Nordic Hydrology, 24, 1993, 31-52

Suspended Sediment Yield in the Baltic Drainage Basin

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The aim of this paper is to quantify the spatial distribution of suspended sediment yield in the Baltic Sea drainage basin, and to quantify the suspended sediment inflow to the Baltic. The sediment yield in the studied area varies in accordance with the potential erosion conditions in the morphological sub-units and reaches values from below 2 to almost 1,000 t/km^2/yr. Topographical, pedological and climatic conditions are decisive for the sediment yield variations. The suspended sediment yield increases generally from north to south, and reaches maximum values in the lower parts of the Carpathians. In contrast, the Scandinavian mountains are characterized by low suspended sediment yield. The suspended sediment load derived from the source areas decreases during its transport to the Baltic as a result of sedimentation processes. In the largest rivers of the area no more than 20 to 30% of the sediment amount flowing from tributaries to the main rivers ends up in the Baltic Sea. The total mass of suspended material flowing to the Baltic Sea is 4,455,000 t/yr, 37% of which is carried into the Baltic proper. 20% of the total supply to the Baltic Sea comes from the Vistula river.

Introduction

The aim of the article is to quantify the present-day pattern of suspended sediment yield in the Baltic Sea drainage basin, and to quantify the suspended sediment inflow to the Baltic Sea. The following issues are treated in the paper:

1) the distribution of sediment yield,
2) the rate of suspended sediment deposition along the largest rivers draining to the Baltic,
3) the suspended material supply to the Baltic Sea.

All values in this article are mean annual values of the suspended sediment transport or yield.

The transport of suspended matter to the Baltic Sea during the period 1961-70 and the mean suspended sediment yield in the different countries of the studied area were presented and discussed earlier by Nilsson (1986). Previous studies or maps of the sediment concentration, load, or yield within different countries of the area are found in the following publications: Atlas Mira (1964), Lisitsyna and Alexandrova (1972), Nilsson (1972), Wartiovaara (1975, 1978), Branski (1975, 1980), Hasholt (1981, 1983, 1986, 1990), Brandt (1982, 1986), Maruszczak (1984), Meriläinen (1986), Kauppi and Pitkänen (1986), and Lajczak (1989, 1990, 1992a). The deposition of suspended sediment along the Vistula and Odra was estimated by Lajczak (1992b, 1992c).

Methods

The Study Area

The Baltic Sea is an inland shelf sea with an area of 415,266 km^2 divided into seven sub-basins of different sizes (Mikulski 1986a). The catchment of the Baltic Sea covers 1,721,200 km^2 (Mikulski 1986a). The study area is presented in Fig. 1.

The suspended matter discharged to the Baltic Sea originates from erosion in the river catchments and also from river channel erosion. The rate of soil erosion depends on five factors (Jansson 1982): climate, relief, geology and soils, vegetation, and man's activities (land use, river regulation, *etc.*). Within this climatic environment the relief energy plays an important role in the spatial variation of erosion and suspended sediment yield (Branski 1975, Maruszczak 1984, Lajczak 1992a). Morphological regions with different potential conditions for erosion and suspended sediment yield are distinguished in this study (Table 1).

The basic characteristics of potential erosion of the morphological units are tabulated in Table 2. The data of Table 2 are obtained from national atlases of the studied countries, and from more detailed publications characterizing environmental conditions of the areas.

Very high potential erosion and sediment yield can be expected in the deforested steep parts of the flysch Carpathians (I.3-I.4) from their characteristics – easily erodible soils, high precipitation, high energy of relief, gully erosion, intensive cultivation, and relatively long period with temperatures above zero (Table 2). The

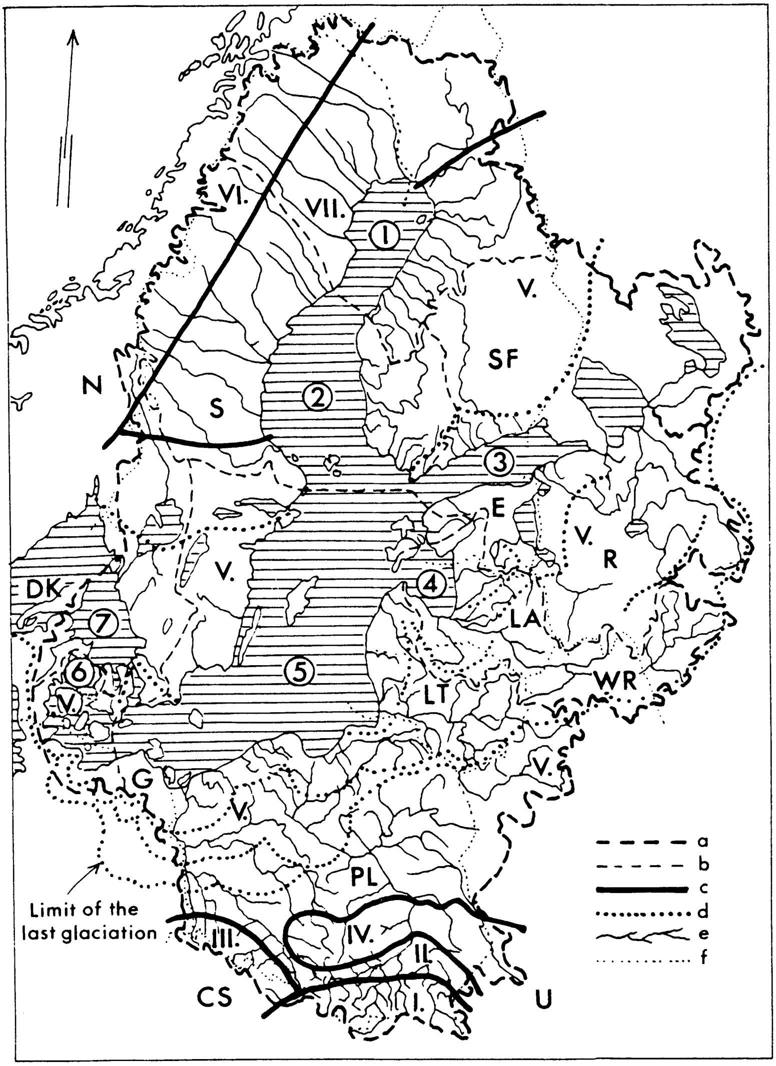

Fig. 1. The Baltic Sea drainage basin. a) border of the area; b) borders of sea sub-basins and their catchments. The Baltic Sea sub-basins, after Mikulski (1986): 1) Bothnian Bay, 2) Bothnian Sea, 3) Gulf of Finland, 4) Gulf of Riga, 5) Baltic proper, 6) Öresund and Belts (the Danish straits), 7) Kattegat; c) borders of main morphological units: I) Carpathian Mts., II) Carpathian foreland, III) Sudety Mts., IV) Middle Poland Upland, V) Lowland area, VI) Scandinavian Mts, VII) Norrland Plateau; d) main moraine ridges formed during the last glaciation; e) rivers with sediment load measurements; f) state borders (CS) Czechoslovakia, DK) Denmark, E) Estonia, G) Germany, LA) Latvia, LT) Lithuania, N) Norway, PL) Poland, R) Russia, S) Sweden, SF) Finland, U) Ukraina, WR) White Russia).

