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Jokivesien tuomien ravinteiden alkuperä, käyttäytyminen ja vaikutukset

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The Finnish coastal waters receive annually on an average 79 000 t of nitrogen and 4 800 t of phosphorus from or via the Finnish territory. The inputs via rivers are 4 200 t of P and 69 000 t of N, i.e. 87 % and 88 % of the total inputs of N and P, respectively. The riverine inputs vary considerably from year to year according to hydrological conditions. The total nutrient inputs have not markedly changed during the 1980s and early 1990s. Compared to the early 1970s the total phosphorus flux has decreased, especially due to the efficient purification of municipal waste waters, whereas the total nitrogen flux, despite decreased industrial inputs, has probably increased due to intensified agriculture, fish farming and municipal loading as well as due to higher atmospheric inputs and increased water flows. Direct point-source loading to coastal waters and to the lower river courses accounted for 17% and 18 % of the annual land-derived inputs of N and P, respectively. The estimated agricultural contributions to coastal waters were 31 % of the N and 35 % of the P inputs. The remaining 52 % of total N and 47 % of total P originated from other anthropogenic sources (e.g. forestry) and natural leaching. Under average summer conditions, point-sources accounted for 54 % and 53 % of the bioavailable inputs of N and P, respectively. The respective estimates for agricultural inputs were 25 % and 20 %. This means that only one quarter of the bioavailable land-derived inputs originated from natural leaching or from diffuse anthropogenic sources other than agriculture.

Nutrient inputs from the land cause extensive eutrophication (new planktonic production and increased biomasses), especially in waters where mixing with open sea water is limited due to complex coastal morphometry or where remineralization and vertical transport of nutrients is effective due to shallowness. Thus the whole Finnish coastal water zone of the Gulf of Finland, the inner and certain central parts of the Archipelago Sea, waters off Uusikaupunki, the Quark archipelago including the Kyrönjoki Estuary, waters off Kokkola-Pietarsaari and the NE Bothnian Bay show increased concentrations of nutrients and chlorophyll-a. The eutrophied area in the Kokemäenjoki Estuary and the near-by waters of the Bothnian Sea is relatively small, despite the largest single nutrient input to the Finnish coastal waters, because of the favourable mixing conditions with open sea water. In the outer Finnish coastal and open waters of the eastern Gulf of Finland eutrophication is mainly due to inputs from the River Neva and the St. Petersburg region.

Estuaries and other semi-enclosed coastal water bodies control external nutrient fluxes both quantitatively and qualitatively. Under summer conditions inorganic nutrient inputs are usually fixed into new organic matter within the coastal water zone. Several coinciding internal processes seem to force the coastal water ecosystems towards N limitation, although the mean bioavailable N:P ratio of the land-derived inputs is 3.4 times the optimal for phytoplankton (the Redfield ratio). However, in the Bothnian Bay phosphorus is the main limiting nutrient of primary production.

The southern and south-western Finnish coastal waters, characterized by complex morphometry and semi-enclosed archipelagic basins, favour nutrient retention and removal, whereas estuaries and coastal waters of the Bothnian Sea and the Bothnian Bay are generally either too open or too shallow for an effective nutrient filtration.The Neva Estuary and the adjacent waters of the eastern Gulf of Finland filter effectively external nutrients due to a two-layer estuarine flow system and successive semi-enclosed basins, thus controlling eutrophication of the whole Gulf of Finland.

This study suggests that decreasing the trophic degree of the Finnish coastal waters requires especially reduction of bioavailable N from the Finnish agriculture and municipalities. In addition to the strong measures already taken against P loading from municipalities, the inputs should be reduced from agriculture and industry (including fish farming). Regarding the Gulf of Finland, a reduction of the high nutrient load from the River Neva-St. Petersburg area would improve the state of both the open Gulf and the Finnish coastal waters.

Keywords: eutrophication, nitrogen, phosphorus, organic matter, nutrient balance, sedimentation, estuaries, coastal waters, Baltic Sea

1 INTRODUCTION

1.1 Monitoring and research on the loading and eutrophication of the Finnish coastal waters

Eutrophication is considered one of the main problems in the Baltic Sea, especially in its coastal waters[1)] (HELCOM 1993a). Rivers contribute the main part of the nutrient inputs to this shallow brackish water basin (Larsson et al. 1985, HELCOM 1993b). Regarding the state of the Finnish coastal waters, the role of riverine loading is especially important, since on an annual basis 80 to 90 % of the total land-derived nutrient load is delivered by rivers.

The earliest data on riverine loading as well as on nutrient concentrations and trophic conditions of the Baltic waters around Finland originate from the 1910s and 1920s (Leegaard 1920, Buch 1932, Holmberg 1935). Regular national monitoring of river water quality started in 1962 (Laaksonen 1970) and monitoring of riverine material inputs to the Baltic Sea in 1970 (Wartiovaara 1975, 1978). The national monitoring of coastal waters begun in 1966 (Kohonen 1974). The river monitoring has continued almost in its original form throughout the years. The most important change took place in 1985, when the sampling strategy was changed from time dependent (monthly) to flow dependent. The coastal water monitoring, on the other hand, has undergone several changes (Pitkänen et al. 1987, II). In fact, before 1979 most of the stations monitored by the water authority (presently the Water and Environment Districts and the Water and Environment Research Institute, WERI, of the National Board of Waters and the Environment, NBWE) were situated in the open parts of the Gulfs of Bothnia and Finland (Kohonen 1974). Since 1979, 100 to 110 coastal water stations have been sampled 2 to 4 times a year and since 1987 12 of these stations have been monitored more intensively, 15 to 20 times a year. In coordination with these programs the Finnish Institute of Marine Research (FIMR) monitores the open Baltic Sea around Finland (e.g. Kahma and Voipio 1989, Perttilä et al. 1994).

The monitoring programs produce information on the amount and variation of riverine inputs to the Baltic Sea and on general responses of coastal water quality to loading. However, the basic monitoring data alone (monthly or less frequent sampling) is insufficient for explaining the real dose-response relationships. For this purpose the relevant internal processes have to be studied by field and laboratory experiments, together with intensive *in situ* studies of physical, chemical and biological state variables.

In Finland the nutrient and trophic dynamics of coastal waters have been intensively studied, especially in the archipelago off Tvärminne and adjacent waters in the western Gulf of Finland. The basic hydro-, nutrient and production dynamics of the area has been described by Niemi (1973, 1975, 1978), Laakkonen et al. (1981), Hällfors et. al (1983), and Niemi and Åström (1987). In the early 1980s a series of field and experimental studies on ecosystem structure and dynamics has been launched in the same area by the PELAG project (e.g. Kuparinen 1984, Project PELAG 1990, Tamminen 1990, Kuosa 1991, Lignell 1993, Kivi et. al 1993, Kuuppo 1994).

The north-eastern Bothnian Bay receives high fresh water inputs together with industrial and municipal waste waters. Hydro- and production dynamical studies in this area were started by Alasaarela (1977, 1979a,b, 1980). Later, also the trophic and sedimentation dynamics and model applications have been investigated in the same area by, e.g., Alasaarela et al. (1986), Tolonen et al. (1988), Koponen et al. (1992), Inkala et al. (1993), Kangas et al. (1993) and Lax and Kangas (1993).

Studies on gross riverine nutrient fluxes to the Finnish coastal waters have been performed by Viro (1953), Wartiovaara (1975, 1978), Pitkänen (1987, I) and Pitkänen et al. (1987, 1988, II). For example, Larsson et al. (1985), Wulff et al. (1990) and HELCOM (1993b) have published estimates on total land-derived nutrient inputs to the Baltic Sea. Up to now, it has not been possible to quantify the filtering effect of coastal waters on gross river fluxes. Also the origin of fluvial nutrients is largely unknown quantitatively. In many Baltic Sea countries, including Finland, studies have been carried out which allow at least a rough partitioning of the total riverine load into its main sources (agriculture, municipalities, industry, forestry, natural background) in the catchments of the rivers (e.g. Siira 1983, Kauppi 1984, Sallantaus 1986, Pitkänen 1987, Pietiläinen and Re-

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[1)] In a global scale, the whole Baltic Sea is a very shallow sea and strongly affected by its catchment and can be thus regarded 'coastal' as a whole. However, in this study the term 'coastal waters' is defined as shallow (mostly < 20 m) and archipelagic or open near-coastal waters. Thus, besides the actual archipelagic waters, also the whole NE Bothnian Bay and the easternmost Gulf of Finland (Neva Estuary) are included in coastal waters.

kolainen 1991, Rekolainen 1993, Knuuttila et al. 1994, Jumppanen and Mattila 1994, VI).

1.2 The estuarine effect

Riverine nutrients undergo various biogeochemical processes during the mixing of river and saline water (e.g. GESAMP 1987, Burton 1988). Since in many areas of the northern Baltic Sea riverine inputs enter open waters via estuaries[2)] or archipelagic areas, attention has to focus on the quantitative and qualitative processes involving nutrients, particularly nitrogen and phosphorus, in coastal waters. Knowledge of these processes is essential for reliable estimates of nutrient inputs into the open Baltic ecosystem. Moreover, studies on estuarine nutrient dynamics provide information for measures against coastal water eutrophication.

Nutrients are transported to coastal waters from direct sources on the coast, via rivers, from the outer sea and via the atmosphere. The amounts and chemical forms of the nutrients control the impact on coastal water ecosystems. The balance of phosphorus (P) is mostly regulated by the exchange between dissolved state (especially inorganic phosphate) and organic or inorganic suspended particulate matter (SPM) (Pomeroy et al. 1965, Liss 1976, Froelich 1988, Sundby et al. 1988), while in the cycle and balance of nitrogen (N) also allochthonous dissolved organic matter (DOM) and molecular N_2 are participating (Billen et al. 1988, Howarth et al. 1988, Seitzinger 1988).

Organic and inorganic SPM enters estuaries via rivers and from the outer sea. Particulate organic matter (POM) is also generated in estuaries themselves by autochthonous planktonic production and possibly also geochemically via the flocculation of colloidal matter during the mixing of river and saline water (Sholkovitz et al. 1976, Postma 1980, Mantoura and Woodward 1983, Kranck 1984, Forsgren and Jansson 1992, Lebo and Sharp 1992). In shallow estuaries and coastal waters a large part of the sedimenting POM reaches the bottom, where substantial amounts of soluble nutrients are rapidly released as a result of bacterial decomposition, autolysis and desorption. Theoretically, nutrients from benthic regeneration and from allochthonous sources can fulfil a large part (in some cases all) of the nutrient requirements of the local primary production in an estuary (Callender 1982, Fisher et al. 1982, Balzer 1984, Wassmann 1991, Kamp-Nielssen 1992). In practice, however, a considerable part of the planktonic production in coastal waters is based on nutrient regeneration in the euphotic layer.

The total net autochthonous production of organic C (prod_{tot}) consists of two parts (Dugdale and Goering 1967):

$$\text{prod}_{\text{tot}} = \text{prod}_{\text{reg}} + \text{prod}_{\text{new}} \qquad (1)$$

The regenerated production (prod_{reg}) is based on nutrient circulation in the planktonic food web, while the new production (prod_{new}) is based on external nutrient sources. Eutrophication is primarily a sign of increased new production (e.g. Tamminen 1990, Wassmann 1991).

Empirically, when longer periods ≥ 1 productive season) are assessed, the ratio f between new and total production:

$$f = \text{prod}_{\text{new}}/\text{prod}_{\text{tot}} \qquad (2)$$

of boreal fjords, estuaries and coastal waters have been observed to vary mostly between 0.3 and 0.4 (Wassmann 1990, 1991, Heiskanen and Leppänen 1994). The f ratio represents the proportion of autochthonous organic matter that is annually exported from the euphotic zone, and is considered to be based on external nutrient sources from re-mineralization outside the pelagic ecosystem (Eppley et al. 1983). In the case of estuaries, in which advective horizontal transport of nutrients is often considerable, also horizontal transport has to be considered as part of external nutrients inducing new production (Wassmann 1991, VII).

In inner estuaries geochemical processes usually dominate nutrient fluxes, because of the high turbidity and strongly varying physicochemical conditions, while in less turbid outer estuaries biological processes usually dominate (Head 1976, Joint and Pomroy 1981, Fisher et al. 1988). The magnitude and direction of internal processes determine

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[2)] An estuary is defined as a semi-enclosed coastal body of water having a free connection with the open sea and within which the sea water is measurably diluted by fresh water from land drainage (Cameron and Pritchard 1963). In the broadest sence of the definition, the whole Baltic Sea can be considered as a large estuary. In the present study the term 'sea water' is considered to correspond to brackish water of the open areas outside a particular estuary or other coastal water area.

whether an estuary acts as a sink or as a source of a chemical constituent. In this study the estuarine filtering efficiency (F) is defined as:

$$F = \Sigma L / \Sigma i \qquad (3)$$

where

L = loss of a chemical constituent by physical, geochemical and biological processes
i = external inputs (riverine + atmospheric + open sea)

The role of coastal waters as a filter of fluvial inputs has been studied already in the 1940s in the Tvärminne-Pojo Bay area in the western Gulf of Finland (Halme 1944). Studies on material balances of estuaries and other semi-enclosed coastal water bodies within the Baltic Sea suggest that coastal waters may have an important role in controlling nutrient inputs to the open Baltic ecosystem (e.g. Wilmot et al. 1985, Heikkilä 1986, Jensen et al. 1988, Jørgensen and Sørensen 1988, Larsson et al. 1988, Floderus and Håkanson 1989, Christiansen et al. 1992, Forsgren and Jansson 1992 and Kamp-Nielssen 1992, Laursen et al. 1992, Yurkovskis et al. 1993, III-V, VII, VIII).

1.3 Objectives of the study

The aims of the present study are:

(1) To estimate the magnitude of the riverine nutrient inputs into the Finnish coastal waters, the possible trends in these inputs between 1970 and 1990 and to estimate the contribution of different primary sources to these nutrients, both annually and during the summer period (I, II, VI).
(2) To estimate the effect of land-derived nutrient loading on average trophic conditions of the Finnish coastal waters, using nutrient and chlorophyll-a concentrations as indicators (II, IV, V, VIII).
(3) To estimate nutrient balances for coastal waters and the effect of estuarine nutrient filtration on the trophic conditions of coastal and open Baltic waters. Two case study areas have been selected: the River Kymijoki Estuary (III, VII) and the River Neva Estuary with its adjacent waters of the eastern Gulf of Finland (IV, V, VIII).

2 STUDY AREAS

2.1 Rivers discharging to the Finnish coastal waters

For the present study 30 Finnish rivers, covering 239 000 km^2, i.e. 89.8 % of the total area discharging to the Baltic Sea from or via the Finnish territory, were selected (Fig. 1, Table 1). The same set of rivers has been used in several earlier studies (Pitkänen 1987, Pitkänen et al. 1987, 1988, I, II) as well as in pollution load compilations of the Helsinki Commission (e.g. HELCOM 1993b). The criteria for the selection were the presence of:

(a) a water quality station with adequate sampling frequency (mostly > 10 a^{-1}) near the mouth of the river, and
(b) a daily flow measurement station in the lower course of the river near the water sampling station

The rivers were divided into two groups: large rivers and coastal rivers (Table 1, Pitkänen 1987, I). The large rivers (Kymijoki, Kokemäenjoki, Oulujoki, Iijoki, Kemijoki and Tornionjoki) are characterized by a large (10 000 to 50 000 km^2) drainage basin, modest or high lake percentage (5 to 20 %) and rather low field percentage (< 10 %, however Kokemäenjoki 16 %). With the exception of the River Tornionjoki, these rivers are regulated by hydro-power plants. Together with the high lake-percentage and the large drainage basin this means that the seasonal flow variation is much smaller and the average residence time of the water much longer than that of small coastal rivers.

