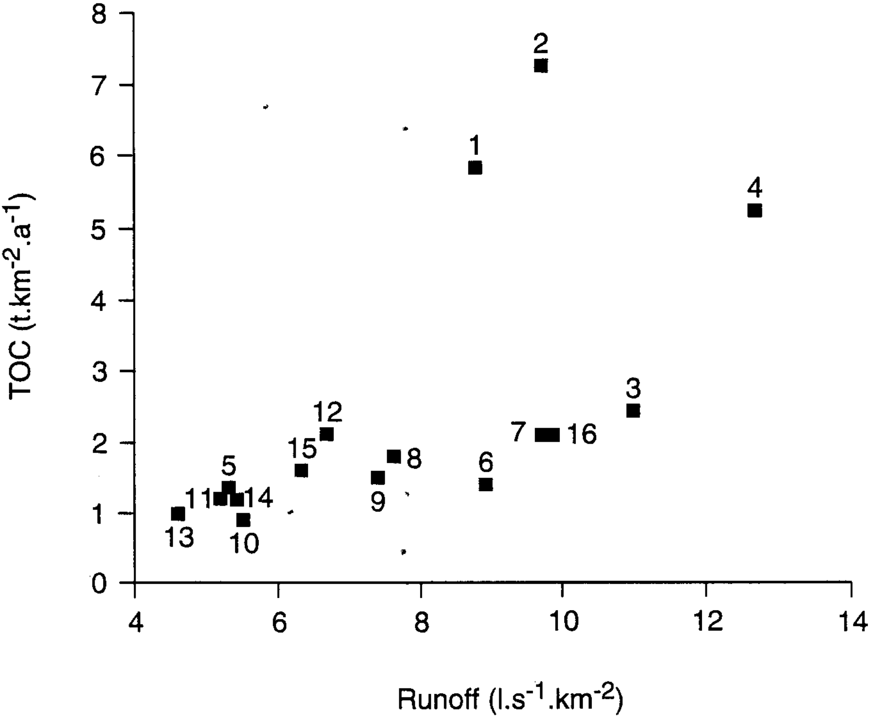

Fig. 6. Mean specific annual TOC exported by the largest Arctic rivers (numbers given in table 5) versus their respective runoff: 1-Onega, 2-N. Dvina, 3-Mezen, 4-Pechora, 5-Ob, 6-Nadym, 7-Pur, 8-Yenisei, 9-Khatanga, 10-Anabar, 11-Olenjok, 12-Lena, 13-Yana, 14-Indigizka, 15-Kolyma, 16-Amguema.

According to our estimation for the Laptev and East Siberian Sea basin rivers, the concentration of dissolved organic nitrogen (DON) is considerably higher than the sum of nitrate and ammonium concentrations (19-30 against 5-6μmol) and makes up 75 to 85 percent of the total dissolved nitrogen (TDN). Meybeck (1992, 1993) gives the same relationship (DON $\gg$ N-NO_3 + N-NH_u) for major unpolluted rivers (for example Amazon) and for global averages while for polluted rivers this relationship is usually opposite (Seine, Volga). The global DON flux by rivers is about 70 percent of the global TDN flux; this value is slightly lower than for the Laptev Sea and the East Siberian Sea (84 percent). The average concentration of dissolved organic phosphorus (DOP) represents 50 to 70 percent of the total dissolved phosphorus (TOP), and the DOP flux represents 69 percent of the TOP flux in these arctic seas. For comparison, P-PO_4^{-3} contributes to about 90 percent of the TOP concentration in small polluted rivers, and the global DOP flux is about 60 percent of the TOP flux (Meybeck, 1993).

TABLE 6

Average TOC concentrations and fluxes for the largest Arctic rivers

	DOC	POC	POC	TOC	DOC/TOC
River,	$mg.l^{-1}$	$mg.l^{-1}$	%	$mg.l^{-1}$	%
N. Dvina (1)	20.1	3.2	23.3	23.4	86
Pechora (1)	12.7	0.3	16.0	13.0	98
Ob (2)	9.1	0.9	2.0	10.0	91
Lena (3)	6.6	1.1	3.8	7.7	86
Mackenzie (4)	5.3	7.3	1.7	12.6	42
Average for world rivers	5.3	4.6	1.0	9.9	55

(1) Artemiev and Romankevich (1988); (2) Nesterova (1960); (3) Cauwet and Sidorov, submitted; (4) Telang (1985); (5) Meybeck (1993).