Table 1 – Areas with different potential conditions for erosion and suspended sediment yield.

Main morphological unit		Sub-unit	
I.	Carpathian Mts	1.	Tatra Mts
		2.	Beskidy Mts, strongly forested
		3.	Beskidy Mts, partially forested with deforested intramountainous basins
		4.	Carpathian Foothills, deforested, covered by loess and loess-like deposits
II.	Carpathian foreland, locally forested		
III.	Sudety Mts	1.	higher part, partially forested
		2.	deforested fore-mountain hills, covered by loess
IV.	Middle Poland Upland, locally forested	1.	parts totally covered by loess
		2.	parts partially covered by loess
		3.	parts without loess
V.	Lowland area, occupying most of the studied area	1.	periglacially formed areas during the last glaciation, partially forested, with lakes and swamps
		2.	the same areas but without lakes and swamps, cultivated
		3.	areas formed during the last glaciation, located at the southern base of main moraine ridges with outwashes and swamps, forested
		4.	areas formed during the last glaciation - moraine hills and ridges, with lakes, partially forested, cultivated
		5.	areas formed during the last glaciation - slopes of main moraine ridges, without lakes and swamps, deforested, cultivated
		6.	clayey flat plains between moraine ridges, deforested, cultivated
VI.	Scandinavian Mts		
VII.	Norrland Plateau	1.	western part, boulder moraine with forests and lakes
		2.	eastern part, boulder moraine, sandy-silty material in river valleys below the highest coastline

more resistant bedrock of the Sudety Mts and the Scandinavian Mts implies lower rates of potential erosion and suspended sediment yield. The lower energy of relief in the Middle Poland Upland should make the erosion and sediment yield very small. The factors characterizing the Lowland areas, particularly areas without moraine hills and ridges, should favour very low sediment yield.

Table 2 – Potential erosion conditions in morphological units in the Baltic Sea drainage basin. The morphological units numbered in Table 1.

Morph. unit	heights in m		typical slopes (°)	cover deposits (bedrock)	type of soil	gully erosion	mean annual precipitation (mm)	No of months with mean temp >0°C	specific runoff (l s^{-1} km^{-2})	lakes	reservoirs	swamps	forest	arable fields	pasture, meadows	river regulation works
	absolute	relative														
I.1	2663	1800	30-60	a,c,d (m, n)	p,r	.	1000-2000	5-6	15-50	...			...		...	
I.2	1725	1000	20-30	d (o)	p,r	.	800-1400	7-9	10-30	.	..	.	....	.	..	
I.3	1000	400	15-25	d (o)	p,r,s, t,u	...	800-1200	8-9	10-20	.	...	.	..	...	..	...
I.4	590	250	10-30	e,f,g,h (o)	r,s, t,u	....	600-1000	9-10	8-15	.	...	.	.	....	..	...
II	300	100	3-5	b,i	r,s	.	500-700	10	5-15	.	..	.	..	...	...	...
III.1	1605	800	15-25	a,c,d (m,n)	p,r	.	800-1200	8-9	15-25	.	...	.	..	...	..	...
III.2	500	200	5-15	f,g (m,n)	s	...	700-900	10	10-15	.	...	.	.	....	..	...
IV.1	390	100	5-10	g (n)	t	....	600-700	10	10-15	.	..	.	.	....	..	..
IV.2	350	100	5-10	f,g (m,n)	s,t	...	600-700	10	10-15	.	..	.	.	....	..	..
IV.3	612	300	15-25	c,d,e,f (m,n)	p,r, s,u	..	600-800	9-10	10-15	.	..	.	...	...	...	..
V.1	150	20	0	b,i,j,l	r,s	.	500	9-10	5	..	.	...	...	..	...	..
V.2	254	50	0	b	r,s	.	500	10	5	.	..	.	.	....	..	...
V.3	150	50	0	i,j,l	r,s	.	500	9-10	5	.	.	....	....	..	...	.
V.4	377	250	5-10	b	p,r,s	..	600-1000	9-10	10-15	....	...	..	...	...	...	..
V.5	300	200	5-10	b	r,s	...	600-1000	9-10	10-15	.	.	.	..	....	...	..
V.6	50	20	0	i,k	u	.	500-600	8-10	5	.	.	...	.	....	...	..
VI	2117	1500	30-60	a,c,d	p	.	400-1600	3-8	15-40	....	....	....	..		...	...
VII.1	1000	400	15-30	a,j,l (m)	p,r	.	400-600	7-9	10-15	....	....	....	....	..	...	...
VII.2	300	200	10	a,j,i, l (m)	p,r t,u	.	350-500	8-9	8-12	..	..	..	...	....	...	..

explanations:

cover deposits:
a boulder moraine
b till
c stony material
d stony-clayey material
e sandy-silty material
f silty-clayey material
g loess deposits
h loess-like deposits
i alluvia
j glaciofluvial deposits
k lake deposits
l peat

bedrock:
(m) crystalline rocks
(n) carbonate rocks
(o) flysch (sandstones, shales etc.)

type of soil:
p stony-clayey
r sandy-clayey
s silty-clayey
t silty
u clayey

intensity of occurence:
. unimportant
.. moderate
... high
.... very high

Data Used and Criticism

The data presented and discussed in this paper are values of suspended sediment load or yield calculated from sediment concentrations measured at river gauging stations. The distribution of the gauging stations is presented in Fig. 2. The total number of gauging stations is 299, located on 188 rivers.

In Sweden and Finland the gauging stations are located mostly at river mouths. The southern and the southeastern parts of the investigated area are more densely covered by gauging stations. Consequently, the spatial distribution of the suspended sediment yield is better expressed in these parts of the studied area. The data base made possible an analysis of suspended sediment load variations and suspended matter deposition along the large rivers Vistula, Odra, Nemunas and Daugava. It has also been possible to make an estimation of the suspended matter supply to the Baltic Sea and its different sub-basins.