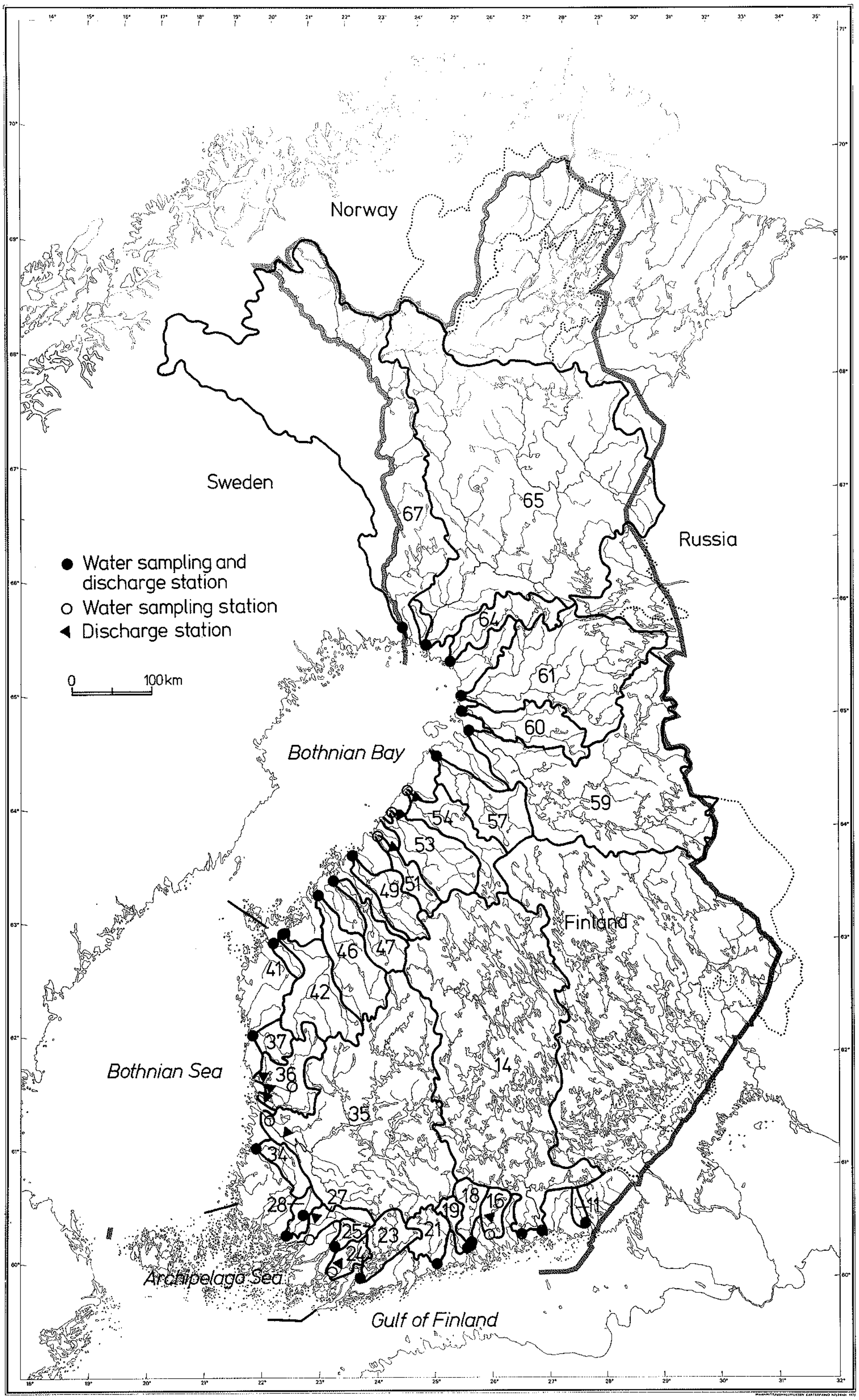

Fig. 1. Rivers discharging to the Finnish coastal waters. See Table 1 for the names of the rivers.

Table 1: Main characteristics of the studied rivers and drainage basins and mean flows of the rivers in 1970–90 and 1986–90. Drainage areas of the rivers and field areas and lake percentagess of the river catchments are from the Environment Data Base of NBWE. The figures for field areas refer to the whole drainage basin, if the lake percentage is below 5. In the case of a higher lake percentage only the lake-poor lower parts of the catchment have been used. River flows have been calculated from the Hydrological Data Base of NBWE. The flows of non-monitored rivers (= other rivers) and of coastal zones (areas between the river basins and the shore line) have been extrapolated on the basis of the small coastal rivers within each of the main catchment areas.

Catchment	River basin (see Fig. 1) no. name	Drainage area, km² (coastal)	Lake area, %	Field area, km² (%)	Mean flow 1970–1990 m³ s⁻¹	Mean flow 1970–1990 l km⁻² s⁻¹	Mean flow 1986–1990 m³ s⁻¹	Mean flow 1986–1990 l km⁻² s⁻¹
Gulf of Finland	11 Virojoki	357	3.8	48 (13.5)	4.4	12.3	4.2	11.8
	14 Kymijoki	37159 (1204)	17.3	296 (24.6)[1]	334.4	9.0	371.0	10.0
	16 Koskenkylänjoki	895	4.4	223 (24.9)	8.4	9.4	9.1	10.2
	18 Porvoonjoki	1273	1.3	363 (28.5)	13.8	10.8	14.8	11.6
	19 Mäntsälänjoki	783	1.5	210 (26.8)	7.5	9.6	7.4	9.5
	21 Vantaa	1686	2.3	397 (23.4)	16.9	10.0	16.7	9.9
	23 Karjaanjoki	2046 (116)	12.2	35 (29.9)[1]	18.7	9.1	20.4	10.0
	other rivers	4223	2.5	843 (20.0)	41.8	9.9	43.5	10.3
	coastal zone	1281	2.5	156 (12.2)	12.7	9.9	13.2	10.3
	Total	49703 (11818)	13.9	2571 (21.8)	458.6	9.2	500.3	10.1
Archipelago Sea	24 Kiskonjoki	1050	5.2	257 (24.5)	9.8	9.3	10.7	10.2
	25 Uskelanjoki	566	0.6	247 (43.7)	5.5	9.7	5.9	10.4
	27 Paimionjoki	1088	1.5	467 (43.0)	9.4	8.6	10.5	9.7
	28 Aurajoki	874	0.3	320 (36.7)	8.5	9.7	9.0	10.3
	other rivers	2554	0.7	683 (26.7)	23.6	9.3	25.8	10.1
	coastal zone	2820	2.1	555 (19.7)	26.2	9.3	28.5	10.1
	Total	8952	1.7	2529 (28.3)	83.0	9.3	90.4	10.1
Bothnian Sea	34 Eurajoki	1336 (719)	12.8	209 (29.1)[1]	10.5	7.9	10.8	8.1
	35 Kokemäenjoki	27046 (6817)	10.0	1838 (27.0)[1]	247.0	9.1	295.0	10.9
	36 Karvianjoki	3438	4.0	350 (10.2)	37.4	10.9	41.2	12.0
	37 Isojoki	1098	0.2	126 (11.5)	15.7	14.3	14.9	13.6
	41 Laihianjoki	506	0.4	131 (25.8)	4.3	8.5	4.3	8.5
	other rivers	4899	0.9	870 (17.8)	51.9	10.6	54.9	11.2
	coastal zone	978	1.6	84 (8.6)	10.4	10.6	11.0	11.2
	Total	39301 (18455)	7.8	3608 (20.0)	377.2	9.5	432.1	10.9
Bothnian Bay	42 Kyrönjoki	4923	1.2	1149 (23.4)	45.1	9.2	47.1	9.6
	44 Lapuanjoki	4122	2.7	859 (20.8)	36.5	8.9	40.7	9.9
	47 Ähtävänjoki	2054 (241)	9.9	32 (13.3)[1]	16.0	7.8	17.7	8.6
	49 Perhonjoki	2524	3.0	239 (9.5)	22.5	8.9	24.4	9.7
	51 Lestijoki	1373 (1010)	5.9	122 (12.1)[1]	12.6	9.2	13.2	9.6
	53 Kalajoki	4247	1.9	634 (14.9)	41.4	9.7	41.4	9.7
	54 Pyhäjoki	3712 (3035)	5.0	284 (9.4)[1]	32.2	8.7	33.2	8.9
	57 Siikajoki	4318	2.2	306 (7.1)	44.3	10.3	43.0	10.0
	59 Oulujoki	22841 (3002)	11.7	149 (5.0)[1]	257.3	11.3	253.7	11.3
	60 Kiiminginjoki	3814	3.2	74 (2.0)	43.1	11.3	43.5	11.4
	61 Iijoki	14191 (10428)	5.8	120 (1.1)[1]	163.2	11.5	159.8	11.3
	64 Simojoki	3160 (2630)	5.7	32 (1.2)[1]	36.9	11.7	36.2	11.5
	65 Kemijoki	51127	4.1	355 (0.7)	543.2	10.6	536.7	10.5
	67 Tornionjoki	35000[2]	4.7	190 (0.5)	390.2	11.1	396.7	11.3
	other rivers	9291	1.7	944 (10.2)	90.1	9.7	92.0	9.9
	coastal zone	1470	0.5	163 (11.1)	14.3	9.7	14.6	9.9
	Total	168167 (141182)	5.1	5652(4.0)	1788.9	10.6	1793.9	10.7
Total		266123 (180407)	7.0	14360 (8.0)	2707.7	10.2	2816.7	10.6

[1] Only the lower part of the catchment poor in lakes.

[2] The part of the catchment discharging to the Bothnian Bay via the River Tornionjoki (ca. 5 000 km² is discharged to the River Kalix in Sweden due to bifurcation).

The coastal rivers have a small drainage basin (400 to 5 000 km^2), a low lake-percentage (usually < 5 %) and a high field-percentage (in the catchments of the Gulf of Finland and the Archipelago Sea from 20 to 40 %, in the catchments of the Bothnian Sea and the Quark from 10 to 30 %). Only in the catchments of the coastal rivers discharging to the middle and northern Bothnian Bay the field-percentage is below 10 %. Intra-annual flow and water quality variations are usually large, and the response to hydrological events (e.g. snow melt, heavy rains) is immediate due to the short residence time (only few days) in these lake-poor catchments.

2.2 Finnish coastal waters

The Finnish coastal waters of the Baltic Sea are non-tidal, shallow and have generally a complex morphometry (Fig. 2). These facts, together with considerable nutrient inputs from the land, make these waters sensitive to anthropogenic eutrophication. The complex coastal morphometry limits both horizontal and vertical mixing, whereas the shallowness enhances re-mineralization and circulation of nutrients between euphotic and aphotic layers and the bottom, thus accelerating eutrophication. However, if the mixed surface layer depth of a semi-enclosed coastal water basin is clearly smaller than the total depth, like in many parts of the middle and outer Archipelago Sea and in the Finnish coastal waters of the Gulf of Finland, sedimentation of nutrients is enhanced and vertical upward transport of re-mineralized nutrients is reduced in summer (Pitkänen et al. 1990, Jumppanen and Mattila 1994, V). This, for its part, declines new planktonic production, i.e. eutrophication.

In the whole Finnish coastal water zone of the Gulf of Finland, the inner and central Archipelago Sea and in the Quark archipelago the horizontal exchange of water is strongly limited by coastal morphometry. The coastal water area of the north-eastern Bothnian Bay (from Raahe to Tornio) is open, but the mean water depth of less than 10 m (and the ice-cover in winter) limits mixing of the large river discharges with the open Bay water (Alasaarela 1980). On the contrary, at the middle coasts of the Bothnian Sea and the Bothnian Bay an only narrow belt (0 to 5 km) of islands and islets and relatively deep waters (20 to 40 m) immediately outside the archipelagic zone support the most effective mixing conditions within the Finnish coastal waters.

Compared to the Estonian and Russian coastal waters of the Gulf of Finland or the Swedish coastal waters of the Gulf of Bothnia, the mixing conditions at the Finnish coast are poor, not to mention the conditions at the middle and southern Baltic Sea, where coastal waters usually are both open and deep. However, despite the simple coastal morphology, many of the larger rivers of the middle and southern Baltic Sea enter the sea via estuarine-like basins.

Vertical mixing of river and saline water is especially weak in winter due to the regular ice cover. Under the ice river water, often mixed with waste water, spreads and only slowly mixes with the heavier brackish water. Low saline and nutrient-rich waters cover much larger areas than during the ice-free season (II), when shear stress by wind causes effective mixing of surface waters above the thermocline. This wintertime phenomenon is most extensive in the north-east Bothnian Bay (Alasaarela 1977, 1979a, 1980) and the north-east Gulf of Finland (Pitkänen et al. 1990), both receiving considerable river discharges and being ice-covered for at least 4 months per year.

2.3 Estuarine waters

Kymijoki Estuary. The River Kymijoki has two main outlets to the Gulf of Finland. The semi-enclosed basin off the western mouth forms an estuary with an area of 52.5 km^2, a volume of 0.23 km^3, a mean depth of 4.3 m and a maximum depth of 16 m (Fig. 3, III, VII). The exchange of water between the estuary and the open Gulf of Finland takes place via the 800 m wide Sound of Suursalmi. In addition to the western branch of the River Kymijoki (mean flow ca. 140 m^3 s^{-1}), the estuary receives fresh water from the small River Taasianjoki (mean flow ca. 5 m^3 s^{-1}). The theoretical residence time of the estuary is about 2 weeks.

During open water seasons the mixed layer depth (MLD) is regulated by the vertical salinity distribution (affected mainly by wind and fresh water input) and varies between 3 and 5 m, whereas the thermocline usually can be found at depths of 5 to 10 m. Hydrodynamically the estuary is stratified and non-tidal. The salinity of the outflowing surface layer varies from 0 to 3 ‰, whereas the salinity of the deeper inflow is 4 to 5 ‰ (III). A very steep halocline at the depth of about 2.5 m separates the two layers during the ice-covered period from December

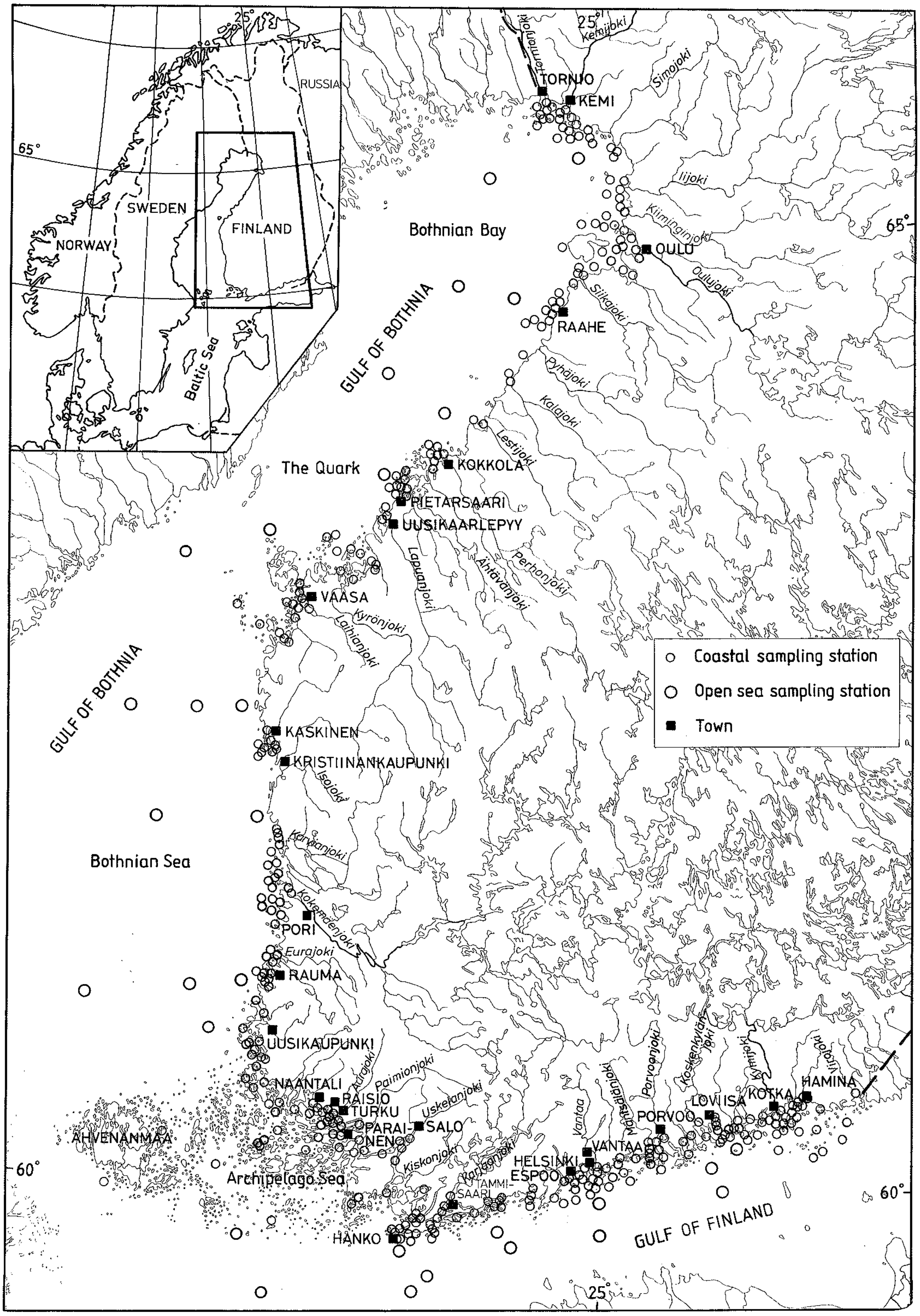

Fig. 2. The Finnish waters of the Baltic Sea and the sampling stations used in paper II and in the present study.