TECTONIC CONTROL OF RIVER DISCHARGE

Budgets of Dissolved Salts and Silicate for the Arctic Ocean

Tectonic control of river discharge.—Milliman and Syvitsky (1992) have shown that suspended sediment load yields are a log linear function of the basin area and topography while climate, runoff, and other factors controlling sediment discharge are generally less determinant. Let us compare the main characteristics of the river basins and the water chemistry in Western and Eastern regions of the Eurasian basin (table 9). The boundary between the two large regions crosses the Laptev Sea basin and follows the mainstream of the Lena river. It is the boundary between the Eurasian and North American tectonic plates.

The Eastern Eurasian region (its area is 4 times lower than the area of the Western Region) represents a relatively young (Mesozoic and Cenozoic) mountainous folded country (elevation 1000-3000 m). One can meet here a large variety of igneous and sedimentary rocks. Both alkaline and acidic types are among igneous rocks, while among sedimentary rocks there is a mixture ranging from clays to carbonates.

To the west of the Lena river, are situated the East-Siberian West-Siberian and to the west from Uzal mountains the East-European platforms, respectively.

The East-Siberian platform is older than the East Eurasian region. Ancient metamorphic rocks (gneiss, schists, quartzites, et cetera) and large intrusions of mainly acidic igneous rocks are spread in this region. In vast lowlands–syneclises, the complexes of sedimentary rocks are distributed with a lot of carbonates and salts. The West-Siberian platform is the great depression of the Earth's crust, the surface of which is made of lose quaternary deposits layered on Cenozeic sedimentary rocks. Among these sedimentary rocks, there are both marine and terrestrial formations, mainly of silicate composition.

TABLE 7

Average concentrations of dissolved nutrients for the largest Arctic rivers ($\mu g\ at.l^{-1}$)

Rivers	SiO_2	NO_3	NH_4	DON	TDN	PO_4	DOP	TDP
EURASIAN ARCTIC BASIN								
Barents and White Seas								
Onega	124	11				0.5		
N. Dvina	126	6				0.6		
Mezen	114	11				0.9		
Pechora	109	5				0.1		
Kara Sea								
Ob (4)	164	1.6				1.4		
Nadym	155	10				6.0		
Pyr	164	3				4.0		
Yenisei (4)	107	1				0.3		
Laptev Sea and East-Siberian Sea (2)								
Khatanga	53	2	3	29	34	0.2	0.2	0.4
Anabar	43	2	3	18	23	0.1	0.1	0.2
Olenjok	45	2	4	29	35	0.1	0.2	0.3
Lena	70	3	3	33	39	0.3	0.7	1.0
Yana	52	2	3	21	26	0.1	0.2	0.3
Indigirka	47	2	3	29	34	0.2	0.3	0.5
Kolyma	67	2	4	29	35	0.3	0.5	0.8
Tundra	33	2	4	19	25	0.1	0.1	0.2
Chukchi Sea without Alaska (1)								
Amguema	98	2				0.4		
Eurasian Arctic river (2)								
Average	95	4.2				0.5		
NORTH AMERICAN ARCTIC BASIN (3)								
Beaufort Sea								
Mackenzie	67	3.6			9	0.2		
Chukchi Sea, Alaska								
Kobuk	57		1.4	19				
Kuparuk	28	0.7	2.4					

(1) Tarasov and others (1988); (2) Authors' estimates; (3) Telang and others (1991); (4) Smirnov (personal communication, 1994).

The East-European platform is the oldest one of all the Eurasian basin. It is characterized by a quiet tectonic regime and plain relief (Russian plain). Very thick sedimentary cover is spreaded over all the territory; it is composed mainly of silicate and carbonate rocks and very often of salt deposits. After the elevation, the west Eurasian region is connected to lowland (100-500 m) and upland (500-1000 m) basins.