The data have been obtained from different sources. The sources of the data base and the different sampling and calculation techniques used are listed in table 3. It must be stressed that the values of the suspended sediment load or yield used in this paper have been calculated by the hydrological surveys in the different countries. The accuracy of the values depends on sampling methods, laboratory analysis techniques, calculation methods, the length of the records, and the hydrological conditions during the investigation period.

The techniques of water sampling differ between the different countries. In Sweden, water sampling is done with a depth-integrating technique (Nilsson 1969, 1971). Between 0 and 30 samples are taken per month depending on the water discharge. There is more frequent sampling during spring snowmelt. In Finland, point samples are taken 1 m below the water surface (Wartiovaara 1975). On average, twelve samples are taken per year in big rivers and four samples a year in small rivers (Kauppi and Pitkänen 1986). A comparison was made in two Finnish rivers between depth-integrated sampling and point sampling. In one of the rivers, the depth-integrating technique gave 2% higher concentration values than point sampling but in the other river no difference was found (Nilsson 1986). In Denmark, the depth-integrating technique was introduced in 1969 (Hasholt 1983, 1986). In Poland, sediment concentration is measured from bridges or banks at 07.00 hrs every day at a point 1/3 from the water surface (*cf* Branski 1975). The water stage is also read at 07.00 hrs. In the former USSR water samples are taken at fixed hours with point or integration technique. Point sampling is made for depths under 2.5 m. Depending on the flow depth H, samples are taken in one point at $0.6H$ or $0.5H$ if $H<0.4$m otherwise in two points, $0.2H$ and $0.8H$ (Gidrometeoisdat 1975). Water level observations and water samplings are done once a day at 08 hrs during the low flow period, and twice a day at 08 hrs and 20 hrs or more times during flood events or fast diurnal water level changes in small rivers.

A comparison of the laboratory analysis techniques used in Finland, Sweden and Denmark has been made (Nilsson 1986). Samples from the same mixtures of

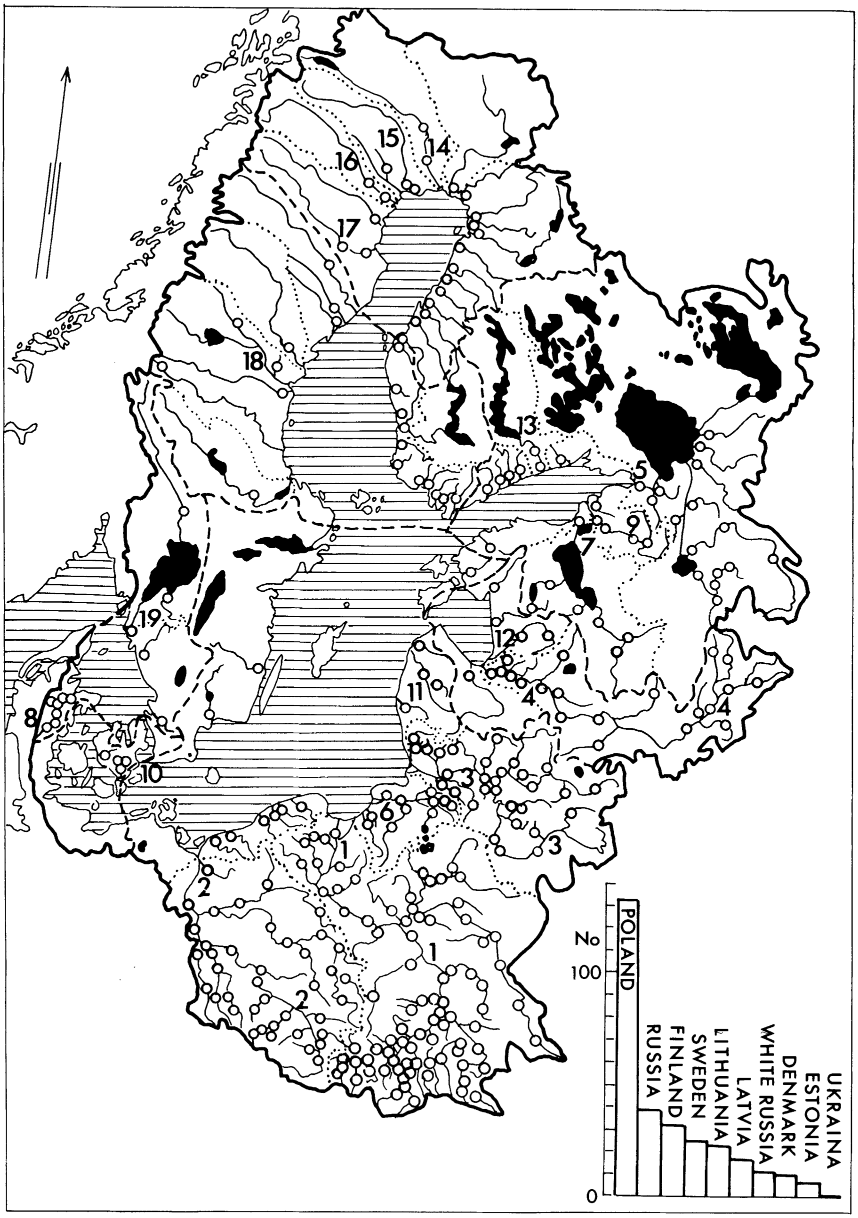

Fig. 2. Distribution of suspended sediment measuring stations. The number of stations in each country is presented. Dotted line shows the divide of catchments with an area larger than 25,000 km^2. Larger rivers are numbered: 1) Vistula, 2) Odra, 3) Nemunas, 4) Daugava, 5) Neva, 6) Pregola, 7) Narva, 8) Gudenå, 9) Luga, 10) Suså, 11) Venta, 12) Gauja, 13) Kymijoki, 14) Torne Älv, 15) Kalix Älv, 16) Lule Älv, 17) Skellefte Älv, 18) Indalsälven, 19) Göta Älv.

known sediment concentrations were sent to laboratories in the three countries. The laboratories in Finland and Denmark obtained slightly higher concentrations than the actual concentrations, while the Swedish laboratories using the IHD analysing method gave results close to the expected values (Nilsson 1986). The laboratory techniques in Poland and the former USSR were not checked. In Poland the drying is not done in an oven.