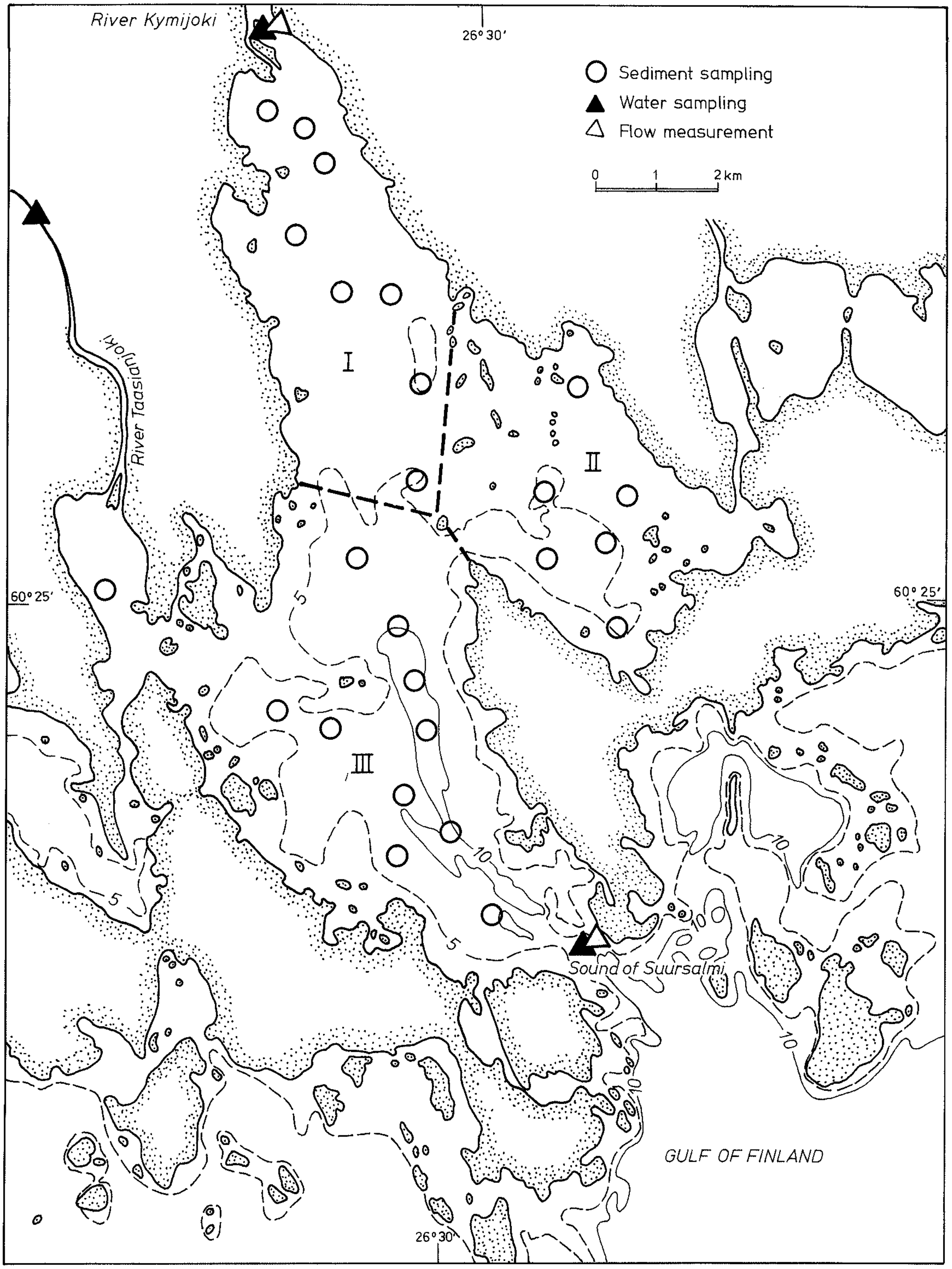

Fig. 3. The Kymijoki Estuary.

to April, while during the ice-free season advection dominated vertical mixing takes place, increasing the salinity of the outflowing surface layer and causing an inward compensation flow near the bottom.

Neva Estuary and the eastern Gulf of Finland. The easternmost Gulf of Finland (east from the Seiskari-Koivisto transect, Fig. 4) forms the estuary of the River Neva (the largest river discharging to the Baltic Sea) with an area of about 3 200 km^2 (IV, V, VIII). Both topographic and hydrodynamic features separate the estuary from the open Gulf. The innermost estuary (the Neva Bay, 400 km^2) behind the flood protection barrier is very shallow (< 6 m). This barrier basin contains almost exclusively fresh water from the River Neva (VIII).

The Finnish archipelago (1 500 km^2, Fig. 4) clearly forms a separate sub-area of the eastern Gulf, consisting of several semi-enclosed basins (Pitkänen et al. 1990, V). In addition to the Neva Bay there are four larger bay areas in the eastern Gulf. The Bay of Vyborg is semi-enclosed, whereas the three others (Narva Bay, Luga Bay and Koporskaja Bay) have a wide and sill-free connection with the open Gulf or with the Neva Estuary.

The mean depth of the Neva Estuary is ca. 20 m and the maximum depth is 48 m. The estuary receives fresh water from the River Neva (long-time mean flow 2 460 m^3 s^{-1}, summertime flow 3 000 to 3 500 m^3 s^{-1}, Carlsson and Bergström 1993). Water with the open Gulf is mainly exchanged via the sound between the islands of Koivisto and Seiskari where the depth is generally less than 20 m, with some 20 to 30 m deep channels. South of Koivisto the average depth is only about 5 m, and the sill depth is 15 m. Thus only exchange of the mixed surface layer water can take place via this route. The theoretical residence time of the Neva Estuary is ca. 6 months and that of the whole eastern Gulf ca. 1 year (IV).

A clear thermohaline stratification prevails in the estuary under summer conditions (V, VIII). In general, the thermocline can be found at depths between 10 and 20 m, whereas especially in the inner estuary (excluding the Neva Bay which is usually non-saline) the salinity gradually increases from surface to bottom without any clear halocline, indicating effective vertical mixing. However, the estuary does have a typical 2-layer current system with low-saline outflow and high-saline inflow (V). Mixing and flow conditions are largely dependent on weather conditions, especially on wind velocity, and on water level oscillations.

3. MATERIAL AND METHODS

3.1 Water sampling and analyses

The monitoring studies (I, II, VI and the formely unpublished material from 1986–90) are based on national monitoring data from 360 coastal water and open sea stations and 31 river stations (Figs. 1 and 2). The estuarine studies (III-V, VII, VIII plus formely unpublished sediment data) are based on data resulting from different research projects.

3.1.1 Monitoring studies of rivers and coastal waters

A total of 110 coastal water stations and all the river stations were sampled and analyzed by the coastal Water and Environment Districts and the open sea reference stations by R/V Aranda of FIMR. The other coastal water stations were sampled and analyzed by local research consultants, under the supervision of the Water and Environment Administration. The coastal water samples were transferred to laboratories in dark, cooled boxes and analyzed within 24 hours after sampling. The delay between sampling and analyzing may have impaired the reliability of the summertime results of inorganic nutrients, because at that time these concentrations in coastal waters can be very low (< 2 mg m^{-3}). The analyses of total N and total P as well as the analyses of NO_3-N, NO_2-N and NH_4-N (referred to as DIN) and PO_4-P were performed according to Finnish standard methods from unfiltered samples (Koroleff 1976, 1979). Chlorophyll-*a* was analyzed after filtering (Whatman GF/C) according to Lorenzen (1967).

The sampling frequency of the rivers in 1986–90 was mostly between 10 and 20 per year (Table 2). In some of the small rivers also less samples were taken. In coastal waters the sampling frequency was from 2 to 4 annually (II). The 5-year mean values for the late summer period (July-September) is mostly calculated from 5 values per station.

3.1.2 Estuarine waters

In the Kymijoki Estuary (Fig. 3) concentrations of suspended particulate matter (SPM, Whatman GF/C), total organic carbon (TOC, Carlo Erba IR-analyzer), and total and inorganic nutrients (Koro-

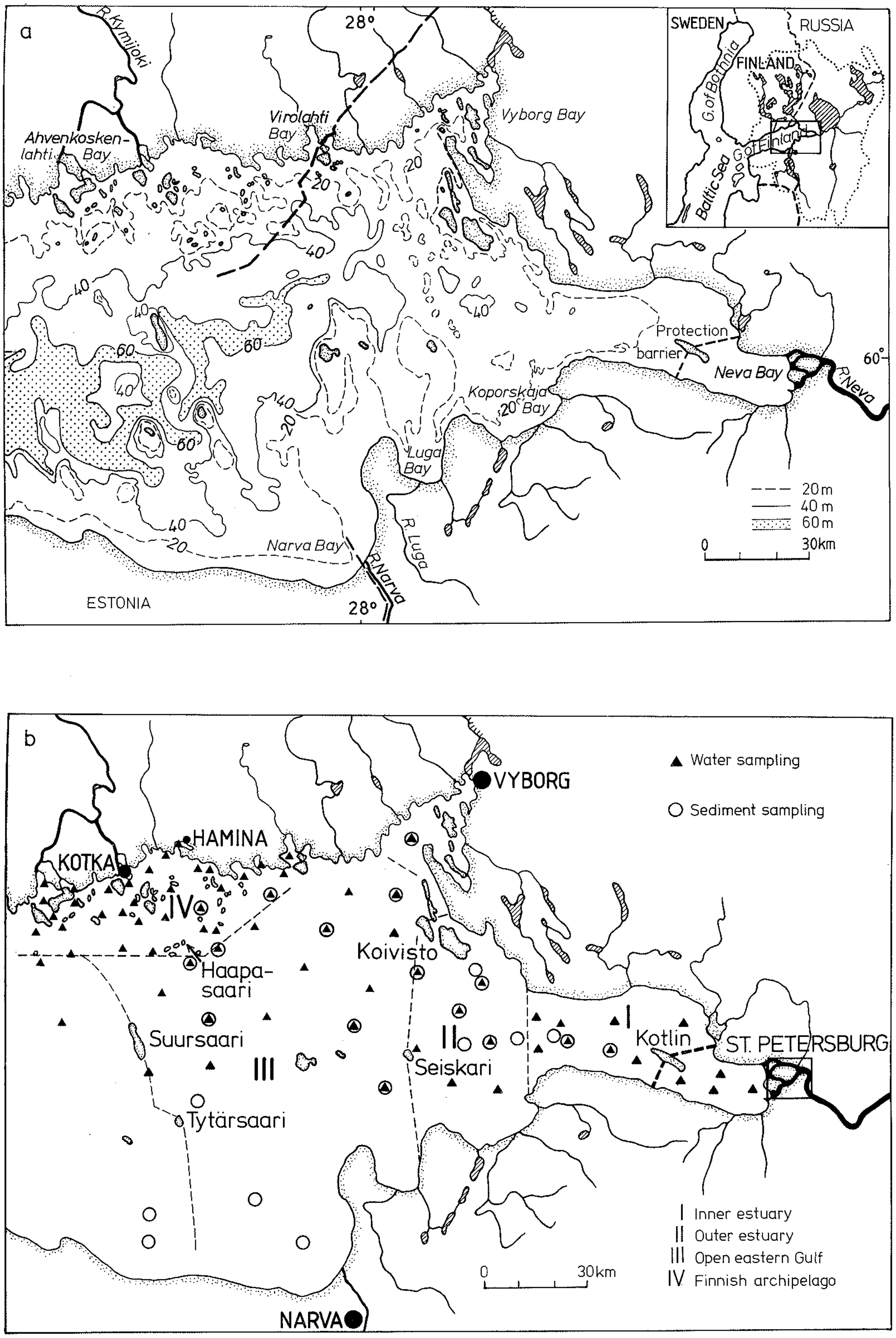

Fig. 4. The Neva Estuary and the eastern Gulf of Finland.

leff 1976, 1979) were analyzed from unfiltered samples according to Finnish standard methods (III, VII). Water samples were taken by a Ruttner-sampler (2.5 l) from a depth of 1 m in the middle of the river (below the hydro-power plant in the Kymijoki) and in the outlet of the estuary, where also the inflowing deeper water (6 m) was sampled. The sampling was performed 2 to 3 times a week during the spring flood period in April-May in 1985. In June-November the samples were taken every second week. In December-March, when variations in concentrations were small (III), the samples were taken only once a month. The annual amount of samples (covering the year of 1985) for each variable varied between 17 and 45, with highest frequencies for SPM and phosphorus compounds, which show a strong seasonal variation, and with lower frequencies for the more steady nitrogen compounds and organic carbon.

In the Neva Estuary and the eastern Gulf of Finland three cruises (5 east-west transects of data between the open Gulf and the Neva Bay) were made with R/V Muikku during Augusts 1990–92 (Fig. 4, IV, V, VIII). Water samples were taken with a large (23 l) Limnos sampler from the depths of 1, 3, 5, 10, 15, 20, 30,..., 1–2 m above the bottom. Temperature, salinity, density, pH and oxygen were analyzed at 1 m intervals using a CTD-sond (in 1990 from discrete samples, analyzed in the ships laboratory). Inorganic nutrients were analyzed in dublicate immediately after sampling onboard (Koroleff 1976, 1979) using a Beckmann spectrophotometer with a 7.5 cm cuvette. The detection limits for NO_3-N and NH_4-N were 1 mg m^{-3}, and for PO_4-P 0.5 mg m^{-3}.

Samples for total nutrient analyses were preserved (total N: deep-freezing, total P: H_2SO_4) and analyzed after the cruises in the Laboratory of the Kymi Water and Environment District (peroxide sulphate oxidation, Koroleff 1976, 1979). Chlorophyll-*a* from composite samples (2 × Secchi depth) was filtered (Whatman GF/C) immediately after sam-

Table 2. Number of chemical analyses of the studied rivers in 1986–1990.

River	Total N	NH_4-N	NO_3-N	Total P	PO_4-P
Virojoki	32	0	0	32	0
Kymijoki, W branch	96	63	43	96	65
Kymijoki, E branch	81	52	30	60	53
Koskenkylänjoki	43	25	12	43	17
Porvoonjoki	50	49	49	50	48
Mäntsälänjoki	20	0	0	20	0
Vantaa	51	50	50	51	50
Karjaanjoki	83	80	59	82	57
Kiskonjoki	19	0	0	19	0
Uskelanjoki	34	0	0	33	0
Paimionjoki	72	68	54	73	62
Aurajoki	57	55	52	57	57
Eurajoki	28	12	0	28	0
Kokemäenjoki	76	74	63	77	66
Karvianjoki	19	0	0	19	0
Isojoki	64	49	27	64	46
Laihianjoki	35	0	0	35	0
Kyrönjoki	74	58	35	79	63
Lapuanjoki	85	73	68	84	73
Ähtävänjoki	81	9	0	89	38
Perhonjoki	123	71	67	124	65
Lestijoki	92	74	59	91	58
Kalajoki	102	80	65	103	80
Pyhäjoki	63	60	51	60	61
Siikajoki	92	84	81	93	85
Oulujoki	85	86	73	83	87
Kiiminginjoki	80	75	65	74	78
Iijoki	63	61	59	63	63
Simojoki	52	53	39	51	50
Kemijoki	55	56	40	56	58
Tornionjoki	55	58	35	57	57

pling and analyzed after the cruises (Lorenzen 1967). *In vitro* primary production was analyzed by the ^{14}C method (Steemann-Nielsen 1952) with incubation time of 2h at 20 °C and 5 klux illumination. The samples were filtered using Millipore 0.45 µm filters and counted by a Wallac liquid scintillation counter at WERI after the cruises. Phytoplankton species and biomass were counted from composite samples, preserved with acid Lugol's solution, by a Zeiss inverted microscope by the Utermöhl (1957) technique at WERI.

3.2 Flow and current measurements and water balance calculations

Daily water flows of the studied rivers were obtained from the Hydrological Data Base of the NBWE (I-III, VI, VII). The flows in estuaries and coastal waters were measured by recording current meters (model Aanderaa, III, V, VII). The daily flow averages were calculated as arithmetic means from the basic measurements, which are recorded every 10 or 15 minutes. From the Neva Estuary results of an Acoustic Doppler Current Profiler (ADCP) onboard R/V Muikku have been used (V).

Estimates of the daily mean current velocity in the estuaries were obtained by stepwise regression from the northern and eastern wind speed components and the river flow as independent variables (Sarkkula 1989, III, V, VII):

$$V = a\,Q_R + b\,W_N + c\,W_E \tag{4}$$

where

V = daily mean current velocity (cm s^{-1})
Q_R = daily mean river inflow ($m^3\ s^{-1}$)
W_N = daily mean wind speed component from the north (m s^{-1})
W_E = daily mean wind speed component from the east (m s^{-1})

Other variables, such as water level fluctuation, were not included in equation (4), because they did not improve the regression.

Monthly mean flows ($m^3\ s^{-1}$) in the outlet of the Kymijoki Estuary were obtained by multiplying the monthly mean current velocities by the effective cross-sectional area of the low-saline surface layer (III, VII). The thickness of the outflowing surface layer for each month was calculated as a mean from vertical salinity profiles measured during every sampling. Water exchange below the halocline was estimated as the residual from the monthly water balance of the estuary. The water balance was calibrated by using salinity as a conservative variable. The annual input and output of salt was balanced by multiplying the effective cross-sectional area of the outflowing mixed surface layer by a coefficient of 0.91.

For the Neva Estuary and the eastern Gulf of Finland the annual water balance was estimated on the basis of monitoring data from 1981–1990 on salinities (conservative substance) of the outflowing surface and inflowing deep water, and from the estimated river inflow (Q_R) of 3 300 $m^3\ s^{-1}$ to the eastern Gulf (Knudsen's flow equations, IV):

$$Q_1 = S_2\,Q_R / (S_2 - S_1) \tag{5}$$

$$Q_2 = S_1\,Q_R / (S_2 - S_1) = Q_1 - Q_R \tag{6}$$

where

Q_1 = mean annual outflow of the surface layer ($m^3\ s^{-1}$)
Q_2 = mean annual inflow of the deep layer ($m^3\ s^{-1}$)
S_1 = mean salinity of the surface layer (psu, weighted annual mean using data from the depth of 10 m)
S_2 = mean salinity of the deep layer (psu, weigted annual mean using data from the depth of 40 m)

3.3 Sediment sampling and analyses

The sediment samples were taken with a gravity corer (Axelsson and Håkanson 1978) and a mini-Mackereth vacuum corer (Figs. 3 and 4, III, VII). At some shallow stations of the Kymijoki Estuary the surface of the sediment was sampled with a Hiller-type peat sampler. The core samples taken from the Neva Estuary and the eastern Gulf of Finland (n = 24) were slized into 10–20 mm thick sub-samples and deep-frozen immediately onboard R/V Muikku, while the samples of the Kymijoki Estuary (12 core samples and 13 0 to 2 cm surface samples) were slized and deep-frozen within 12 hours after sampling. The length of the cores varied from 20 to 40 cm in both areas.