Table 9 shows that the rivers of East Eurasia in comparison with the rivers of West Eurasia are characterized by a lower water discharge,

TABLE 8

Nutrient export from the Eurasian territory into the Arctic Ocean (10^3 t.a^{-1})

Rivers	SiO_2	NO_3	NH_4	DON	TDN	PO_4	DOP	TDP
Barents and White Seas								
Onega	117	2.5				0.3		
N. Dvina	820	8.8				2.0		
Mezen	166	3.5				0.6		
Pechora	791	9.1				0.4		
Other area	688	1.2				1.3		
Total	2580	25.1				4.5		
Kara Sea								
Ob	4130	42.0				17.0		
Nadym	156	1.9				2.5		
Pyr	324	1.6				3.3		
Yenisei	4010	53.0				7.3		
Other area	2490	10.0				5.7		
Total	11100	108.5				36.0		
Laptev Sea								
Khatanga	270	2.6	3.4	34.1	40.1	0.5	0.5	1.0
Anabar	45	0.5	0.7	4.3	5.5	0.1	0.1	0.2
Olenjok	97	1.1	1.8	14.3	17.2	0.1	0.2	0.3
Lena	2200	21.7	21.0	243.0	286.0	4.2	11.0	15.2
Yana	106	1.0	1.4	10.3	12.7	0.1	0.2	0.3
Tundra	94	1.4	2.4	12.8	16.6	0.1	0.2	0.3
Total	2810	28.3	30.7	319.0	378.0	5.1	12.2	17.3
East-Siberian Sea								
Indigirka	170	1.8	2.4	24.4	28.6	0.4	0.6	1.0
Kolyma	520	4.0	6.6	52.8	63.4	1.0	2.0	3.0
Tundra	110	1.7	2.9	15.4	20.0	0.1	0.2	0.3
Total	800	7.5	11.9	92.6	112.0	1.5	2.8	4.3
Chukchi Sea without Alaska								
Amguema	54	0.9				0.3		
Other area	66	1.9				0.7		
Total	120	2.8				1.0		
For the Eurasian Arctic basin								
Total	16900	172.2				47.0		

higher TSM concentrations and lower concentrations of TDS, dissolved organic carbon, silica, and nutrients. The TSM/TOS ratio is very low, 0.1 to 0.5 (except for the Rechora River), in the western region relatively to the eastern one's the ratio increases to 1.6-3.6).

It is interesting to note that the East Eurasian rivers (Yana, Alazeya, Indigirka, and Kolyma) are more similar to the North American Arctic Rivers (the Mackenzie River is given as an example—table 9) than to the rivers located on the West of the Lena River basin.

TABLE 9

Comparative characteristics of river waters and basins of West and East Eurasian regions (to west and to east from the Lena River)

Parameter	West Eurasia	East Eurasia	Mackenzie river
Area, $10^6 km^2$	10000	3050	1805
Elevation, m	10-1000	500-3000	1000-3000
Discharge			
km^3	2360	600	249
$l.s^{-1}.km^{-2}$	5–15	4–9	7.9
TSM			
$g.m^{-3}$	10-80, av. 29	20-210, av; 78	168
$10^6 t.a^{-1}$	68	47	42
$t.km^{-2}.a^{-1}$	2-19*, av. 6.8	2-36, av. 15.4	23
TDS			
$mg.l^{-1}$	40-225	18-60	196
$10^6 t.a^{-1}$	234	33	96
$t.km^{-2}$	9-68, av. 23.4	4-20, av 11	47.8
TOC			
$mg.l^{-1}$	5–24	6–10	12.6
$t.km^{-2}.a^{-1}$	1–7	1–2	1.7
SiO_2, $\mu g.l^{-1}$	45-165	30-100	67
NO_3, $\mu g.l^{-1}$	2–11	2	3.6
PO_4, $\mu g.l^{-1}$	0.1-1.4	0.1-0.4	0.2

* Excluding the Pechora river (32.4 $t.km^{-2}.a^{-1}$)

There are some significant differences between the physico-chemical characteristics of river waters from these two large regions of the Eurasian basin, although both belong to the same climatic zone. This first consideration let's us assume that the morphological (or tectonic) control is more significant for the suspended sediment yield of these river systems than the climatic factors. This preliminary conclusion is in good agreement with the conclusions given by Milliman and Syvitski (1992) about the primary role of the tectonic factor (and basin area) in controlling the TSM fluxes of the majority of the river systems in the world. However, the dissolved fluxes (TDS) do not correlate with tectonics and are presumably controlled by other factors.