The calculation methods are of especially great importance for the magnitude and accuracy of the calculated load. For instance, in Poland, where the sediment concentration and water discharge at 07.00 hrs are multiplied to get the daily load, the maximum values of the suspended matter concentration during flood events are generally missing in the calculations. This affects the representativity of the data and the magnitude of the calculated load, especially in small mountainous rivers with very rapid variations in water discharge and turbidity. The load is corrected by the parameter K which corrects the load based on point measurements to load for the whole cross profile. The K is calculated from measurements of velocity and sediment concentration made 5-10 times every year in profiles of a cross section. Froehlich studied a small river, Kamienica Nawojowska, in the western Carpathians, with a catchment area of 239 km^2. Suspended load during a few days of large summer floods reached 95% of the annual suspended load (Froehlich 1972, 1973, 1975). Such dynamic suspended sediment transport must be measured more than once a day. Froehlich (1982) also compared daily values of sediment transport in the small tributary stream during seven months when using daily and hourly measurement values. The daily loads varied between -100% to +839% between daily and hourly measurements (Froehlich 1982 p. 113). Suspended load based on measurements made every one to three hours during flood events and every day during inter-flood periods tabulated in Froehlich (1975, pp. 82-83) has been compared for the purposes of the present article with the sediment transport received from the Polish Hydrological Survey relating to the same period. The more frequent measurements gave 2 to 3 times higher suspended load compared to data received from measurements at 07.00 hrs. Consequently, it is realistic to assume twice as high values in the Carpathians as those indicated in this article. However, with increasing catchment area the variations in turbidity and water discharge are less rapid, and the daily load calculated with data at 07.00 hrs is closer to the load that is actually transported.

In the former USSR the measured sediment concentration in a profile or a point is corrected by an equation to obtain a mean concentration for the whole river cross section. Load is calculated with two methods, either by using daily measurements at fixed hours, or with sediment rating curves.

In Denmark computations are made on daily concentration values found by linear interpolation between measured concentration values. Daily concentration is multiplied with daily discharge.

In Sweden, water discharge and sediment load (g/s) are log-transformed to develop sediment rating curves. A systematic error always arises when equations are developed through log-transformation. In Sweden, there is no correction for the bias obtained due to log regression. Therefore, this method may also produce load values that are too low, especially in small rivers which have a wide scatter of data. In a small river in the Swedish mountains with a drainage area of about 340 km^2 the load calculated with a log regression equation using the same water discharges as on the sampling occasions, amounted to 1/3 of the load calculated from the measured concentrations of the sampling occasions (Jansson 1985a, 1985b). In larger rivers, the magnitude of the underestimation of sediment load due to the log transformation technique without correction for bias is probably much smaller but is impossible to estimate without further research.

In Finland, the mean of measured concentrations during a month is calculated. Mean monthly concentration is multiplied by mean monthly water discharge (Kauppi and Pitkänen 1986). This procedure must give a completely random value. As about 12 water samples are taken per year the means may often be the value of only one measurement. In the case of no concentration measurements during a month the missing concentration is replaced by the mean of annual measured concentration. As a general rule it may be said that the multiplication of monthly means is not a good procedure because it introduces an underestimation of the load. A comparison can be made with the use of mean values in an investigation in Costa Rica (Jansson 1992). A 30% higher annual load value was obtained if hourly water discharges were used together with a sediment rating curve, compared to when daily water discharges (as a mean of the hourly water discharges) were used. Monthly means probably give a much larger underestimation of the load.

Only long periods of measurements give mean annual load values that are near the long-term averages. The length of the measurement period and the years investigated are different in the various countries (Table 3). In Finland, Poland, Sweden and in countries that earlier belonged to the USSR, concentration measurements have been made regularly by the hydrological surveys of these countries, and the data series are long. In Denmark, no regular observations on sediment transport have been made. However, some investigations have been carried out during shorter periods (Table 3).

Mikulski (1986b) calculated the average water inflow to the Baltic Sea for the period 1921-75. During the period 1961-70 the water inflow was average, but during 1971-75 below average. According to Probst (1989), there was a humid period in 1960-70 and a dry period after 1970. The dry period began earlier for rivers in the northern part of the area. Vistula was not affected by this dry period but the water discharge was above average even after 1970. In southwestern Sweden and Finland, the drought extended until 1980 (Probst 1989). Consequently, in Denmark, Finland, and Sweden the load of the analysed period might be lower than the long-term average, whereas in Poland it might be above the average.

Table 3 – Sources and measurement and calculation techniques of the data used in the paper.

Country	Publications used or origin of computer lists	Frequency and type of water sampling	Calculation technique	Period of analysis
Sweden	computer lists fr. SMHI	0-30 times a month, more frequent during spring melting. Depth-integrated sampling	sed. rating curve on load in g/s, daily Q is used	2-15 years during 1967-1981 (14 stations cover 10 years or more)
Finland	computer lists fr. Kauppi and Kauppila Kauppi and Pitkänen (1986)	4-12 times/yr. point sampling 1m below surface. (From 1985 sampl. more often during spring highwater)	monthly mean Q_i from Q_{daily}, monthly mean conc. (C_i) from measurements. Annual load = $\sum_{i=1}^{12} aQ_iC_i$	1976-84
Denmark	Hasholt (1974, 1983, 1986), Heise (1974), Höst-Madsen and Edens (1974)	2 sampl./week on average, adapted to water discharge. Depth-integrated sampling. In Suså periods with turbidity measurements and automatic sampl.	daily load from sediment rating curves of conc. and linear interpolation of conc.	1 to 3 years during the period 1970-1979
Poland	computer lists fr. IMGW, Warszaw, Hydrological yearbooks: Vistula Odra drainage basin	every day at 07.00 hrs, during high water every 2-5 days, point sampl. at 1/3 from the water surface	the point conc. is multiplied by a coefficient. Daily load calculated from measurements at 07.00 hrs.	10-20 years during 1961-1980
Estonia Latvia Lithuania Russia White Russia Ukraina	USSR Committee for the IHD (10 volumes) Dedkov and Mozzerin (1984)	point sampling for depths <2.5m, otherwise integrated sampling, at fixed hours	load from daily measurements. Sediment rating curves are also used	1965-1974 1-27 years during 1951-1980
Norway	no data			
Germany	no data			
Czechoslovakia	no data			