The sediment analyses were performed at the Laboratory of the Mikkeli Water and Environment District. Dry weight (dw) and ignition loss were analyzed according to the Finnish standard SFS 3008 (1981). Total N and total P were determined by co-digestion after Zink-Nielsen (1975). Organic matter was decomposed using strong sulpuric acid. Nitrate and nitrite were reduced to ammonia with Devarda solution. The formed ammoniumsulphate was distilled and ammonium was titrated (Starck and Haapala 1984). Inorganic phosphate complexes and organic P were converted to orthophosphate by sulphuric and analyzed according to SFS 3025 (1986).

3.3.1 Sediment datings

For the Kymijoki Estuary radioactive methods (^{210}Pb and ^{137}Cs, performed by the Reactor Laboratory of the Technical Research Center of Finland) did not give sufficiently clear results for sediment dating, probably because of the long residence time of the water of this large (37 000 km^2) and lake-rich drainage area and the physical and biological disturbance of the sediment surface (Häsänen 1977, Walling and Qingping 1992, III, VII). However, the strong concentration gradient of mercury, caused by heavy discharges of Hg into the lower River Kymijoki particularly during the late 1950s and early 1960s (Kokko and Turunen 1988), could be used for estimating sedimentation rates (Lindberg and Harris 1977, Förstner and Wittman 1981, Parks and Hamilton 1982, Tolonen et al. 1988, Nakamishi et al. 1989). Hg-profiles were analyzed (Jerome 511 goldplate apparatus, digestion with nitric acid) from six different cores at the University of Joensuu.

Also in the Neva Estuary and the eastern Gulf of Finland the ^{210}Pb results showed great variablity, probably due to the same reasons as in the Kymijoki Estuary. However, the vertical ^{137}Cs distribution of the cores clearly demonstrated a peak concentration caused by the Chernobyl fallout, and the mean sedimentation rate during the recent 6 – 7 years could be calculated.

3.3.2 Echo-soundings

In order to survey the potential accumulation bottoms, echo-sounding graphs were recorded both in the Kymijoki Estuary (Atlas Monograph 58, III, VII) and in the eastern Gulf (Atlas Deso 10 onboard R/V Muikku). On the basis of these echographs, chemical data of sediment samples and morphometric features (bathymetric maps) bottoms of active sediment accumulation were distinguished from erosion and transportation bottoms (Håkanson 1986). The criteria for accumulation bottoms were:

(a) clear (> 2 m thick) accumulation of soft material according to echograps,
(b) dry weight of the sediment surface < 15 % of wet weight, and
(c) content of organic carbon of the sediment surface > 40 mg g^{-1} (dw)

3.3.3 Calculation of sediment accumulation rates

For the calculation of sediment accumulation rates in the Kymijoki Estuary it was assumed that the annual accumulation rate of dry matter has been constant since the Hg maximum found in the cores and that the observed Hg distribution in the sediment corresponds to the known temporal variations in the Hg discharge into the lower course of the river (VII).

The annual sedimentation rate of wet SPM (v, mm a^{-1}) was calculated as:

$$v = (z/a) \cdot (c_{PM}/c_{PM(s)}) \qquad (7)$$

where

z = depth of the Hg maximum in the sediment cores (mm)
a = number of years from the Hg loading maximum
c_{PM} = mean concentration of particulate matter above the Hg maximum (mg g^{-1})
$c_{PM(s)}$ = concentration of particulate matter of the sediment surface (0 to 2 cm, mg g^{-1})

The annual accumulation rate of dry particulate matter (S_{SPM}, g m^{-2} a^{-1}) was then calculated for each of the three sub-basins of the Kymijoki Estuary (Fig. 3) by:

$$S_{SPM} = v \cdot c_{PM(s)} \cdot d_s \qquad (8)$$

where

d_s = sediment density of the 0 to 2 cm layer (g cm^{-3})

The values for $c_{PM(s)}$ and d_s in equation (8) represent mean values calculated from all the data of each of the three sub-basins of the estuary.

Estimates of the accumulated amounts of organic C, N and P ($S_{C,N,P}$) are:

$$S_{C,N,P} = S_{SPM} \cdot c_{C,N,P} \tag{9}$$

where

$c_{C,N,P}$ = mean concentration of organic C, total N and total P (mg g^{-1}) in each sediment layer considered

Due to the fact that vigorous physical, microbiological and geochemical processes are taking place near the sediment-water interface (e.g. Carignan and Flett 1981, Balzer 1984, Andersen ad Jensen 1992), the calculations were performed using both mean values of the sediment surface (0–2 cm) and of the totally anoxic (10–20 cm) layer in equation (9).

In the Neva Estuary and the open eastern Gulf of Finland the accumulation rate of SPM was calculated according to equations (7) and (8). Accumulation rates of total N and total P were estimated according to equation (9) using chemical data from the anoxic 5 to 10 cm sediment depth.

3.4 Flux calculations

Annual material input from the rivers ($i_{R,(a)}$) as well input ($i_{S,(a)}$) and output ($o_{S,(a)}$) through the sound between the Kymijoki Estuary and the open Gulf of Finland were calculated by multiplying the monthly flows by the mean monthly concentrations (I-III, VI, VII):

$$i_{R(a)} = \sum_{m} c_{R(m)} Q_{R(m)} \tag{10}$$

$$o_{S(a)} = \sum_{m} c_{1(m)} Q_{1(m)} \tag{11}$$

$$i_{S(a)} = \sum_{m} c_{2(m)} Q_{2(m)} \tag{12}$$

where

$c_{R(m)}$ = river concentration of a substance in month m (mg m^{-3}, arithmetic mean in the case of several samples, seasonal average in the case of a missing value)
$c_{1(m)}$ = monthly mean concentration in the surface layer of the outlet of the estuary (mg m^{-3})
$c_{2(m)}$ = monthly mean concentration below the halocline of the outlet of the estuary (mg m^{-3})
$Q_{R(m)}$ = monthly river flow (m^3 s^{-1})
$Q_{1(m)}$ = monthly flow in the surface layer of the outlet of the estuary (m^3 s^{-1})
$Q_{2(m)}$ = monthly flow below the halocline of the outlet of the estuary (m^3 s^{-1})

For the Kymijoki Estuary the general mass balance equation was used for estimating annual material fluxes (III, VII):

$$dm/dt = \Sigma\, i - o + s + a + p \tag{13}$$

where

m = mass of a substance in the estuary
t = time
$\Sigma\, i$ = $i_R + i_A + i_S$ = total input from rivers (i_R), from direct atmospheric deposition (i_A) and through the sound from the open Gulf (i_S)
o = output to the open Gulf
s = net exchange with sediment due to biological, geochemical and physical processes
a = net exchange with the atmosphere due to biological processes
p = net gain/loss due to internal biological and geochemical processes

For periods long enough (at least one year) one can assume $dm/dt \approx 0$, and the balance becomes:

$$o = \Sigma i + (s + a + p) \tag{14}$$

If $s + a + p < 0$, the output to the open sea is smaller than the total input, i.e. the estuary acts as a sink (filter) for a substance.

In the balance study of the Neva Estuary and the eastern Gulf of Finland (IV) the advective exchange of nutrients between the eastern and the western Gulf was calculated on the basis of Knudsen's flow equations (Q_1 and Q_2 from equations (5) and (6)) and the weighted annual concentrations (10-year-period) of the respective water layers (c_1 and c_2) of a representative station (south of the Island Haapasaari, see Fig. 4):

$$o = Q_1\, c_1 \tag{15}$$

$$i = Q_2\, c_2 \tag{16}$$

3.4.1 Reliability of the flux calculations

It should be noted that equation (10) probably underestimates the true fluxes in rivers in which intra-annual flow and concentration variations are high, i.e. in small rivers with low lake percentage and high proportion of agricultural land (cf. Walling and Webb 1985, Ekholm 1992, VI, Table 1). According to the studies made for the River Paimionjoki based on 20 to 50 annual samples and flow weighted annual concentrations (Ekholm 1992), the 'true' fluxes of small agricultural rivers can be up to 20 % higher than those obtained by equation (10). The present mean estimates for the River Paimionjoki (average annual n = 14 in 1986–90, Table 2) are, however, close to those obtained by Jumppanen and Mattila (1994) from frequent data (n = 20 to 50) by using short hydrological periods and representative concentrations. In any case, the use of more sophisticated methods than equation (10) requires higher sampling frequencies than available for most rivers of the present study ($< 20\ a^{-1}$).

For Kymijoki the material from 1985 (n = 47 for total P and n = 28 for total N) allows the use of daily flows and flow weigted concentrations:

$$i_{R(a)} = \sum_{m} Q_{R(m)} \left[\sum_{i} c(t_i)\, Q(t_i) \,/\, \sum_{i} Q(t_i)\right] \qquad (17)$$

where

$c(t_i)$ = concentration of a sample at time t_i
$Q(t_i)$ = mean flow on the sampling day t_i

According to results for the River Kymijoki by Ekholm (unpublished), equations (10) and (17) give similar results for both total N and total P. In a Monte Carlo simulation (sub-sample size of 12), the bias (deviation from the true value) of equation (10) was only 1 % for both total N and total P, whereas the scatter (dispersion around true value) was 6 % for total N and 8 % for total P. Thus for large rivers the estimates of the present study can be regarded close to the real fluxes, while in small lake-poor rivers (strong concentration variations) with low annual sampling frequencies (Table 2) underestimates are to be expected. However, the relative error in a single river seldom exceeds 20 % on an annual level, and is clearly smaller when 5 year mean values are used. The estimates on total nutrient inputs to the Finnish coastal waters are probably quite near to real values (total error < 10 %).

3.5 Estimation of municipal, industrial and agricultural nutrient fluxes

Municipal and industrial inputs to the coastal waters and to the rivers were calculated as 5-year mean values using the periods 1979–83 (II) and 1986–90. The data were obtained from the Data Bases of Municipal and Industrial Waste Waters of the NBWE. In the river catchments with considerable percentage of lakes (> 5 %), only input to the lower part of the river (below the lake area) was taken into account, because lakes effectively retain nutrients (Laaksonen 1970, Wartiovaara 1978, I).

Calculations of agricultural nutrient fluxes to coastal waters were based on the field percentage of river catchments (Table 1, Environment Data Base, NBWE) and on specific flux estimates based on the river fluxes of the present study as well as on studies by Kauppi (1984), Pitkänen (1987), Rekolainen (1989), Pietiläinen and Rekolainen (1991) and papers I and VI. It was assumed that in river catchments with low lake percentage (i.e. short residence time of water) the nutrient flux would not undergo substantial quantitative changes (I, VI).

The following mean specific values for agricultural nutrient inputs to the coastal waters of the different sea areas were used:

Sea area	Total N (kg field-km^{-2} a^{-1})	Total P (kg field-km^{-2} a^{-1})
Gulf of Finland	2 000	120
Archipelago Sea	1 600	150
Bothnian Sea	1 600	120
Bothnian Bay	1 600	100

3.6 Concentration-salinity plots and loss calculations

In the eastern Gulf of Finland the quantitative spatial dynamics of N and P compounds was studied, employing the classical approach of sea salt as a conservative variable in an estuary. Five different data sets from the three cruises by R/V Muikku in 1990–1992 were used in the calculations (VIII).

The losses ($L_{N,P}$) from the surface layer of the Neva Estuary were calculated by curve fitting. The linear part of the concentration-salinity dependence of the outermost estuary and of the open Gulf was extrapolated to zero salinity. The difference between this hypothetical concentration (c_1, based on the assumption that the open sea concentration would be a result of pure dilution) and the observed mean concentration at the zero salinity in the innermost Neva Estuary (c_2, according to the five data sets) was then multiplied by the mean annual flow from the River Neva (Q_R):

$$L_{N,P} = (c_2 - c_1)\, Q_R \qquad (18)$$

3.7 Nutrient depletion experiments

To study the roles of N and P as production limiting factors in estuarine waters receiving considerable land-derived nutrient inputs, a series of nutrient depletion experiments along the salinity gradient from the inner Neva Estuary towards the open Gulf was conducted at four sampling sites, representing the inner Neva Estuary, the outer Neva Estuary, the transition zone between the outer estuary and the open Gulf and the open eastern Gulf, respectively (Fig. 4, VIII).

The experiments were made as deck incubations onboard R/V Muikku. Surface layer water (0 to 2 m) was filled into 2 l bottles and nutrients (NO_3-N, NH_4-N and PO_4-P) were added (10 mg m^{-3} P, 40 mg m^{-3} N). Depletion rates were calculated as difference per unit time between start and end-point concentrations (measured in duplicate). Incubations started before noon and were terminated at the end of the light cycle (8 to 12 hours). Chemical analyses were performed onboard immediately after termination as described in Chapter 3.1.2.

4 RESULTS AND DISCUSSION

4.1 Origin and fluxes of riverine nutrients

External nutrient input is only one of the numerous factors controlling the trophic degree in coastal waters. In addition to complex responses and interactions of a pelagic food web to external changes, the trophic degree of a particular coastal water area is very much dependent on factors like coastal morphometry and hydrography. Nutrient fluxes between euphotic and aphotic water layers and the bottom sediment are largely dependent on these factors (see Chapter 1.2). However, under vertically stagnant summer conditions a river, an outlet of a waste water treatment plant or a floating fish farm may be the only notable external nutrient source for the planktonic food web, thus crucially controlling the level of new production.

4.1.1 Spatial and temporal variations in nutrient loading to coastal waters

The total riverine nutrient fluxes into the Finnish coastal waters were estimated as 69 000 t a^{-1} of N and 4 200 t a^{-1} of P (Table 3). The fluxes vary considerably from year to year according to hydrological conditions (I). Inorganic N comprised 47 % of the riverine total N, while in the case of P the inorganic (unfiltered) proportion was 43 %. In the rivers discharging to the Archipelago Sea and in small agricultural rivers dicharging to the Gulf of Finland and to the southern Bothnian Bay the proportion of DIN rised to 50–70 % of the total riverine inputs. In the rivers discharging to the north-eastern Bothnian Bay the average proportions were considerably lower, from 20 to 25 %. Proportions of inorganic P of total P varied from 40 to 60 % in small coastal rivers and from 15 to 40 % in large rivers. The inorganic N:P-ratio was highest in the rivers discharging to the Gulf of Finland (35) and smallest in the rivers discharging to the Archipelago Sea (13) and to the Bothnian Bay (13).

In general, fluxes of both total and inorganic N to the coastal waters were more strongly dependent on agricultural activity (field percentage) in the drainage basins than the inputs of total and inorganic P (Fig. 5). N is easily lost from fields in soluble form, whereas inorganic phosphates readily adsorb on particles in the fields and are lost mostly due to soil erosion (Kauppi 1984, Rekolainen 1993). In the small coastal rivers discharging to the middle Bothnian Bay the high proportion of peat soils in the catchments increases the losses of inorganic P (cf. Sallantaus 1986), whereas the high percentage of acid sulphate soils clearly decreases the fluxes of P in the rivers discharging to the Bothnian Sea and the Quark (Fig. 5, VI). A higher lake percentage in river catchments decreased fluxes of P more strongly than fluxes of N (I).

The fluxes of total N and P estimated for the period 1986–90 are slightly lower than those calculated for the period 1979–83 (Pitkänen 1987, I). Taking into account that the mean water flow in 1986–90 was slighly lower than in 1979–83 (Pitkänen 1987, Table 1) and that the total point-source

P loading has somewhat decreased during the 1980s (NBWE 1993, Repo and Hämäläinen 1994), the flow-weighted sampling seems to produce somewhat higher estimates of total riverine inputs than monthly sampling. However, as could be expected, in small agricultural rivers with low lake-percentage (especially in the catchment of the Archipelago Sea), the flow proportional sampling produces clearly higher estimates than does the temporally uniform sampling (Table 3, Pitkänen 1987, I). It is also clear that in rivers with strong flow and concentration variations the present calculation procedure and relatively low sampling frequency still underestimates the real fluxes (Walling and Webb 1985, VI, Chapter

Table 3. Mean annual (I) and summertime (July — September, II) water flows (Q_R, $m^3\ s^{-1}$) and fluxes of N and P compounds of the Finnish rivers to the Baltic Sea in 1986—1990 (t). Values for the non-monitored rivers have been obtained by extrapolation from the fluxes of the monitored small coastal rivers (point loads subtracted).The values in brackets indicate percentages of summertime fluxes of total annual fluxes.