Dissolved-salt budget.— The exchange of water between the Arctic Ocean and the Pacific Ocean occurs through the shallow Bering Strait, and with the North Atlantic and the Norwegian and Greenland Seas, through the Fram Strait. The Arctic water is exported through the Canadian archipelago.

In this part of the paper, we consider the definition of the Arctic Ocean borders given by Codispoti and Owens (1975), which excludes the Greenland and Norwegian Seas, Baffin Bay, Hudson Bay, and Hudson Strait but includes the Barents Sea, without the Scandinavian part, and the Kola Peninsula. With such boundaries, the Arctic Ocean catchment area is $17 * 10^6 km^2$ (13.0 for the Eurasian basin and 4.0 for the North American basin), and the river runoff is $3700 km^3$ per yr (2960 and 740, respectively, see table 1) (Ivanov, 1985). The sensitivity of the chemical budgets to this water balance must be stressed.

In recent years, the estimations of water masses flowing into and out of the Arctic Ocean region were significantly modified. We use here the latest published estimate of inputs and outputs of water (Aagaard and Carmark, 1989).

Our dissolved-salt budget for the Arctic Ocean is presented in table 10. We evaluated the river input of dissolved salts as follows: for the Eurasian Arctic rivers, we used the values given in table 4; the total input of salts is $267.1 * 10^6 t$ per yr; for the North American rivers, we took the measured input for the largest river, the Mackenzie ($42.7 * 10^6 t$ per yr), and we used a mean concentration of $80 mg\ l^{-1}$ for the remaining smaller rivers (492 km^3 per yr of water). So we estimate the total river input of salts to the Arctic Ocean at $350 * 10^6 t$ per yr or $0.011 * 10^6 kg\ s^{-1}$.

TABLE 10

Dissolved salt budget for the Arctic Ocean

Region	Transport of water $10^6 m^3.s^{-1}$	Salinity ‰	Transport of salts $10^6 kg.s^{-1}$	% of total
INPUT				
Bering Strait	0.8	32.5	26	14.8
River discharge	0.12	0.1	0.01	0.01
Precipitation, evaporation	0.03		0	
Fram strait				
0-400 m	1.2	34.98	42	23.8
>400 m	2.4	35.05	84.1	47.8
Norwegian current	0.7	34.4	24.1	13.6
Total	5.25		176.2	100
OUTPUT				
Canadian archipelago	1.7	34.2	58.14	33.1
Fram strait				
sea ice	0.1	4.00	0.4	0.2
polar water	1.0	33.7	33.7	19.2
Atlantic deep water	2.0	34.9	69.8	39.7
Spitzbergen-Frans Josef Land	0.4	34.4	13.8	7.8
Total	5.25		175.8	100

TABLE 11

Silica budget for the Arctic Ocean

Region	Transport of water $10^6 m^3.s^{-1}$	Salinity ‰	Transport of salts $10^6 kg.s^{-1}$	% of total
INPUT				
Bering Strait	0.8	26.5	21.2	38.6
River runoff		-35	-28	
Eurasia	0.094	95	8.9	16.2
N. America	0.024	125	3	5.5
Precipitation, evaporation	0.03	8.4	0.25	0.5
Fram strait	3.6	5.0	18	32.8
Norwegian current	0.7	5.0	3.5	6.4
Total	5.25		61.6	100
OUTPUT				
Canadian archipelago	1.7	17.0	28.9	50.2
Fram strait				
sea ice	0.1	1.0	0.1	0.2
polar water	1.0	9.0	9.0	15.6
Atlantic deep water	2.0	8.0	16.0	27.8
Spitzbergen-Frans Josef Land	0.4	9.0	3.6	6.2
Total	5.2		57.6	100

When it is compared with the output from the Arctic Ocean, the salt budget appears to be totally balanced (table 9). If the significance of the river input of dissolved salts in the budget of the whole Arctic Ocean is negligible, its influence may become important in shallow shelf seas, such as the Laptev Sea, which plays a major role in the ice regime of the whole Arctic Ocean (Thiede and others, 1993).