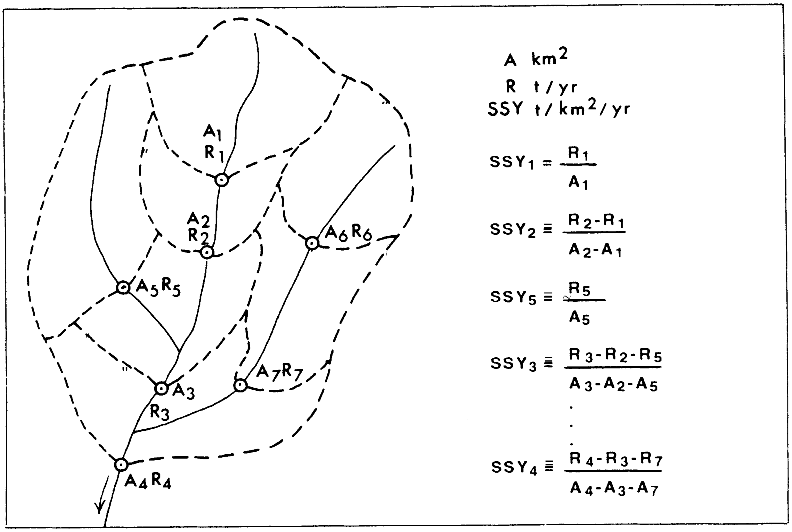

Fig. 3. The way of calculating suspended sediment yield in successive downstream sub-catchments. A) catchment area; R) suspended sediment load.

Calculations of Sediment Yield for Sub-Catchments

Average annual values of suspended sediment yield in subsequent downstream sub-catchments have been calculated according to the method presented in Fig. 3. If the suspended load decreases downstream, the sediment yield for that sub-catchment has not been considered.

Some of the sub-catchments are situated wholly within one of the specified morphological units of the studied area, others cover more than one unit.

Results

Spatial Distribution of Suspended Sediment Yield

The spatial distribution of average annual suspended sediment yield within the Baltic Sea catchment is presented in Fig. 4. Calculation errors have to some extent been concealed by the wide sediment yield classes used. The suspended sediment yield within the Baltic Sea catchment shows a spatial distribution that is in accordance with the potential erosion conditions in the morphological sub-units (Table 2, Figs. 4 and 5). From Fig. 5 we can see that the highest yields, far in excess of 50 t/km^2/yr, are typical for the Carpathians. The Carpathian Foothills are the strongest eroded sub-area (about 380 t/km^2/yr on average). The average sediment yield in the Sudety Mts (unit III) is 30 t/km^2/yr, and 70 t/km^2/yr in their fore-mountain hills. In

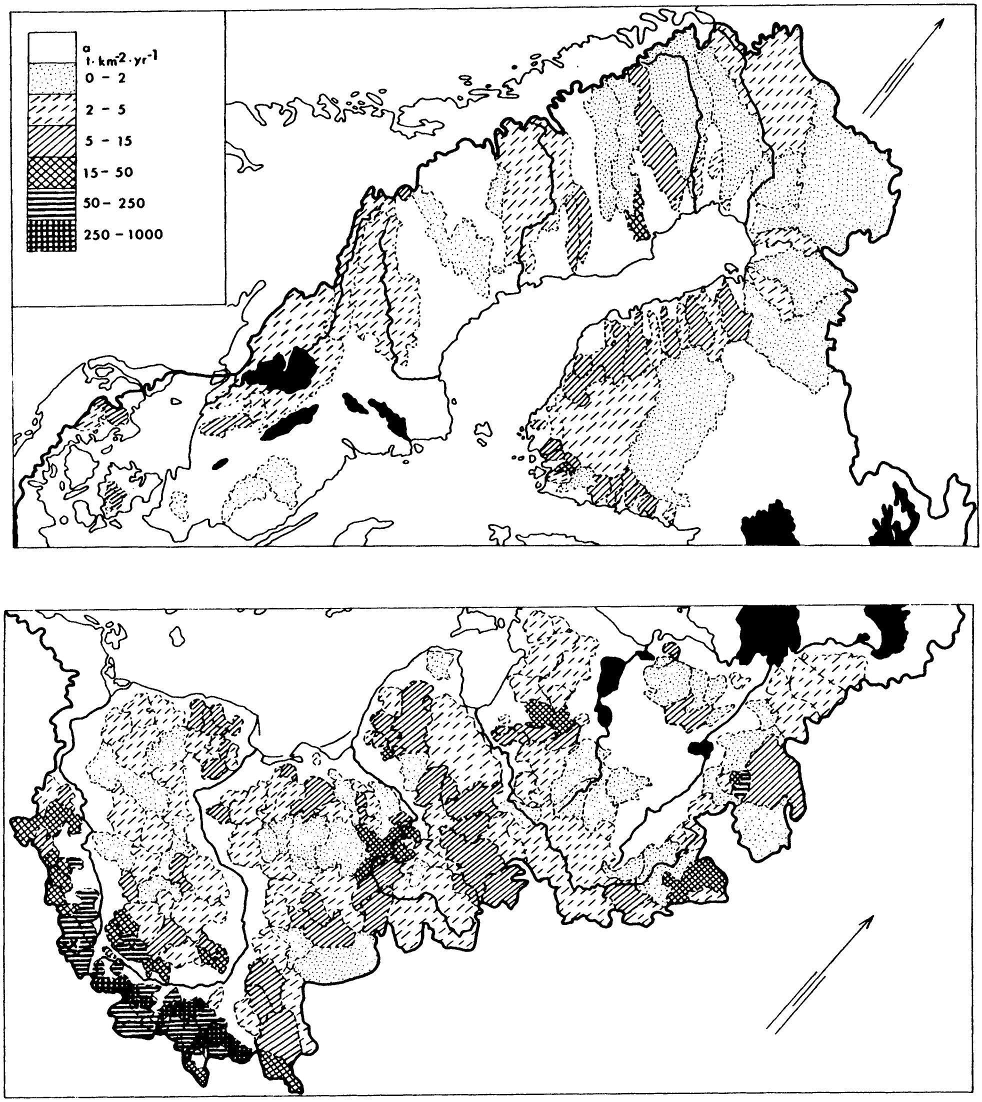

Fig. 4. Suspended sediment yield in sub-catchments of the Baltic Sea drainage basin. a) area with no measurements or areas with intensive sediment deposition in river valleys. x) increased suspended sediment yield due to an intensive sediment supply from mining regions.