River	Q_R, $m^3\ s^{-1}$		Total N, t		Inorganic N, t		Total P, t		Inorganic P,t	
	I	II	I	II	I	II	I	II	I	II
Virojoki	4.2	1.7	160	19 (12)	..	..	8	1.2 (15)	..	..
Kymijoki	371.0	358.6	7220	1587 (22)	2930	570 (19)	327	86.9 (27)	57	16.9 (30)
Koskenkylänj.	9.1	4.0	550	46 (8)	280	19 (7)	30	2.0 (7)	11	0.9 (8)
Porvoonjoki	14.8	9.4	1540	235 (15)	1220	164 (13)	63	8.9 (14)	38	5.8 (15)
Mäntsälänjoki	7.4	4.3	520	59 (11)	..	..	26	2.8 (11)	..	..
Vantaa	16.7	8.7	1400	162 (12)	1050	109 (10)	68	7.8 (11)	35	3.7 (11)
Karjaanjoki	20.4	14.3	680	88 (13)	410	35 (9)	27	4.5 (17)	13	2.1 (16)
Non-monitored	56.7	33.1	3170	321 (10)	2480	152 (6)	154	14.8 (10)	84	7.5 (9)
Total to Gulf of Finland	500.3	434.1	15240	2517 (17)	8370	1049 (13)	703	128.9 (19)	238	36.9 (16)
Kiskonjoki	10.7	5.1	360	25 (7)	..	..	23	3.5 (15)	..	..
Uskelanjoki	5.9	3.1	440	40 (9)	..	..	42	4.8 (11)	..	..
Paimionjoki	10.5	4.4	810	56 (7)	570	33 (6)	78	5.4 (7)	45	3.2 (7)
Aurajoki	9.0	5.2	640	59 (9)	420	30 (7)	56	6.7 (12)	32	3.4 (11)
Non-monitored	54.3	26.7	3250	237 (7)	2680	168 (6)	292	29.0 (10)	201	19.2 (9)
Total to Archipelago Sea	90.4	44.5	5500	417 (8)	3670	231 (6)	491	49.4 (10)	278	25.8 (9)
Eurajoki	10.8	6.2	670	97 (14)	..	..	28	5.4 (19)	..	..
Kokemäenjoki	295.0	222.5	11040	1788 (16)	6310	815 (13)	590	133.3 (23)	252	50.5 (20)
Karvianjoki	41.2	22.3	1330	184 (14)	..	..	100	17.7 (18)	..	..
Isojoki	14.9	8.1	510	66 (13)	260	28 (11)	31	4.1 (13)	16	2.2 (14)
Laihianjoki	4.3	2.3	390	41 (11)	..	..	10	1.7 (17)	..	..
Non-monitored	65.9	35.6	2470	306 (12)	2590	274 (11)	147	24.5 (17)	155	20.4 (13)
Total to Bothnian Sea	432.1	297.0	16410	2482 (15)	9160	1117 (12)	906	186.7 (21)	423	73.1 (17)
Kyrönjoki	47.1	28.2	3140	386 (12)	1930	233 (12)	135	24.7 (18)	71	13.1 (18)
Lapuanjoki	40.7	25.7	2220	289 (13)	1410	141 (10)	118	17.5 (15)	55	8.0 (15)
Ähtävänjoki	17.7	13.4	460	83 (18)	..	..	22	4.7 (21)	9	1.8 (20)
Perhonjoki	24.4	20.7	850	157 (18)	380	40 (11)	72	18.0 (25)	39	8.0 (21)
Lestijoki	13.2	12.7	400	80 (20)	180	22 (12)	36	7.3 (20)	20	4.1 (21)
Kalajoki	41.4	42.6	1830	427 (23)	940	145 (15)	158	42.0 (27)	76	18.1 (24)
Pyhäjoki	33.2	29.8	1040	187 (18)	430	56 (13)	63	11.7 (19)	37	6.8 (18)
Siikajoki	43.0	39.5	1270	276 (22)	420	66 (16)	116	22.9 (20)	68	12.8 (19)
Oulujoki	253.7	203.8	3020	586 (19)	650	90 (14)	182	33.4 (18)	81	10.4 (13)
Kiiminginjoki	43.5	34.0	770	127 (16)	170	19 (11)	56	8.5 (15)	26	3.0 (12)
Iijoki	159.8	130.5	2040	388 (19)	420	45 (11)	139	25.2 (18)	53	8.6 (16)
Simojoki	36.2	27.2	600	98 (16)	120	12 (10)	36	4.3 (12)	13	1.1 (8)
Kemijoki	536.7	459.3	6290	1255 (20)	1430	158 (11)	411	53.9 (13)	133	15.2 (11)
Tornionjoki	396.7	450.9	4120	888 (22)	740	51 (7)	358	51,7 (14)	106	15.2 (14)
Non-monitored	106.6	87.6	3730	608 (16)	2110	225 (11)	244	48.1 (20)	118	21.4 (18)
Total to Bothnian Bay	1793.9	1605.9	31780	5835 (18)	11330	1303 (12)	2146	373.9 (17)	905	147.6 (16)
Total	2816.7	2381.5	68930	11251 (16)	32530	3700 (11)	4246	738.9 (17)	1844	283.4 (15)

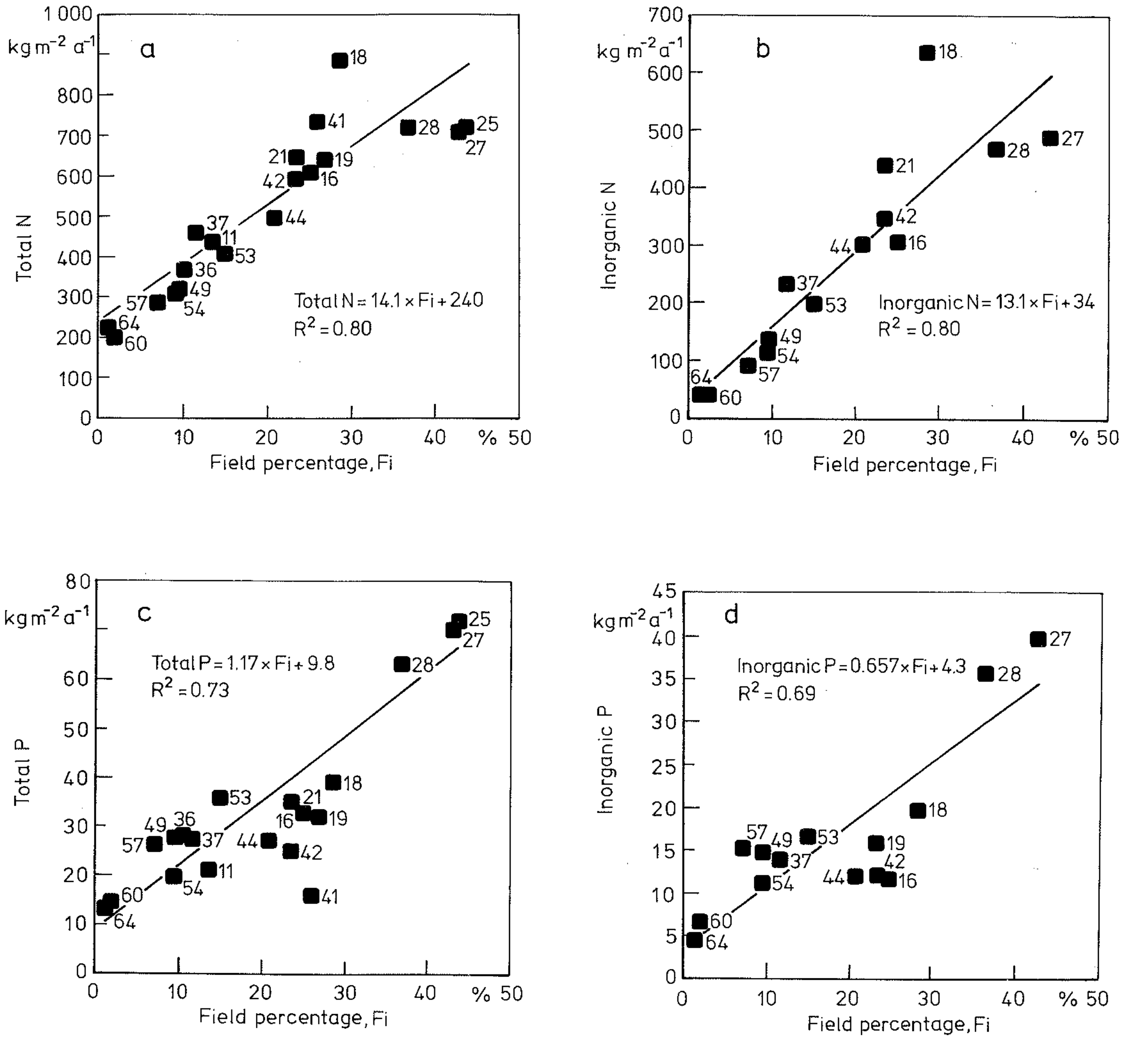

Fig. 5. Dependence of riverine nutrient fluxes on field-percentage in the river catchments with lake-percentage < 5 %. a) total N, b) inorganic N, c) total P, and d) inorganic P. Point-source inputs have been substracted from river fluxes.

3.4.1).

During 1986–90 the total land-derived inputs into the coastal waters were 79 000 t a^{-1} of N and 4 800 t a^{-1} of P. Thus, on an annual basis rivers are responsible for 87 % and 88 % of the total land-derived inputs of N and P, respectively (Tables 3, 4 and 7). In the catchments of the Gulf of Finland and the Archipelago Sea the riverine proportions were clearly lower (ca. 75 %) than the national average, while over 90 % of the land-derived nutrient inputs to the Bothnian Bay reach the coastal waters via rivers.

The share of direct industrial and municipal nutrient input to coastal waters from the total land-derived input has changed quite little compared to the early 1980s (Table 4, II). The decrease in direct municipal loading of P by 120 t a^{-1} during the 1980s was largely compensated by increased loading from the wood processing industry and from fish farming (60 ta^{-1}). During the late 1980s and early 1990s P input from the Finnish forest industry has, however, decreased strongly (350 t a^{-1} from 1988 to 1992, Repo and Hämäläinen 1994) and this trend is expected to continue during the next few years (Valttila 1993).

In the early 1970s inputs of P to coastal waters have been higher than in the beginning of the 1990s, especially due to a decrease of about 1 500 t a^{-1} in municipal loading of the whole country in the 1970s (NBWE 1993). This decrease can be seen in the P fluxes of the Rivers Kymijoki, Vantaa, Porvoonjoki, Kokemäenjoki and Oulujoki (Pitkänen et al. 1987, I, Table 2). The same trend is also apparent in the estuaries and adjacent coastal waters off the mouths of these rivers, as well off the main municipalities at the Finnish coast (Pitkänen et al. 1987).

In contrast to P, the total input of N to coastal waters has probably increased, despite decreased total industrial loading especially in the early 1970s, due to increased inputs from agriculture, municipalities, fish-farms and via the atmosphere as well as due to increased riwer flows (Repo and Hämäläinen

Table 4. The direct municipal and industrial inputs of nitrogen and phosphorus to the Finnish coastal waters in 1986–90 (Data Bases of Municipal and Industrial Pollution Loads, NBWE). The data on the loading from fish farms is from 1992 (Repo and Hämäläinen 1994). The values in brackets indicate the estimate on bioavailable proportion of the input in cases where the bioavailable load deviates from the total load.

Coastal Region	Nitrogen, ta^{-1}			Phosphorus, ta^{-1}		
	municipal	industrial	total	municipal	industrial	total
Kotka–Hamina	210	208	418	8.2	34.3	42.5
Loviisa	25	1	26	0.6	0.0	0.6
Porvoo	123	96	219	3.6	4.4	8.0
Helsinki–Espoo	3658	1	3659	107.1	0.1	107.2
Tammisaari	45	-	45	2.3	-	2.3
Hanko	63	22	85	2.5	1.1	3.6
Fish farms	-	112	112	-	17.2	17.2
Other regions	99	-	99	2.7	-	2.7
Total to the Gulf of Finland	4223	440 (336)	4663 (4559)	127.0 (88.9)	57.1 (50.2)	184.1 (139.1)
Hanko	3	26	29	0.7	0.1	0.8
Salo	70	8	78	1.8	0.1	1.9
Turku–region	891	141	1032	28.9	0.6	29.5
Fish farms	-	410	410	-	55.7	55.7
Other regions	20	0	20	1.0	0.0	1.0
Total to the Archipelago Sea	984	585	1569	32.4 (22.7)	56.5	88.9 (79.2)
Uusikaupunki	70	62	132	1.4	5.1[2]	6.5
Rauma	88	108	196	2.5	32.7	35.2
Pori	321	49	370	8.0	13.9	21.9
Kaskinen	-	177	177	-	46.6	46.6
Vaasa	169	-	169	7.6	-	7.6
Fish farms	-	147	147	-	19.4	19.4
Other regions	39	7	46	5.7	1.3	7.0
Total to the Bothnian Sea	687	550 (408)	1237 (1095)	25.2 (17.6)	119.0 (103.2)	144.2 (120.8)
Pietarsaari	123	175	298	2.1	37.2	39.3
Kokkola	135	451	586	1.2	4.5	5.7
Raahe	66	104	170	1.6	3.6	5.2
Oulu	492	235	727	9.7	30.9	40.6
Kemi	98	308	406	4.4	66.5	70.9
Tornio[2]	100	93	193	9.2	0.1	9.3
Fish farms	-	35	35	-	4.5	4.5
Other regions	123	26	149	3.4	3.5	6.9
Total to Bothnian Bay	1137	1427 (1069)	2564 (2206)	31.6 (22.1)	150.8 (123.9)	182.4 (146.0)
Total	7031	3002 (2398)	10033 (9429)	216.2 (151.3)	383.4 (333.8)	599.6 (485.1)

- = No input

[1] The figure does not include leaching of P from the local waste gypsum deposit of a fertilizer factory

[2] Including the Town of Haaparanta in Sweden. The municipal load of N is estimated on the basis of P load.

1992, Rekolainen 1993, I, II, VI, Table 4). In accordance with this, especially agricultural rivers show increasing N trends (Pitkänen 1987, I, VI, Table 3). The effect of decreased industrial N loading is evident in two rivers. In the River Oulujoki a strong decrease took place in the early 1970s (Alasaarela 1979b, I) due to an efficient reduction of industrial discharges to the lower course of the river. In the River Kymijoki a similar trend was due to closing down a sulphite pulp mill in the mid 1970s (Lempinen 1981, Pitkänen 1987).

4.1.2 Contributions of direct and diffuse sources to river fluxes

If industrial and municipal inputs to the rivers (below lake areas in the lake-rich catchments, Tables 1 and 5) are considered to behave conservatively before entering coastal waters, the annual proportion of waste water based inputs from the land-derived inputs is 17 % and 18 % for total N and P, respectively (compared to 13 and 12 %, respectively, for direct coastal discharges, Table 7). On an annual basis waste waters contain 31 % of the N and 35 % of the P input to the Gulf of Finland , whereas for the Bothnian Bay the corresdponding figures are considerably lower, 11 % for both N and P. The point-source N loading originates mainly from municipal waste waters, whereas industry (including fish farming) is the main point-source of P.

Agricultural loading comprises 31 % of the N and 35 % of the P input annually (Tables 6 and 7). The figures are highest for the Archipelago Sea (57 % of the N and 65 % of the P inputs), and smallest for the Bothnian Bay, where agriculture contributes 26 % of total N and 24 % of total P inputs. The background discharge (natural leaching, forestry, atmospheric inputs) is highest for the Bothnian Bay (63 % of the annual N and 65 % of the annual P inputs) and lowest for the Archipelago Sea (19 % of N and 18 % of P). The high background values for the Bothnian Sea (56 % of N and 42 % of P) are partly explainable by the strong point-source loading to the lakes in the middle and upper parts of the River Kokemäenjoki catchment, which are evidently not capable of retaining the load completely.

In late summer the contribution of point-sources increases in relation to diffuse loading, because most of the agricultural areas are located in lake-poor coastal regions (Table 7). Under normal hydrological conditions nutrient leaching from these areas mainly occurs during spring and late autumn. The average summertime point-source inputs are estimated as 27 % and 28 % of the total inputs of N and P, respectively. The proportions are highest for the Archipelago Sea (60 % of N and 50 % of P), largely due to fish farming, and lowest for the Bothnian Bay (16 % for both N and P).

Regarding the eutrophying effects (i.e. the effect on new planktonic production) of land-derived inputs to coastal waters, the comparison of total annual nutrient inputs from the various sources can be misleading. In nearly all small coastal rivers, as well as in large rivers having a low lake-percentage (< 5 %), a high proportion (up to 50 %, e.g. Jumppanen and Mattila 1994) of the annual nutrient load reaches the coastal waters in April-May, i.e. before or during the vernal phytopklankton bloom. Another high nutrient pulse reaches coastal waters in late autumn (sometimes also in winter in southern Finland), when the lack of light limits primary productivity. The vernal bloom effectively transfers bioavailable N and P to deeper waters and to the bottom (e.g. Leppänen 1988, Heiskanen and Leppänen 1994). Thus, neither the annual flux nor the springtime flux do directly explain the degree of trophy of coastal waters in summer.