Silica budget.—According to our estimate, the average concentration of dissolved silica in the Eurasian Arctic rivers is 95μg at I^{-1}. For the North American rivers, we assumed a mean silicate concentration of 125μg at I^{-1} (Codispoti and Owens, 1975; Walsh, 1989). The total input of silica to the Arctic Ocean is about 12kg at s^{-1} (8.9 for the Eurasian rivers, and 3.0 for the North American rivers).

The volume of water inflow and outflow to and out of the Arctic Ocean and average concentrations of silica (except for the rivers) are taken from Anderson and others (1983) and Walsh (1989).

The river component of silica input to the Arctic Ocean is about a fifth of the total annual input (table 11). The imbalance of silicate is 2.7kg at s^{-1}. The largest part of the total input is through the Bering Strait (2/5). We used an average concentration of silicate in the inflowing Bering waters of 26.5 μg at I^{-1}. It was calculated by Walsh and others (1989), who accepted a balanced silicate budget (with no burial of silicate in the bottom sediments). The average concentrations according to different authors are in the range 23 to 35μg at I^{-1} (Codispoti and Owens, 1975; Anderson and others, 1983; Walsh, 1989).

If we use 35μg at I^{-1} (Codispoti and Owens, 1975) there is an excess of 4.0 kg at s^{-1}; the silicate budget is almost balanced and any large-scale burial of biotic silicate is unlikely. We find some support for this assumption in the behavior of silicate in the Lena River estuary and the Laptev Sea where silicate appears to be a quasi-conservative element (Letolle and others, 1993).

Significance of river nutrient discharge to the Arctic Seas.—To evaluate the new production of organic matter generated by the river input of nutrients, we shall first try to assess the mean primary productivity of the arctic shelf seas.

The data on total primary production (PP) in the Arctic Seas and in the Arctic Ocean are very scarse. Sorokin and Sorokin (1993) estimated (PP) in the Lena River estuary and in the S.E. Laptev Sea during the SPASIBA-91 expedition. They evaluated the total PP of microplankton in the Laptev Sea in September 1991 as follows:

0.11 – 0.28	gC m^{-2} d^{-1}	(S < 15 per mil)
0.03 – 0.11	"	(S > 15 per mil)
0.02 – 0.18	"	(S > 28 per mil)

Considering a production period of about 3 months, the TPP can be estimated to 2 to 25 g C m^{-2} y^{-1} (avg 12).

According to Sorokin and Sorokin (1993) the turnover time of P and N in the Lena estuary is about 10 to 15 days, and no limitation of production by nutrients exists. The PP in river and in estuarine regions is mainly light limited owing to the high turbidity of estuarine waters.

The average value measured in the Laptev Sea is in good agreement with the estimate for all shallow Arctic (27 gC. m^{-2} y^{-1}; 0-200 m), given by Subba Rao and Platt (1984).

Assuming the classical Redfield ratios (Sverdrup, Johnston, and Fleming, 1942) of 42 : 28 : 7 : 1 for C : Si : N : P in phytoplankton (on a mass basis) and an average area of 3,13 10^6 km^2 for the Eurasian arctic seas (depth 0-200 m) and the river discharge of nutrients (table 8), we computed the new production which can be sustained by this nutrient source (table 12).

It is obvious that the river discharge of mineral N and P do not play any significant role on the primary production of the Eurasian arctic seas. Whenever the total dissolved forms are considered, the upper limit remains rather low. However the turnover time of N and P which has been estimated to be about 10 to 15 days (Sorokin and Sorokin, 1993) must be considered so as to specify the actual significance of the river input during the 90 days of photosynthetic activity. With a value of about 1 percent, for the mineral forms, we can at most, obtain $1 \times 90/10\text{-}15 \sim 6$ to 9 percent, a value that remains negligible.