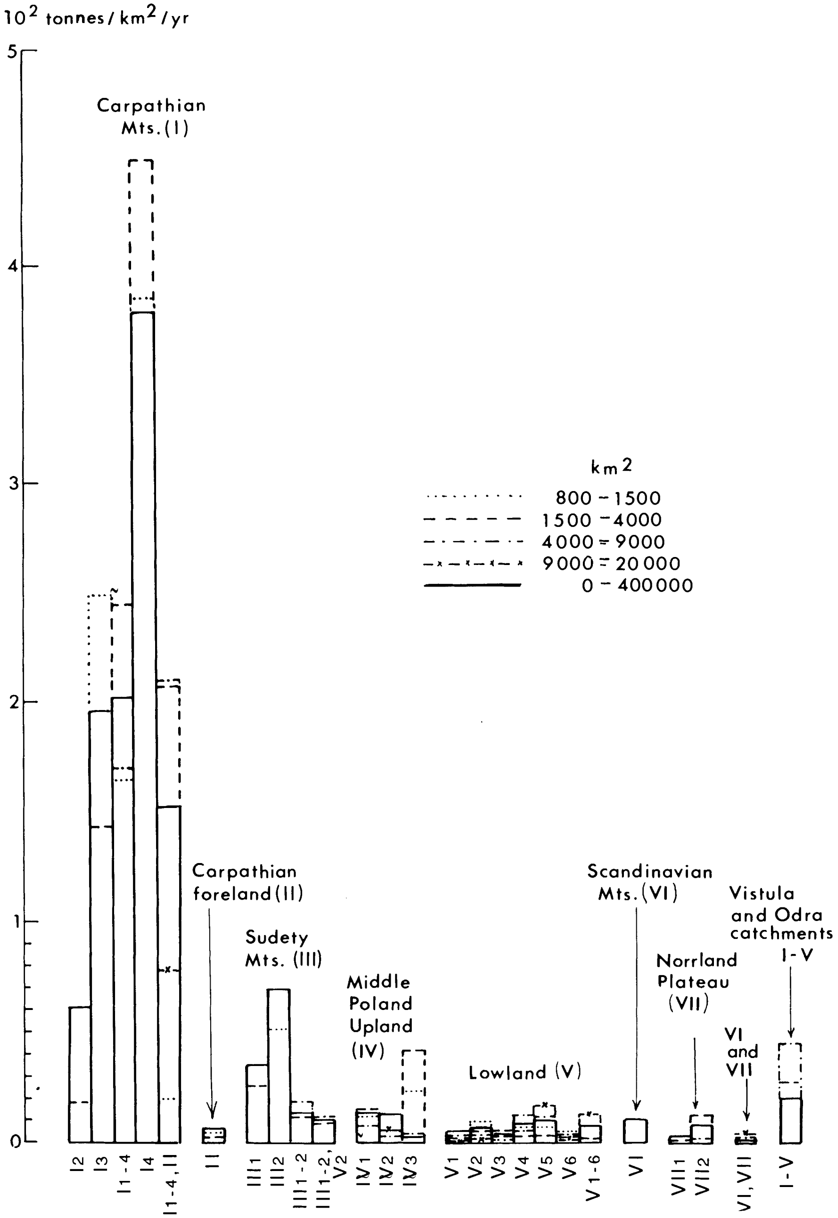

Fig. 5. Mean values of suspended sediment yield in different morphological sub-units. Suspended sediment yield values are calculated for different catchment size classes. The main morphological units are indicated in Fig. 1 and the morphological sub-units of the abscissa are described in Tables 1 and 2. In some cases the drainage basins cover more than one morphological sub-unit.

the Middle Poland Upland the mean sediment yield is 15 t/km^2/yr. Similar values are typical for the Scandinavian Mts and for the eastern part of the Norrland Plateau, where the river valleys are situated below the highest coastline. The Lowland part of the Baltic Sea drainage basin is characterized by low suspended sediment yield, between 3 and 12 t/km^2/yr on average. Only deforested moraine hills and ridges on sedimentary bedrock are strongly eroded, and the suspended sediment yield reaches more than 15 t/km^2/yr, but locally (*e.g.* the Waldai Hills in Russia) over 50 t/km^2/yr. In southern Poland and in northern Czechoslovakia large amounts of mechanical pollutants are locally discharged into the Vistula and the Odra from mining and strongly industrialized areas, thus producing high load values (Fig. 4).

The strongest eroded areas in the Baltic Sea catchment, the Carpathians, are characterized by large variations in suspended sediment yield (Fig. 5). In contrast, the flat Lowland areas have rather uniform suspended sediment yields. Topographical and also pedological and climatic conditions determine the general increase in sediment yield from north to south in the studied area.

Land use conditions also affect the suspended sediment yield. Intensive land use increases sediment yield considerably. The sediment yield is decreased by reforestation and also by large areas occupied by lakes. In the Scandinavian Mts a few rivers drain glaciers. They carry much material but most of it is deposited in lakes situated in the upper part of the Norrland Plateau. For instance, the river Rapaälven carries 230 t/km^2 upstream of the Lake Laitaure but only 21 t/km^2 downstream of the lake (Axelsson 1967). The Norrland Plateau has a relatively small gradient, swamps, and boulder moraines with forests, all of which contribute to low sediment inflow to the rivers. There are also many river channel broadenings, lakes, and reservoirs where sediment is deposited. Further downstream, below the highest coastline, the river valleys are filled with water-transported sediments which are easily eroded, and there is again an increase in erosion and sediment yield (Fig. 4).

Relationships between suspended sediment yield and catchment size have been established. For all morphological units or subunits in the studied area they show a decreasing trend with increasing catchment area (Fig. 6). This gives an indication of sediment deposition along the rivers. Another possible explanation of the decreasing yield with increasing drainage area is that the tributaries in the downstream parts contribute less sediment. Only in the Carpathian Mts (I) and in the Sudety Mts (III) were the area relationships found to be more complicated. In these mountains, the suspended sediment yield increases downstream to the foremountain areas. Downstream of these strongly eroded zones the suspended sediment yield shows a clear decreasing trend, which is caused not only by deposition but also by the substantial decrease in suspended sediment inflow from areas with low relief energy.