The immediate biological availability of N and P inputs from the various natural and anthropogenic sources varies considerably. Probably only ca. 30 % of the agricultural losses of P and 25 % of the P losses from forested areas are directly bioavailable (Ekholm et al. 1991, Pietiläinen and Rekolainen 1991, Ekholm 1994). Regarding municipal and industrial inputs the figures are considerably higher; in the present study it is assumed that 70 % of the municipal P inputs (Ekholm 1991, 1994) and all of the municipal N are bioavailable.

A recent study (Priha 1994) suggests a bioavailability of 80 % for forest industrial P inputs, while there are no results available on the bioavailability of N discharges from the Finnish forest industry. In the late 1980s about one half of the forest industrial waste waters were biologically treated, mostly by the activated sludge method (Valttila 1993). In the non-treated waste waters the proportion of inorganic N is low, usually less than 10 % of total N, while in treated (activated sludge method) waste water the proportion varies considerably, from less than 10 to over 90 % of total N (Pauli 1994, Priha 1994). In the present study 50 % was adopted as an estimate of the proportion of bioavailable N, because, in addition to soluble fraction, a considerable part of N in pulp mill waste waters is in particulate form and evidently releases bioavailable N as a result of decomposition

Table 5. Point-source nitrogen and phosphorus inputs to the Finnish rivers in 1986 – 1990. Only the lower catchment area below larger lake basins is taken into account (Data Bases of Municipal and Industrial Pollution Load; NBWE). The figures in brackets indicate bioavailable inputs.

River	Nitrogen, ta^{-1}			Phosphorus, ta^{-1}		
	municipal	industrial	total	municipal	industrial	total
Virojoki	3	–	3	0.4	–	0.4
Kymijoki	244	359	603	7.3	95.7	103.0
Koskenkylänjoki	4	2	6	0.4	0.2	0.6
Porvoonjoki	411	–	411	13.0	–	13.0
Mäntsälänjoki	19	–	19	0.8	–	0.8
Vantaa	261	47	308	7.3	1.1	8.4
Karjaanjoki	40	1	41	1.5	0.0	1.5
Other rivers	81	1	82	2.0	0.2	2.2
Total to Gulf of Finland	1063	410 (231)	1473 (1294)	32.7 (23.0)	97,2 (78.1)	129.9 (101.1)
Kiskonjoki	7	–	7	0.5	–	0.5
Uskelanjoki	21	10	31	1.1	0.2	1.3
Paimionjoki	38	–	38	1.7	–	1.7
Aurajoki	10	1	11	0.8	0.0	0.8
Other rivers	28	3	31	2.3	0.4	2.7
Total to Archipelago Sea	104	14	118	6.4 (4.5)	0.6	7.0 (5.1)
Eurajoki	91	48	139	1.9	1.7	3.6
Kokemäenjoki	315	49	364	11.7	13.3	25.0
Karvianjoki	59	0	59	2.7	0.1	2.8
Isojoki	2	3	5	0.1	0.7	0.8
Laihianjoki	18	–	18	1.9	–	1.9
Other rivers	51	0	51	2.2	0.0	2.2
Total to Bothnian Sea	536	100 (76)	636 (612)	20.5 (14.4)	15.8 (14.9)	36.3 (29.3)
Kyrönjoki	219	3	222	11.0	0.6	11.6
Lapuanjoki	158	7	165	4.7	1.1	5.8
Ähtävänjoki	5	17	22	0.1	0.5	0.6
Perhonjoki	15	23	38	0.7	1.1	1.8
Lestijoki	13	2	15	0.6	0.5	1.1
Kalajoki	97	3	100	5.1	0.3	5.4
Pyhäjoki	70	16	86	3.1	0.2	3.3
Siikajoki	19	5	24	1.4	1.2	2.6
Oulujoki	15	136	151	1.1	2.4	3.5
Kiiminginjoki	10	–	10	0.7	–	0.7
Iijoki	26	–	26	1.5	–	1.5
Simojoki	12	–	12	1.0	–	1.0
Kemijoki1)	253	101	354	9.8	27.0	36.8
Tornionjoki	34	5	39	1.9	0.1	2.0
Other rivers	30	3	33	1.8	0.9	2.7
Total to Bothnian Bay	976	321 (271)	1297 (1247)	44.5 (31.2)	35.9 (30.5)	80.4 (61.7)
Total	2679	845 (592)	3524 (3271)	104.1 (73.1)	149.5 (124.1)	253.6 (197.2)

– = No input

1) Point-source inputs to the Lake Kemijärvi and to the upper part of the catchment above the lake have been included in calculations as such, due to the short residence time and very strong regulation of the lake.

Table 6. Agricultural inputs of N and P into the different Finnish coastal water areas via rivers and from the coastal zone between the river catchments and the shore-line. The specific loads have been estimated on the basis of Kauppi (1984), Pitkänen (1987), Rekolainen (1993), papers I and VI and the data of the present study. Only the parts of the river catchments below larger lake areas have been taken in account in the calculations.

Coastal water area	Field area, km^2	Total N		Total P	
		$kg\ km^{-2}\ a^{-1}$	$t\ a^{-1}$	$kg\ km^{-2}\ a^{-1}$	$t\ a^{-1}$
Gulf of Finland	2571	2000	5140	120	309
Archipelago Sea	2529	1600	4050	150	379
Bothnian Sea	3608	1600	5770	120	433
Bothnian Bay	5652	1600	9040	100	565
Total	14360	1670[1)]	24000	120[1)]	1686

[1)] Weighted mean value

Table 7. Mean contribution of different nutrient sources to the mean fluxes of total and bioavailable N and P to the Finnish coastal waters annually and in late summer (July-September) 1986–1990. The background includes contributions of forestry, atmospheric inputs and natural leaching (and probably some contribution from municipalities and industries in the lake-areas of the large rivers) and has been obtained by substracting the contributions of agricultural and direct anthropogenic loading from total riverine loading (see Material and methods). It has been assumed that DIN equals bioavailable N in river fluxes and that the proportions of summertime diffuse fluxes (agriculture and background) equal the respective proportions between summertime and annual river fluxes. 25 % of the annual point-source loading and 2/3 of the annual loading from fish farms is assumed to take place during July-September. The values in brackets indicate relative proportions (%). Other assumptions on bioavailability are explained in the text (Chapter 4.1.2).

Area	Source	Total N, t (%)		Bioavailable N, t (%)		Total P, t (%)		Bioavailable P, t (%)	
		annually	in summer	annually	in summer	annually	in summer	annually	in summer
GF	agriculture	5140 (26)	514 (15)	3855 (30)	231 (11)	309 (35)	31 (19)	93 (23)	9 (10)
	industry	850 (4)	253 (7)	567 (4)	189 (9)	154 (17)	46 (28)	128 (32)	39 (44)
	municipalities	5286 (27)	1322 (37)	5286 (41)	1322 (61)	160 (18)	40 (24)	112 (28)	28 (31)
	background	8627 (43)	1467 (41)	3221 (25)	419 (19)	264 (30)	50 (29)	66 (17)	13 (15)
	total	19903	3556	12929	2161	887	167	399	89
AS	agriculture	4050 (57)	284 (29)	3038 (58)	182 (22)	379 (65)	38 (39)	114 (51)	11 (19)
	industry	599 (9)	322 (33)	599 (11)	322 (40)	57 (10)	38 (39)	57 (25)	38 (64)
	municipalities	1088 (15)	272 (27)	1088 (21)	272 (34)	39 (7)	10 (11)	27 (12)	7 (12)
	background	1332 (19)	107 (11)	514 (10)	31 (4)	105 (18)	11 (11)	26 (12)	3 (5)
	total	7069	985	5239	807	580	97	224	59
BS	agriculture	5770 (33)	692 (25)	4328 (42)	476 (32)	433 (41)	74 (34)	130 (34)	22 (25)
	industry	650 (4)	224 (8)	487 (5)	181 (12)	134 (13)	41 (19)	118 (30)	36 (40)
	municipalities	1223 (7)	306 (12)	1223 (12)	306 (21)	46 (4)	12 (5)	32 (8)	8 (9)
	background	10004 (56)	1501 (55)	4217 (41)	506 (35)	437 (42)	92 (42)	109 (28)	23 (26)
	total	17647	2723	10255	1469	1050	219	389	89
BB	agriculture	9040 (26)	1446 (23)	6780 (50)	746 (37)	565 (24)	113 (26)	170 (23)	34 (23)
	industry	1748 (5)	451 (7)	1340 (10)	349 (17)	187 (8)	47 (11)	155 (20)	40 (26)
	municipalities	2113 (6)	528 (9)	2113 (16)	528 (26)	76 (3)	19 (5)	53 (7)	13 (9)
	background	21443 (63)	3860 (61)	3303 (24)	396 (20)	1501 (65)	255 (58)	375 (50)	64 (42)
	total	34344	6285	13536	2019	2329	434	753	151
Total	agriculture	24000 (31)	2936 (22)	18001 (43)	1635 (25)	1686 (35)	256 (28)	507 (29)	76 (20)
	industry	3847 (5)	1250 (9)	2993 (7)	1041 (16)	532 (11)	172 (19)	458 (26)	153 (39)
	municipalities	9710 (12)	2428 (18)	9710 (23)	2428 (38)	321 (7)	81 (9)	224 (13)	56 (14)
	background	41406 (52)	6935 (51)	11255 (27)	1352 (21)	2307 (47)	407 (44)	576 (32)	103 (27)
	total	78963	13549	41959	6456	4846	916	1765	388

by bacteria in coastal waters (cf. Jørgensen and Pauli 1992). Regarding other indusries (including fish farming) all the nutrient inputs are assumed to be bioavailable.

The estimates of bioavailability of the different nutrient sources presented above are very rough, but they offer an alternative approach (compared to the traditional calculations based on total annual amounts) to assess the relative importance of the various nutrient sources for eutrophication of coastal waters (especially during the productive season).

Based on calculations of bioavailable inputs, the relative (%) contribution of point-source loading is about double the contribution based on total nutrients (Table 7). On a national level, municipalities and industry are estimated to be responsible for 30 % of the annual N and 39 % of the annual P loading. The proportion of agricultural bioavailable N increases to 43 % (31 % for total N), whereas the proportion of agricultural bioavailable P decreases to 29 % (35 % for total P). The proportions of background bioavailable nutrients are only 27 and 32 % for N and P, reppectively, whereas the shares calculated from total inputs were 52 % for N and 47 % for P.

If only the late summer period is considered, as much as 54 % of the bioavailable N and 53 % of the bioavailable P inputs originate from municipal and industrial waste waters, whereas the respective contributions of diffuse loading from agriculture are only 25 % for N and 20 % for P (Table 7). Even for the Bothnian Bay the contributions of point-source N and P are estimated as 43 % and 35 % of total bioavailable inputs, respectively.

In the Gulf of Finland Finnish point-sources are responsible for 70 % of the bioavailable N and 75 % of the bioavailable P inputs. Municipal waste waters (especially in the Helsinki area) elevate the proportion of N, whereas the wood processing industry is the main contributor of P inputs. In the Archipelago Sea point-sources contribute 74 % of the summertime bioavailable N and 76 % of the bioavailable P largely due to intensive fish-farming, whereas the contribution of agriculture was estimated only as ca. 20 %, due to small leaching of nutrients from the fields in summer.

For the coastal waters of the Bothnian Sea industry is clearly a more important source of bioavailable P (40 %) in summer than agriculture (25 %), while for N the situation is the opposite (agriculture 32 %, industry 12 %). The role of municipalities (21 % of N, 9 % of P) is clearly smaller than in the Gulf of Finland and in the Archipelago Sea. In the Bothnian Bay agriculture and municipalities are the main contributors of bioavailable N (37 and 26 %, respectively), whereas in the case of P the proportion of background is 42 % and the shares of industry and agriculture are 26 and 23 %, respectively. The municipal proportion of P is only 9 % of the estimated summertime bioavailable inputs.

4.2 Nutrient distributions and trophic conditions in coastal waters

The most comprehensive data on variables indicating the trophic conditions of the Finnish coastal and adjacent open Baltic Sea waters are those on total N and total P (II). Since 1979 also inorganic nutrient concentrations and chlorophyll-*a* have been included in the regular monitoring programs (Pitkänen et al. 1985, 1987). In addition, total N and total P are analyzed in most of the local recipient monitoring programs based on the Water Act. Although total nutrients do not directly indicate the trophic degree (i.e. primary productivity) of a particular water area, a dependence between total nutrients, phytoplankton biomass and primary productivity has been observed, especially when longer periods or large spatial scales are compared (Niemi 1973, 1975, Alasaarela 1980, Hällfors et al. 1983, Wulff and Rahm 1987, Grönlund and Leppänen 1990, Kangas et al. 1993).

4.2.1 Spatial and temporal variation in nitrogen and phosphorus concentrations

The nutrient distribution in coastal waters in general reflects the land-derived nutrient loading, especially that from rivers (II, V, VIII). In the open sea areas the well-known order of increasing P concentration (and also trophic degree) Bothnian Bay < Bothnian Sea < Archipelago Sea < western Gulf of Finland < eastern Gulf of Finland, can be found both in winter and in summer data. The low P concentration of the Bothnian Bay, despite the considerable inputs, is explained by the high input of riverine iron and effective Fe-P precipitation (Voipio 1969). The distribution of total N is similar to that of total P, except in the Gulf of Bothnia, where no clear south-north gradient can be found, probably due to substantial riverine inputs of stable dissolved organic N to the Bothnian Bay (Table 3, Alasaarela 1980, II). On the contrary, in the Gulf of Finland the high nutrient inputs to the Neva Estuary are very clearly reflected in both total N and total P distributions (V, VIII).

Local nutrient inputs, hydrodynamics and coastal morphometry strongly modify the basic level of N and P in coastal waters (II). The area of increased nutrient concentrations can be relatively small despite the considerable land-derived inputs, if mixing with open sea water is effective, like outside the River Kokemäenjoki Estuary, which receive the highest single inputs of N and P within the Finnish coastal waters (Tables 3 to 5). On the other hand, relatively small inputs can increase nutrient levels in a large area, if horizontal mixing conditions are restricted by complex coastal morphometry, like in the inner Archipelago Sea and in the coastal waters of the Gulf of Finland. Deeper coastal waters, formed by successive semi-enclosed basins with permanent density stratification, favour nutrient sedimentation in summer (Pitkänen et al. 1990, V). As a result, late summer concentrations of the surface layer can be even lower than in the respective open sea area, where sedimentation is less effective due to a thick mixed surface layer (VIII). In shallow coastal waters (e.g. the north-eastern Bothnian Bay and in the Quark) with no permanent thermocline, effective vertical mixing keeps nutrient concentrations on an elevated level.

The wintertime spreading of nutrient-rich riverine water immediately below the ice cover can be seen especially in the total N distribution in the north-east Bothnian Bay and the north-east Gulf of Finland (II). The north-eastern Bothnian Bay receives a total fresh water discharge of ca. 1 700 m^3 s^{-1} from several Finnish and Swedish rivers (Alasaarela 1980). In the north-eastern Gulf of Finland the increased wintertime N concentartions are mostly due to the flow of nutrient-rich water from the River Neva (Pitkänen et al. 1990).

An exceptional distribution of total P prevails during winters in the easternmost Finnish archipelago of the Gulf of Finland (II). The basic level is relatively high (about 40 mg m^{-3} of P) due to the wintertime re-mineralization and weak density stratification. In addition the large inputs from the Neva Estuary spread to the whole north-eastern Gulf and further increases the concentration. On the other hand, the wintertime P concentration of the River Kymijoki is low (10 to 20 mg m^{-3}, III) due to the effective retention of P in the lake-rich middle and upper parts of the catchment and negligible diffuse loading in the lower catchment in winter. As a result, surface layer concentrations of P are clearly lower in an area of about 1 000 km^2 off the mouths of the River Kymijoki than in the surrounding coastal and open Gulf waters.

4.2.2 Chlorophyll-*a* vs. nutrients

The inorganic nutrient content during the prebloom period, together with local hydrodynamics and weather conditions, determine the intensity and length of the spring-bloom of phytoplankton (Niemi 1973, 1975, Hällfors et al. 1983, Niemi and Åström 1987). However, the wintertime nutrient concentration do not directly control the level of planktonic production of the following summer, because the vernal production maximum effectively transfers nutrients from the euphotic layer to deeper waters and to the bottom (Leppänen 1988, Heiskanen and Leppänen 1994).

Especially in the nutrient-rich Gulf of Finland the spring-bloom leads to a sedimentation of massive amounts of bioavailable nutrients from the euphotic layer. The level of regenerated production in the following summer depends on the amounts of bioavailable nutrients that remain in the mixed surface layer after this sedimentation. In loaded (inner) coastal waters, the pelagic plankton cummunities receive more or less a continuous nutrient replenishment either from the land or as a result of upward vertical transport of regenerated nutrients in waters with no permanent pycnocline (this happens also in deeper waters as a result of intensified vertical mixing and the erosion of the thermocline caused e.g. by heavy winds). The external input of nutrients lead to an increased new production, i.e. eutrophication.

The basic open sea chlorophyll-*a* level (1–2 mg m^{-3} in the Gulf of Bothnia, 2 to 5 mg m^{-3} in the Gulf of Finland, see Table 8) drasticly increases in coastal waters (Pitkänen et al. 1985, 1987, 1990, IV, V, VIII). Clearly eutrophied areas cover the whole coastal water zone of the Gulf of Finland, the whole inner and certain middle parts of the Archipelago Sea, the archipelago off Uusikaupunki, the Kokemäenjoki Estuary, the Quark archipelago, the archipelago off Kokkola-Pietarsaari and the north-eastern Bothnian Bay from Raahe to Tornio. In the same areas also total N and total P concentrations, as well as wintertime concentrations of inorganic N and P are higher compared to the the basic open sea level.