TABLE 12

Contribution of the river discharge of nutrients to the primary production of the Arctic seas ($g.cm^{-2}.y^{-1}$ and % of total primary production)

	All Eurasian Arctic		East Siberian Sea	Laptev Sea	
	$g.cm^{-2}.y^{-1}$	% TPP	$g.cm^{-2}.y^{-1}$	$g.cm^{-2}.y^{-1}$	% TPP
Si	3.8	14	0.65	4	33
N-NO3	0.2	1	< 0.1	< 0.1	< 0.1
TDN			0.7	4.5	37
P-PO4	0.2	< 1	< 0.1	0.14	1
TDP			0.2	1.5	12
Total primary production 0-200 m	av. 27 (1)			2-25	av. 12

(1) Subba Rao and Platt (1984) for all shallow Arctic.

Assuming the same turnover time for all Eurasian Arctic, we obtained a value for N and P ≤ 1 percent.

If TDN and TDP are considered, the new production due to river nutrient discharge into the Laptev Sea is increased to 37 percent and 12 percent for N and P, respectively. Unfortunately TDN and TDP are only available for the Laptev and East Siberian Seas.

With regard to silica, the values reach 14 percent for the whole Eurasian Arctic and 33 percent for the Laptev Sea. This last number is difficult to explain due to the much longer turnover time of silica.

It can be concluded that the river discharge of nutrients do not play a major role in the total primary production of the Eurasian Arctic seas, most likely of the order of 10 percent as compared to other sources.

CONCLUSIONS

In this paper, based upon new data and on a re-assessment of historical data, we evaluated the fluxes of water, sediments, major elements, and nutrients from the Eurasian basin to the Arctic Ocean. New data allowed computation of the budgets for dissolved salts and silicate for the Arctic Ocean. Our new values of total water and suspended matter discharges from the Eurasian land mass (drainage basin = $13.10^6 km^2$) are $2960 km^3$ per yr and $112.10^6 t$ per yr, respectively; that is about 8.5 percent of the water and less than 1 percent of the suspended sediment world rivers. These new values are in good agreement with those of Milliman and Meade (1983) who previously pointed out that the annual sediment discharge is so small ($84.10^6 t$) that any likely change in discharge values would have little impact on the worldwide or Eurasian values. A first assessment of the river water and basin characteristics of the West Eurasian region (west from the Lena River which is at present located at the boundary between the Eurasian and North American tectonic plates) relative to the East Eurasian region (east from the Lena River) has shown very significant differences between these two regions.

The Western region rivers are characterized by higher water discharge, TDS, TOC, SiO_2, and nutrient concentrations and by lower concentrations of TSM than in the eastern part.

The East Siberian rivers (the Yana, Alazeya, Indigirka, Kolyma) are even more similar to the North American Arctic rivers than to the rivers located westward of the Lena. Keeping in mind that all the Eurasian basin belongs to the same climatic zone we conclude that the topography (or tectonics) is the most important factor controlling the suspended sediment yield of Eurasian river systems. Our conclusion is very preliminary, and the problem requires more comprehensive consideration.

Our calculations of dissolved salt and silica budgets for the entire Arctic Ocean have shown that both budgets are practically balanced. The significance of the river input of dissolved salts in the budget is negligible, and the river component of silicate input is about ⅕ of the total annual input to the ocean. The almost balanced silicate budget suggests the absence of any large-scale burial of biotic silicate in the Arctic Ocean.

A first estimate of the significance of river nutrient discharge showed its very low contribution to the productivity of the Eurasian Arctic shelf seas.

Although the calculations of TOC, TIC, and nutrient budgets for the Arctic Ocean would be of considerable value in assessing the role of the Arctic environment on the global scale, the paucity of the riverine flux evaluations for these components did not allow us to develop their budgets for the entire Arctic Ocean.

Acknowledgments

The authors wish to express their personal gratitude to J.D. Milliman and one anonymous reviewer for their stimulating reviews, which greatly improved this manuscript. R. Griffiths carefully revised the English language, and P.Prat drew the figures and prepared the tables; both are greatly acknowledged.

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