A similar decreasing trend in suspended sediment yield has been found for the longitudinal profiles of the large rivers Vistula and Odra (Fig. 6). The decrease is

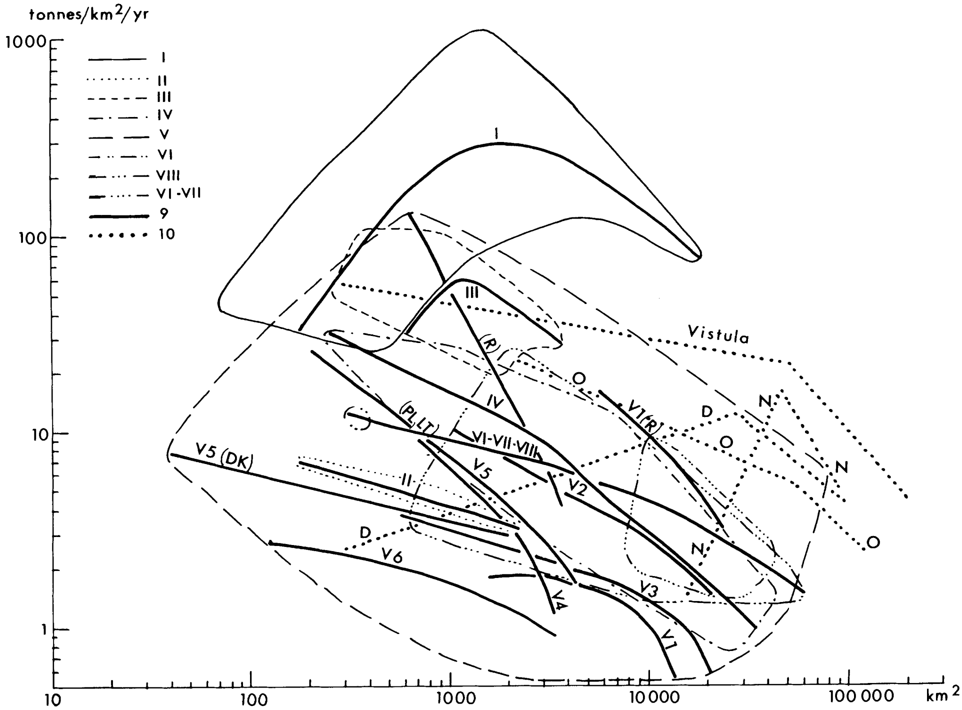

Fig. 6. Relationships between suspended sediment yield and the size of catchments within morphological units. Envelopes of fields of the relationships for morphological subunits numbered as in Tables 1 and 2. 9) regression lines; 10) relationships for some large rivers: V) Vistula, O) Odra, N) Nemunas, D) Daugava.

rapid downstream of their last mountainous tributaries. In the case of the large lowland rivers, the Nemunas and the Daugava, the suspended sediment yield increases downstream from the flat periglacially formed areas to the moraine hills and ridges of youngest Pleistocene. Downstream of these hills a clear decreasing trend in the suspended sediment yield has been found.

Suspended Sediment Deposition along Large Rivers

The rates of suspended sediment deposition within the catchments can be calculated more in detail for large rivers which have a dense network of sediment gauging stations (Fig. 7). Cumulative suspended sediment load entering the main river from tributaries is represented as curve A, and the actual sediment load calculated from measurements in the main river as curve B. The A curves show the suspended matter transport in a hypothetical situation without sedimentation in the river valleys. The difference between the two curves shows the deposition rate, which also includes material deposited in reservoirs. The sediment deposition

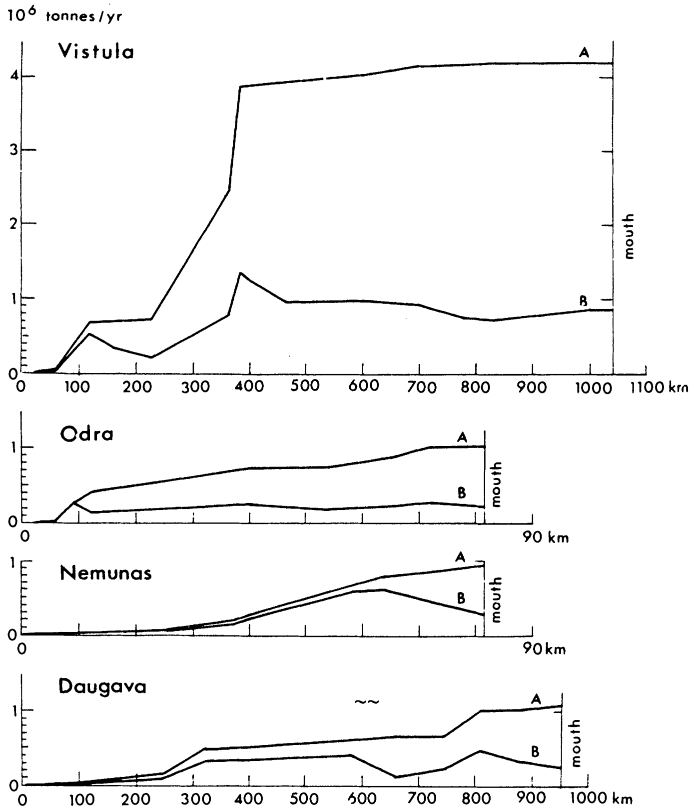

Fig. 7. Hypothetical cumulative sediment inflow to the main river, (curve A) and actual sediment load in the main river calculated from measurements (curve B) in the longitudinal profiles of four large rivers draining to the Baltic Sea.

along the rivers is 80% in the Vistula, 78% in the Odra, 70% in the Nemunas, and 70% in the Daugava.

A large part of the sediment deposition in the Vistula River takes place where the river gradient changes from a steep inclination in the Carpathians to a small gradient in the Middle Poland Upland and the Lowland area. Sediment is deposited on river banks, on the flood plain and in reservoirs. No more than 20-30% of the total amount of the suspended sediment load feeding the largest rivers in their source areas is delivered to the Baltic Sea. In Finland and Sweden, the fluvial sediment transport is reduced by deposition in a large number of lakes and reservoirs.

Suspended Sediment Inflow to the Baltic

The gauging stations near the river mouths have been used to calculate the mean

Table 4 – Mean annual suspended sediment inflow to the Baltic Sea. The numbers of the sea sub-basins are found in Fig. 1.

Sub-sea of the Baltic	No.	Type of values	Suspended sediment inflow	t/yr	%
Bothnian Bay	1	measured areas	614,000		
		estimated areas	100,000	714,000	16.0
Bothnian Sea	2	measured areas	472,000		
		estimated areas	96,000	568,000	12.7
Gulf of Finland	3	measured areas	775,000		
		estimated areas	20,000	795,000	17.8
Gulf of Riga	4	measured areas	504,000		
		estimated areas	7,000	511,000	11.6
Baltic proper	5	measured areas	1546,000		
		estimated areas	108,000	1654,000	37.1
The Sound and the Belts	6	measured areas	2,000		
		estimated areas	10,000	12,000	0.3
Kattegat	7	measured areas	165,000		
		estimated areas	36,000	201,000	4.5
Baltic Sea	1-7	measured areas	4078,000		
		estimated areas	377,000	4,455,000	100.0

annual suspended sediment inflow to the Baltic Sea. The inflow to the sea by rivers without sediment gauging stations has been approximately estimated in analogy with neighbouring rivers with such measurements, allowing for the size of their drainage areas. The Danish contribution to the Danish Straits was made on the basis of data from the Suså and Tude rivers, and to the Kattegat on the basis of data from the Gudenå river. Load from unmeasured areas of the former USSR are estimated by using the Lisitsyna and Alexandrova (1972) formulae. It must be stressed that most large rivers draining into the Baltic Sea have regular suspended sediment concentration measurements at their mouths. Table 4 presents the average annual suspended sediment inflow to the sub-basins of the Baltic Sea. The suspended sediment inflow to the sea by rivers carrying more than 20,000 t/yr is shown in Fig. 8.