In the inner coastal waters of the Gulf of Finland, especially off Helsinki-Espoo and Kotka-Hamina, point-source loading (N from municipalities and P from industries, Tables 7 and 8) is the main land-derived nutrient source causing the observed eutrophication together with the coastal morphometry. In the inner Archipelago Sea the main contributors are diffuse loading from agriculture (both N and P) and N from municipal waste waters, while in the middle parts of this area intensive fish farming causes eutrophication (Jumppanen and Mattila 1994). In the Bothnian Sea industrial waste water load is the primary source of eutrophication off Uusikaupunki, and, in addition, municipalities and agriculture increase phytoplankton biomasses in the River Kokemäenjoki Estuary and adjacent waters. In the Quark archipelago intensive agriculture and municipal nutrients cause eutrophication. Off Kokkola and Pietarsaari in the Bothnian Bay industrial waste water is the main antrophogenic contributor to increased plankton biomasses. In the northeastern Bothnian Bay local wood-processing and chemical industry causes eutrophication, with municipalities as a considerable additional source of N. Due to the small field-percentage of the river catchments discharging to the nort-eastern Bothnian Bay (Table 1), the role of agriculture remains relatively small, but forestry may be a significant source of nutrients here (cf. Sallantaus 1986).

Despite the high inorganic N:P-ratio of the land-derived inputs (Table 7), the role of N as the limiting nutrient for planktonic production in late summer seems to be more important than that of P. It is probable that the anthropogenic inputs of bioavailable N (rather than P) in the first place regulate eutrophication of the Finnish coastal waters, excluding the physically limited (turbidity, currents) innermost waters and the merely P limited coastal waters of the Bothnian Bay (see Chapter 4.4.1, Alasaarela 1980, Tamminen 1990, Kangas et al. 1993, Kivi et al. 1993, Tamminen et al. 1993, VIII).

The high chlorophyll-*a* level of the easternmost Gulf of Finland is due to heavy nutrient loading and estuarine hydrodynamics of that sea area (Tables 7 and 8 , IV, V, VIII). In the mixing zone (the inner Neva Estuary, Fig. 4) of the nutrient-rich surface flow from the River Neva and the bottom-near saline flow from the western Gulf, high summertime chlorophyll-*a* concentrations between 10 and 20 mg m^{-3} (up to 10 times the level of the westernmost open Gulf) have been frequently analyzed in extensive, 20 to 30 m deep non-archipelagic waters. Depletion rates of inorganic nutrients up to 10 times those of the open Gulf have been measured from the

Table 8. The main anthropogenic and physical factors controlling the trophic degree in the eutrophicated Finnish coastal waters and the eastern Gulf of Finland (Pitkänen 1987 et al. II, III, IV, V, VII, VIII and data from 1986–90). Nutrient sources: A = agriculture, F = forestry, I = industry (mainly chemical wood processing), Fi = fish farming, M = municipalities. Physical controls: S = shallowness, RHM = restricted horizontal mixing, SSB = stratified semi-enclosed basin, EH = estuarine hydrography. Brackets indicate uncertainty due to lack of data.

Area	Chlorophyll-*a* ($mg\ m^{-3}$)		Nutrient sources					Physical controls			
	concentration level	background	A	M	I	F	Fi	S	RHM	SSB	EH
NE Bothnian Bay	2– 5	1–2	x	x	x	(x)		x	x		
Kokkola-Pietarsaari	2– 4	1–2	x	x	x			x	x		
The Quark1)	2– 5	1–2	x	x				x	x		x1)
Kokemäenjoki Estuary2)	2–10	1–2	x	x	x			x	x		x
Uusikaupunki3)	2– 5	1–2		x	x			x	x		
Inner Archipelago Sea	3–10	1–2	x	x			x	x	x	x	x
Middle Archipelago Sea	2– 4	1–2					x		x	x	
Western Gulf of Finland (Tammisaari–Loviisa)	3–10	2–3	x	x				x	x	x	x
Eastern Gulf of Finland (Loviisa–Hamina)	5–10	3–5	x	x	x			x	x	x	x
Neva Estuary	5–20	ca. 5	x	x	x			x		x	x

1) Including the Kyrönjoki Estuary

2) Physical conditions support effective mixing and rapid dilution immediately outside the estuary

3) P loading from the gypsum waste deposit of a local fertilizer plant increases industrial P loading compared to that presented in Table 3

same area (VIII). Total N and total P concentrations are 1.5 to 3 times those of the open Gulf. The highest concentrations (up to 1 000 mg m^{-3} N and 85 mg m^{-3} P, VIII) have been measured in the non-saline Neva Bay. Phytoplankton biomasses are, however, clearly lower (5 to 10 mg m^{-3} chl-*a*) here than immediately outside the Bay, due to the physical limitations of primary production (IV, VIII).

Due to an intensive planktonic production a large part of the high external nutrient input is transferred to aphotic waters within the estuary (V, VIII). A part of the sedimented nutrients is regenerated and returned back to the euphotic layer via vertical estuarine mixing. The rest is lost either via sedimentation or denitrification. The regenerated nutrients are repeatedly biologically fixed and sedimented. Thus under summer conditions, planktonic biomasses mostly based on regenerated production, outwell from the estuary to the open Gulf of Finland. The phytoplankton biomass of the open eastern Gulf (4 to 5 mg m^{-3} chl-*a*, Table 8) is about double that of the open western Gulf (Niemi 1975, Pitkänen et al. 1987, Grönlund and Leppänen 1990). The corresponding west-east gradient in both total N and total P is, however, only slight (II) indicating that the main part of both total N and total P in the open Gulf is hardly bioavailable. The higher basic chlorophyll level of the open eastern Gulf compared to the western Gulf can be explained with the more efficient vertical mixing (i.e. less stable density stratification) and higher deep water concentrations of bioavailable nutrients in the eastern Gulf (V, VIII).

Under the conditions of a thin mixed surface layer, eutrophic waters from the Neva Estuary can spread along the northern coast of the Gulf as far as to the eastern Finnish waters, 150 km from the mouth of the River Neva (VIII). In general the clearly eutrophied waters cover the estuarine area to the transect between the islands of Seiskari and Koivisto, 90 km west from the river mouth.

The level of chlorophyll and total nutrients of the easternmost Finnish archipelago of the Gulf of Finland (excluding the innermost waters) is usually very close to that of the open eastern Gulf (Pitkänen et al. 1987, 1990, V). Trophic conditions of the open eastern Gulf govern the basic trophic degree in the archipelago. In fact, under calm late summer conditions (strong and steady pycnocline), the middle and outer Finnish archipelago, characterized by 30 to 40 m deep semi-enclosed basins, shows nutrient and chlorophyll levels even lower than those of the adjacent open Gulf waters. This is due to favourable conditions for sedimentation of planktonic production caused by physical stability of these semi-enclosed basins and indicates a considerable filtering capacity of external nutrient inputs for this type of coastal waters (see Chapter 4.4.2, V).

4.3 Nutrient transport in estuaries and coastal waters

The quantitative behaviour of riverine nutrient fluxes were studied in two estuarine areas (Kymijoki and Neva) with different morphometrical and hydrodynamic conditions (see Chapter 2.3). A common and very important feature of both estuaries is the continuous and high input of riverine nutrients. Results from the Kymijoki Estuary (III, VII) can be, with certain precautions, generalized to other small semi-enclosed estuaries with a relatively short residence time, whereas the Neva Estuary and its adjacent waters (IV, V, VIII) alone receive about 20 % of the total nutrient load of the whole Baltic Sea (HELCOM 1993b), thus playing an important role in its overall nutrient balance.

4.3.1 Sediment accumulation

About one half of the bottom area (26 km^2) of the Kymijoki Estuary accumulates sediments, the other half being transportation or erosion areas (VII). The sedimentation rate of wet SPM averages 7.7 mm a^{-1} and the critical depth for accumulation varies between 0 and 12 m, depending on morphometry and the strength of bottom-near currents. Estimated net annual amounts of 1 200 g m^{-2} of dry matter, 49 g m^{-2} of organic C, 4.2 g m^{-2} of N and 1.4 g m^{-2} of P are deposited annually on the accumulation bottoms. The sediment retention corresponds to 56 % of the external inputs of SPM, 13 % of the external P, and 2 % of both the external N and the external organic C inputs.

The mean accumulation rate for SPM estimated for the estuary falls within the limits obtained for other estuaries and coastal waters of the Baltic Sea, and it is also close to that estimated for the Chesapeake Bay in the Atlantic Ocean (Brügman and Lange 1983, Officer et al. 1984, Georgyevskiy and Kuptsov 1986, Heikkilä 1986, Tolonen et al. 1988, Kamp-Nielssen 1992). Compared to the open Baltic Sea waters, the sediment accumulation rate of SPM of the Kymijoki Estuary is up to one order of magnitude higher (Niemistö and Voipio 1974, Niemistö et al. 1978, Jonsson et al. 1990).

According to the sediment data and echo-soundings obtained during the cruises of R/V Muikku in 1992–94 (Pitkänen and Sandman, unpublished), 1 200 km^2 of the bottoms in the Neva Estuary can be classified as accumulation areas. In the whole eastern Gulf (including the estuary and the Finnish archipelago) the corresponding area is 3 600 km^2. Also here the critical depth for permanent sediment accumulation varies strongly: In the Neva Estuary from 15 to 30 m and in the open Gulf between 40 and 60 m. Near the sill area (Kymijoki–Suursaari-Bay of Narva) even bottoms at 70 to 80 m depth are eroded due to heavy shear stress by the strong near-bottom currents.

^{137}Cs datings (10 cores, Pitkänen and Sandman, unpublished) suggest that the mean sedimentation rate of wet SPM of the eastern Gulf is 11 mm a^{-1} (variation from 3 to 20 mm a^{-1}). The mean dry weight of the sediment surface was 12 % (n = 24) of wet weight. The estimate of 1.1 g cm^{-3} for the sediment density (Niemistö et al. 1978) gives a mean accumulation rate of 1 500 g m^{-2} a^{-1} of particulate matter for the accumulation area. The sediment concentrations of 4.9 mg g^{-1} for N and 1.4 mg g^{-1} for P (means from the anoxic 5 to 10 cm layer) suggest accumulation rates of 7.4 mg m^{-2} a^{-1} for N and 2.1 mg m^{-2} a^{-1} for P for the eastern Gulf.

For the whole eastern Gulf these estimates lead to an accumulation of $5.4 \cdot 10^6$ t a^{-1} of SPM, $27 \cdot 10^3$ t a^{-1} of N and $7.6 \cdot 10^3$ t a^{-1} of P. The P accumulation is close to that obtained by balance calculations ($7.4 \cdot 10^3$ t a^{-1}, IV). The total loss of N has been estimated as 96 000 t a^{-1} including denitrification (IV). Calculations based on salinity-concentration plots suggest a net loss of of $2.9 \cdot 10^3$ t a^{-1} of P and $39 \cdot 10^3$ t a^{-1} of N from the euphotic layer of the Neva Estuary (VIII). A part of these losses is finally deposited and/or denitrified not until outside the actual estuary. The correspondence between the different estimates is good, and suggests a substantial sediment accumulation capacity of P for the Neva Estuary and for the whole eastern Gulf.

4.3.2 Estuarine material balances

The high accumulation efficiency for SPM of both the Neva and the Kymijoki Estuaries is evidently due to the favourable current system and the morphometry (see Chapter 2.3, III, VII). However, in the Kymijoki Estuary the sediment accumulation of total N (2% of the input) but also that of total P (13 %) remains small. Due to the relatively short residence time (ca. 2 weeks), a large part of the riverine nutrients flows through the estuary unaffected, either as a constituent of allochthonous DOM (especially N) or associated with inorganic SPM (especially P). During low autochthonous production (November-April), also most of the soluble inorganic nutrients flow through the estuary unaffected (VII).

In estuaries and coastal waters (as well as in fresh water bodies) denitrification is usually a much more important loss process for N than sedimentation (Seitzinger et al. 1988). Balance calculations (VII) suggest that in the Kymijoki Estuary the annual loss (caused by combined sedimentation and denitrification) is about three times that of pure sedimentation, which is, however, still only 6 % of the annual input of total N to the estuary.

The loss estimates for the whole eastern Gulf of Finland are as high as 34 % of total external (land-derived, atmospheric, open sea) N and 38 % of external P inputs (IV). Of the combined land-derived and atmospheric inputs (inputs from the western Gulf omitted) the corresponding proportions are 69 % for N and 100 % for P. Concentration-salinity plots (VIII) suggest considerable filtering efficiency also for the Neva Estuary: about 40 % of the losses of both N and P within the eastern Gulf seems to take place in the estuarine area. On the other hand, the innermost estuary (the Neva Bay) has probably only a marginal effect on the total loss of nutrients, due to its shallowness, strong currents and short residence time (IV, V, VIII).

The estimated relative losses of both N and P are clearly higher for the Neva Estuary than for the Kymijoki Estuary. Morphometry and hydrodynamics favour filtering of SPM in both estuaries. However, large volume and long residence time of the Neva Estuary (ca. 6 months) compared to that of the Kymijoki Estuary (ca. 2 weeks) supports both biological and geochemical processes to transfer much larger proportions of external N and P from the water to the bottom sediment or to the atmosphere in the Neva Estuary.

Perttilä et al. (1994) obtained loss estimates of $130 \cdot 10^3$ t a^{-1} of N (denitrification and sedimentation) and $20 \cdot 10^3$ t a^{-1} of P for the whole Gulf of Finland, compared to 96 000 t a^{-1} of N and about 7 500 t a^{-1} of P obtained for the eastern Gulf in this study and in paper IV. Considering that the surface area of the eastern Gulf is about 40 % of that of the whole Gulf, and that the loss processes probably are more efficient in the eastern Gulf, the estimates for the loss of N are in good agreement.

4.4 Eutrophication and estuarine filtration efficiency

As emphasized earlier in this study, the total annual input of nutrients does not necessarily correlate well with the summertime trophic degree of a coastal water area. Thus an attempt was made to evaluate land-derived bioavailable nutrient inputs to coastal waters (Chapter 4.1.2). Similarly it is also important to assess the quantitative effect of estuaries and coastal waters on external bioavailable inputs of nutrients.

4.4.1 Nitrogen and phosphorus as production limiting factors in coastal waters

For phytoplankton growth the total nutrient input entering the Finnish coastal waters (N:P ≈ 16:1 w/w, Table 7) clearly indicates extra N relative to P, when compared to the optimum for phytoplankton of 7:1 w/w (Redfield et al. 1963). If only bioavailable nutrient inputs are considered, a still higher mean N:P ratio of 24:1 is obtained. Thus, the coastal waters receive from the land a very strong surplus (3.4 times the Redfield ratio) of bioavailable N relative to P. In the atmospheric inputs the ratio is even higher: total N:P ≈ 70:1 for the whole Baltic Sea (HELCOM 1987).

In the innermost archipelagoes and estuaries the biological production is often limited by physical conditions (despite extra bioavailable N and P), especially due to turbidity and/or high concentrations of riverine humic substances, decreasing light penetration of water (Chapter 1.2, Alasaarela 1980). Strongly varying physical conditions, especially salinity fluctuations, often hamper the adaptation of algae in innermost estuaries. Outside the innermost coastal waters the physically limited situation rapidly changes towards nutrient limitation.

Results from the Neva Estuary suggest that pelagic coastal ecosystems with a sufficient residence time of water tend to strive from the high towards optimum inorganic N:P ratios, and further on towards N deficiency, despite the strong surplus of N in land-derived inputs (IV, VIII). The open Bothnian Bay is the only clearly P limited water area of the Baltic Sea (Alasaarela 1980, Alasaarela et al. 1986, Tamminen et al. 1993, Kangas et al. 1993). In the coastal waters of this sea area, however, also N deficiency is possible. Conditions for denitrification are not as favourable as in the other parts of the Baltic Sea, especially due to the long winter and low autochthonous production of organic matter (Seitzinger 1988). In addition riverine iron probably effectively precipitates P (Voipio 1969).

Several coinciding internal processes decrease the bioavailable N:P ratios of the euphotic layer in coastal and estuarine ecosystems (IV, VIII):

(1) Denitrification of oxidized inorganic N compounds into free N_2 is responsible for substantial losses of N in estuaries and coastal waters (e.g. Seitzinger et al. 1984, Rönner 1985). In the Baltic Sea as well as in ocean estuaries, the role of denitrification as a permanent sink of N is much more important than sedimentation (Larsson et al. 1985, Seitzinger 1988, Floderus and Håkanson 1989, Wulff et al. 1990). Due to originally high inorganic N:P-ratios, a large potential source of inorganic N in sub-thermocline waters and the relatively unstable vertical stratification, the role of the opposite process, uptake of atmospheric N_2 by certain blue-green algae, evidently remains small in the estuaries of this study (Howarth et al. 1988, Pitkänen et al. 1990, V).