The material discharged past the river mouths can be transported into the open sea, except for the Odra and the Nemunas which discharge the suspended load into shallow and isolated lagoons (Szczecin Lagoon and Curonian Lagoon). However, the material supplied by these two rivers can also partially be transported into the open sea.

The total amount of suspended sediment material transported to the Baltic Sea is 4,455,000 t/yr, 37% of which is supplied to the Baltic proper (Table 4). Part of that material is deposited in the lagoons mentioned earlier. The suspended load delivered to Kattegat and to the Danish straits is very small.

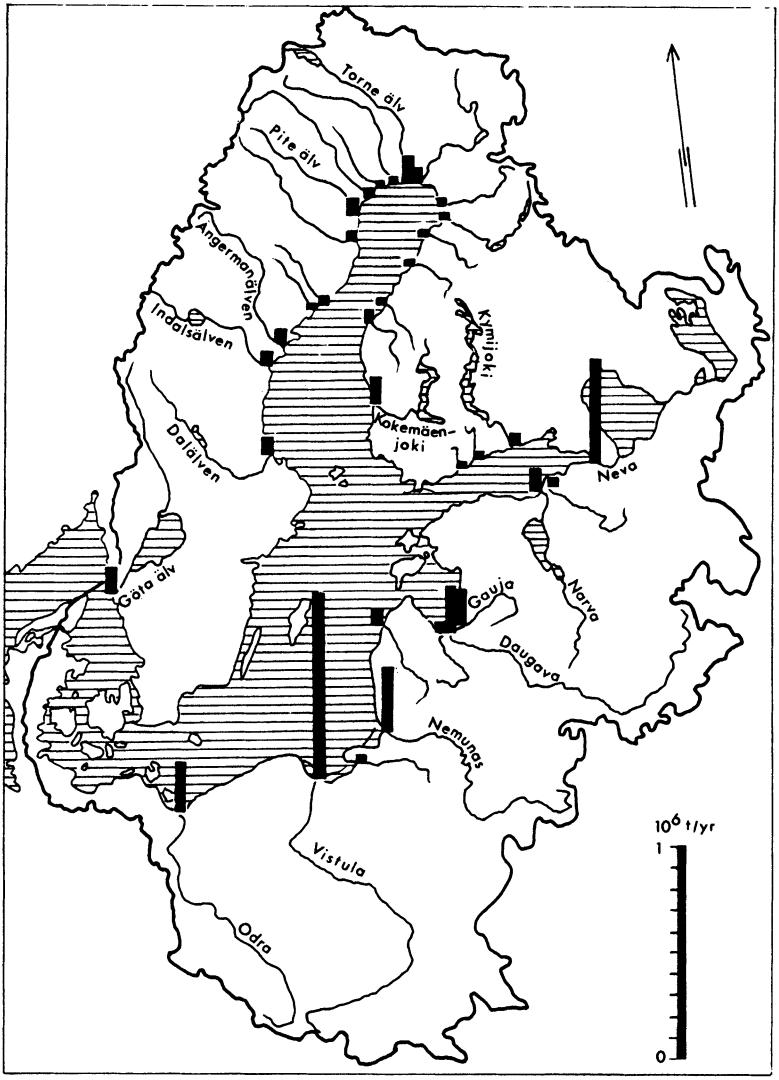

Fig. 8. Mean annual inflow of suspended sediment to the Baltic Sea. The sediment inflow from rivers discharging more than 20,000 t/yr are shown.

The Vistula river is the main source of suspended matter supplied to the Baltic (Fig. 8). The contribution by this river reaches 866,000 t/yr, *i.e.* 20% of the total supply to the whole Baltic Sea (and 52% of the discharge to the Baltic proper). The river Neva discharges 506,000 t per year, *i.e.* about 12% of the total supply to the Baltic Sea (and about 64% of the amount carried to the Gulf of Finland). Three rivers contribute 200,000-300,000 tonnes each per year to the Baltic Sea. Five rivers contribute 100,000-200,000 t/yr each, and seven rivers 50,000-100,000 t/yr each to the Baltic Sea.

The supply of suspended matter by the rivers discharging to the Bothnian Bay and to the Bothnian Sea is more uniform along the coast as there are no large rivers.

Assessment of Results

The suspended sediment yield reaches maximum values in the flysch Carpathians. Only in that part of the area does the sediment yield reach values similar to those of the strongly eroded mountains in Europe. The sediment yield in the rest of the area is very low.

Much of the material transported by large rivers is deposited before it reaches the Baltic Sea. About 80% of the material in the Vistula and the Odra, and 70% in the Nemunas and the Daugava, is deposited along the rivers in channels, on the floodplains, and in lakes and reservoirs. Some of this deposited material is polluted, as chemicals easily adhere to material within the finest grain sizes and as there are colloidal and solid matter from waste material that is often contaminated with heavy metals. Not only the Baltic Sea is being polluted but also the areas along the large rivers.

In comparison with the data included in other publications, *e.g.* Atlas Mira (1964), the values given in this article of suspended sediment transport at the mouths of large rivers draining to the Baltic Sea are small. The calculated and estimated annual suspended material supply to the Baltic Sea is 4,455,000 t. The value calculated by Nilsson (1986) amounts to 7,500,000 t/yr. The great difference between these two estimations is mainly due to different calculation periods and to different calculation methods. Nilsson (1986) used sediment transport data for the period 1961-70 and had to make rough estimations for large areas which had no or sparse load data. More sediment transport data have been available for the present study and estimations for areas without load data are made to a smaller extent. A longer time period is considered in this study including data, if available, for the drier period 1970-1980 (Table 3). In the Vistula there was no decrease in water discharge during 1970-80. Nevertheless, sediment transport decreased very much as a result of sedimentation in new reservoirs.

Acknowledgements

The cooperation for this article has been made possible through a scholarship from the Swedish Institute to Adam Lajczak.

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Received: 15 September, 1992
Accepted: 11 February, 1993

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