(2) Increasing salinity (increasing anion concentration) and decreasing concentrations of PO_4^{3-} and SPM along the gradient from the innermost estuary towards the open sea affect the adsorption-desorption balance of phosphate, favouring the release of PO_4^{3-} from SPM (Pomeroy et al. 1965, Froelich 1988), whereas in Finnish rivers about 50 % of the N is bound to DOM (Table 3), most of which releases bioavailable N only slowly (Burton 1988).

(3) The net accumulation of P in bottom sediments in saline and brackish waters is probably less efficient compared to that in freshwater sediments. It has been suggested (Curtis 1989, Caraco et al. 1990) that in saline water systems the adsorbed PO_4^{3-} ions are released from iron(III) oxyhydroxides as a result of the reduction of SO_4^{2-} to S^{2-} and Fe^{3+} to Fe^{2+} and the formation of insoluble FeS in the anoxic sediment. The process thus reduces the adsorption capacity of saline water sediments. In addition, several anions (SO_4^{2-}, OH^-, etc.) compete with PO_4^{3-} for the free adsorption sites under oxic conditions near the sediment surface.

(4) In stratified estuaries, like in the Neva and Kymijoki Estuaries, the bottom-near flow towards the head of the estuary usually contains inorganic N and P in lower ratios than the surface

layer consisting mostly of riverine water with high N:P-ratio. Thus the vertical mixing decreases the orginally high riverine N:P-ratio.

(5) Several blue-green algae, e.g. *Planktothrix agardhii* (dominating in the Neva Estuary in late summer, V), accumalate P in their cells while being in aphotic, nutrient-rich water layers (e.g. Reynolds and Walsby 1975), thus transporting bioavailable P into the euphotic layer as a result of vertical mixing.

(6) The mean residence time of bioavailable P in the euphotic layer seems to be much longer than that of N due to the more effective circulation of P in the pelagic food web and thus a less effective sedimenation from the euphotic layer (e.g. Tamminen 1989, Wulff et al. 1990).

When the physically limited innermost coastal waters are ignored, N seems to be the primary limiting nutrient during most of the productive season in the Gulf of Finland excluding the inner Neva Estuary (Tamminen 1990, Kivi et al. 1993, Tamminen et al. 1993, IV, VIII), in the Archipelago Sea (Tamminen et al. 1993) and in the Bothnian Sea (Tamminen et al. 1993). In the open Bothnian Bay P clearly limits phytoplankton growth, while in the coastal Bothnian Bay also N may be limiting at times (Alasaarela 1980, Alasaarela et al. 1986, Kangas et al. 1993, Tamminen et al. 1993). In the Neva Estuary the situation varies considerably depending on the actual hydrodynamic conditions because of the high NO_3-N content of the sub-thermocline waters: effective vertical mixing and high mixed layer depth (MLD) favour P limitation, while stagnant conditions and relatively low MLD favour N limitation (VIII).

4.4.2 Estuarine filtration of bioavailable nutrients

In order to estimate the role of estuarine nutrient losses in eutrophication, data on bioavailable nutrient fluxes are essential. On the basis of the studies on nutrient limitation in the Finnish coastal waters (see the previous Chapter), the fluxes and estuarine behaviour of N seems to be more important for coastal water eutrophication than that of P (excluding innermost coastal waters and the Bothnian Bay), and therefore the present chapter deals mostly with N.

The contribution of new production in the Kymijoki Estuary was estimated as 32 g m^{-2} a^{-1} of C (VII). Assuming that the uptake of external DIN by plankton is equvivalent to this new (export) organic C (cf. Dugdale and Goering 1967, Eppley et al. 1983, Wassmann 1990) and that the mean C:N ratio of the autochthonous production is 6:1 (w/w, Redfield et al. 1963, Leppänen 1988), 5.3 g m^{-2} a^{-1} of N is needed annually for the new planktonic production, equaling 280 t a^{-1} for the whole estuary. This means that external inputs of DIN (ca. 900 t during the productive season) easily cover the nitrogen demands of the local primary production, and a part of the external N outwells to the adjacent (mostly N limited, Tamminen et al. 1993) coastal waters. It is also evident that due to the high inorganic N:P-ratio and low inorganic P concentrations (mostly < 5 mg m^{-3}) either P or physical factors control primary production in the estuary proper.

According to the balance calculations of the Kymijoki Estuary (VII) the loss of N totals 370 t a^{-1}, and 110 t a^{-1} of N accumulates annually in the bottom sediments. It is assumed that the loss of N is entirely due to the uptake of inorganic N in autochthonous production and the subsequent sedimentation and denitrification, i.e. dissolved organic N would behave conservatively within the estuary. Thus an estimate of 260 t a^{-1} (9.7 g m^{-2} a^{-1} for the accumulation area) is obtained for denitrification in the estuary. This value corresponds well with denitrification rates obtained in Danish coastal waters (Jensen et al. 1988, Jørgensen and Sørensen 1988, Kamp-Nielsen 1992).

The combined estuarine filtration (total loss) for N corresponds 18 % of the annual inorganic inputs into the estuary (20 % of the riverine inputs). According to the assumption that the loss is totally due to uptake of DIN in planktonic production and subsequent sedimentation and denitrification during the productive period between May and October, an amount equvivalent to 40 % of the inputs of DIN during this season would be lost within the estuary before the water enter the near-by coastal waters (VII), where N is the most probable limiting nutrient (Tamminen et al. 1993, VIII).

According to Shiskin et al. (1989), the mean primary production of the eastern Gulf of Finland is 105 g m^{-2} a^{-1} of C. Using the *f*-ratio of 0.35 (see Chapter 1.2), an estimate of 37 g m^{-2} a^{-1} of C is obtained for new production. This production needs 6.2 g m^{-2} a^{-1} of N, equaling 79 000 t a^{-1} of N for the whole eastern Gulf. The estimate is very close to that obtained for the total N loss in the eastern Gulf (96 000 t a^{-1}, IV) and emphasizes the importance of biological loss processes. The annual input of total N was estimated as 280 000 t a^{-1} (IV). However, probably not more than ca. 50 % of this is in inorganic form (V, VIII). Further assuming that one half of the inorganic input of N (i.e. 70 000 t) reach the eastern Gulf during the productive season, it seems reasonable to conclude that at least part of the productive season is N limited in the eastern Gulf (see Chapter 4.4.1).

The estimated total loss of N (ca. 96 000 t a^{-1}, IV) equals ca. 70 % of the estimated total inputs of inorganic N to the eastern Gulf and exeeds the combined riverine inorganic and point-source inputs (ca. 70 000 t a^{-1} N, HELCOM 1993b). Together with the substantial P losses (see Chapter 4.3.2, IV, VIII) it is clear that the Neva Estuary with the adjacent waters of the eastern Gulf of Finland strongly control trophic conditions of the whole Gulf. However, despite the strong filtration capacity of the eastern Gulf, the input of N is so high that a net transport of N to the western Gulf of Finland takes probably place (especially in winter and spring, Pitkänen et al. 1990), causing eutrophication there (IV).

Results of the estuarine studies (III-V, VII, VIII) suggest that in the archipelagic (complex morphometry, stratified semi-enclosed basins) coastal waters of the Gulf of Finland and the Archipelago Sea the filtering effect on bioavailable nutrient inputs may be substantial, especially during the productive season (Table 8). On the other hand, in the more open and/or shallow coastal waters of the Bothnian Sea and the Bothnian Bay this filtering effect remains generally small, and probably it is negligible relative to other nutrient fluxes. In the strongly loaded, estuarine-like eastern Gulf of Finland the filtering capacity is substantial, crucially controlling eutrophication of the whole Gulf. However, during the seasons of low biological production the nutrient-rich riverine waters reach the open sea without any significant biological filtering in coastal waters.

5 CONCLUSIONS

This study investigates the fate and eutrophying effects of land-derived nutrient fluxes to the Finnish coastal waters and to the eastern Gulf of Finland, the Baltic Sea. On an average 79 000 t of nitrogen and 4 800 t of phosphorus enter annually the coastal waters from or via the Finnish territory. The inputs via rivers are 69 000 t of N and 4 200 t of P, i.e. 87 % and 88 % of the total inputs of land-derived N and P, respectively. The riverine inputs vary considerably from year to year depending on hydrological conditions.

The average total level of nutrient inputs did not substantially change during the 1980s and early 1990s. However, the nutrient loading from forest industry has clearly decreased since the late 1980s. Compared to the 1970s, the total phosphorus input has decreased due to the efficient treatment of municipal waste waters. The total nitrogen input, despite lower industrial discharges, has probably increased since the early 1970s due to intensified agriculture, increased fish farming, higher atmospheric inputs, increased loading from municipalities, as well as due to increased river flows. If point-source loading to the lower courses of rivers is put in the same category as direct coastal point-sources, municipal and industrial inputs constitute 17 % and 18 % of the total land-derived N and P, respectively. The estimated agricultural contribution to coastal waters is 31 % of the N and 35 % of the P inputs. The remaining 52 % of total N and 47 % of total P originate mostly from natural leaching, forestry, and atmospheric deposition.

Most of the riverine inputs enter the sea before or during the vernal peak of planktonic production, and a large part of the land-derived bioavailable nutrients is transferred to aphotic waters or to the bottom via sedimentation of the bloom. Furthermore a large part of the land-derived nutrients is not directly available for biological production in coastal waters. Under average summer conditions, municipal and industrial inputs were estimated to account for 54 % of the bioavailable N and 53 % of the bioavailable P inputs. The respective estimates for agricultural inputs were 25 % for N and 20 % for P. Thus only about one quarter of the summertime inputs of bioavailable nutrients to coastal waters originate from other anthropogenic activities and from natural leaching.

Nutrient inputs from the land cause extensive eutrophication (new planktonic production and increased plankton biomasses), especially in areas where horizontal mixing conditions are limited due to complex morphometry or in shallow waters, where the lack of permanent density stratification enhances vertical transport of nutrients from aphotic waters and the bottom to the euphotic layer. Thus the whole Finnish coastal water zone of the Gulf of Finland, the inner and certain middle parts of the Archipelago Sea, the archipelago off Uusikaupunki, the Quark archipelago including the Kyrönjoki Estuary, the archipelago off Kokkola-Pietarsaari and the NE Bothnian Bay from Raahe to Tornio show elevated concentrations of nutrients and increased phytoplankton biomasses. Also the strongly loaded Kokemäenjoki Estuary in the Bothnian Sea is eutrophied. The eutrophied area is, however, relatively small due to favourable mixing conditions immediately outside the actual estuary. In the outer coastal and open waters of the eastern Gulf of Finland the eutrophication is mainly caused by the huge nutrient inputs from the River Neva and the St. Petersburg region.

Estuaries and other stratified, semi-enclosed coastal water bodies regulate external nutrient fluxes both quantitatively and qualitatively. In summer the land-derived inorganic N and P are almost completely fixed into new organic matter within the coastal water zone. Thus eutrophication caused directly by land-derived inputs is mostly restricted to coastal waters. Under certain physical conditions eutrophic waters from the Neva Estuary can spread along the northern coast of the Gulf of Finland as far as to the eastern Finnish archipelago, 150 km from the mouth of the River Neva. In general the clearly eutrophied waters cover the estuarine area to the transect between the islands of Seiskari and Koivisto, 90 km west from the river mouth. The claerly higher phytoplankton biomasses of the open eastern Gulf compared to western Gulf are most probably due to more effective upward transport of re-mineralized nutrints from the deep water to the euphotic layer in the eastern Gulf.

Several coinciding internal processes seem to force the coastal water ecosystems towards N limitation, although the estimated mean bioavailable N:P ratio of the inputs from the Finnish territory is 3.4 times the optimal for phytoplankton (the Redfield ratio). This phenomenon is very clear in the eastern Gulf of Finland. Depending on physical conditions, N, P or both limit primary productivity in the Neva Estuary, whereas in the open Gulf N seems to be the principal limiting factor, despite the fact that the high N:P-ratio of the external inputs suggests P limitation.

In estuaries and coastal waters, where coastal morphometry favours a two-layer estuarine flow system or permanent density stratification with sufficiently large depth and long residence time of the water, substantial amounts of nutrients from land-derived sources and from the open Baltic are retained or removed by biogeochemical processes. The Neva Estuary with its adjacent waters of the eastern Gulf of Finland filters 34 % of the total N and 38 % of the total P inputs (corresponding 69 % of the land-derived and atmospheric N and 100 % of the corresponding P inputs). Results from the Kymijoki Estuary and the adjacent coastal waters indicate that during the productive season the southern and south-western Finnish coastal waters, characterized by archipelagoes and stratified, semi-enclosed basins, favour nutrient retention and removal, thus slowing down the eutrophication process of coastal and open waters of the Baltic Sea. The coastal waters and estuaries of the Bothnian Sea and the Bothnian Bay, however, are in general too open and/or shallow for an effective nutrient filtration.

The results of this study suggest that decreasing the trophic degree of the Finnish coastal waters requires measures especially against inputs of bioavailable N from agriculture and municipalities. However, in the Gulf of Finland local measures are not sufficient, and substantial reductions of both N and P inputs in the River Neva – St. Petersburg area are needed. Despite the strong measures already taken in Finland against P loading of waters, also the bioavailable inputs of this nutrient should be further reduced, especially from agriculture and industry.

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To Hanna, Karoliina, Teemu and Aino

Helsinki, December 1994 Heikki Pitkänen

YHTEENVETO

Tutkimuksessa selvitettiin maalta peräisin olevan ravinnekuorman rehevöittäviä vaikutuksia Suomen rannikkovesissä ja itäisellä Suomenlahdella. Suomen rannikkovesiin joutuu vuosittain jokien välityksellä sekä rannikon asutuksesta ja teollisuudesta 79 000 tonnia typpeä ja 4 800 tonnia fosforia. Jokien osuus kuormasta on 69 000 tonnia typpeä ja 4 200 tonnia fosforia, toisin sanoen 87 % typen ja 88 % fosforin maalta tulevasta kokonaiskuormasta. Hydrologisen vaihtelun vuoksi jokien tuomien ravinteiden määrä vaihtelee voimakkaasti vuodesta toiseen.

Ravinnekuormien kokonaismäärissä ei voitu todeta huomattavia yleistason vaihteluita 1980-luvun ja 1990-luvun alun aikana, vaikka metsäteollisuuden ravinnekuorma onkin selvästi laskenut 1980-luvun lopulta alkaen. Verrattuna 1970-lukuun fosforin kokonaiskuorma rannikkovesiin on laskenut, mikä johtuu lähinnä asutusjätevesien voimakkaasti tehostuneesta puhdistuksesta kyseisellä vuosikymmenellä. Sen sijaan typen kokonaiskuorma on todennäköisesti nykyisin suurempi kuin 1970-luvulla, huolimatta teollisuuden pienentyneestä kuormasta. Tämä johtuu maatalouden tehostumisesta, kalankasvatuksen lisääntymisestä, asutusjätevesien typpikuorman ja typpilaskeuman kasvusta sekä valumien ja jokien virtaamien keskimääräisestä noususta. Mikäli jokien alujuoksuille tuleva pistemäinen ravinnekuorma rinnastetaan suoraan rannikolta tulevaan kuormitukseen, on asutuksen ja teollisuuden jätevesien yhteinen osuus 17 % typen ja 18 % fosforin kokonaiskuormasta. Maatalouden osuus on 31 % typpikuormasta ja 35 % fosforikuormasta. Jäljelle jäävä 52 % typestä ja 47 % fosforista on peräisin lähinnä luonnon huuhtoumasta, metsätaloudesta ja laskeumasta.

Huomattava osa jokien tuomista ravinteista päätyy rannikkovesiin keväällä ennen planktontuotannon kevätmaksimia. Ravinteita sedimentoituu kevätkukinnan mukana syviin vesikerroksiin ja pohjalle eivätkä talven ja kevään aikana veteen kertyneet ravinteet siten vaikuta suoraan kesän rehevyysoloihin. Lisäksi merkittävä osa jokien tuomista ravinteista on biologisesti vaikeasti käytettävässä muodossa. Tarkasteltaessa pelkästään kesäaikaista (heinäkuu-syyskuu) tilannetta, asutuksen ja teollisuuden jätevesien osuus on huomattavasti suurempi kuin kokonaiskuormia vuositasolla verrattaessa: peräti 54 % biologisesti käyttökelpoisen typen ja 53 % käyttökelpoisen fosforin kuormasta arvioitiin olevan peräisin rannikkovesiin ja jokien alajuoksuille johdetusta pistekuormituksesta. Maatalouden osuudet ovat tässä tarkastelussa vastaavasti selvästi pienemmät kuin kokonaisvuosikuormia verrattaessa: kesällä keskimäärin 25 % käyttökelpoisesta typestä ja 20 % fosforista on peräisin maataluodesta. Laskelman mukaan vain noin neljäsosa rannikkovesiin kesäaikana joutuvista biologisesti käyttökelpoisista ravinteista on peräisin muista ihmisen toimista ja luonnosta.

Ravinnekuormitus aiheuttaa rehevöitymistä (uutta planktontuotantoa ja kohonneita biomassoja) erityisesti alueilla, joilla rannikon rikkonaisuus hidastaa joki- ja jätevesien sekoittumista ulkomeren murtoveden kanssa. Matalilla rannikkovesialueilla, joille ei kesällä muodostu pysyvää lämpötilakerrostuneisuutta, pohjalla tai sen läheisyydessä mineralisoituneet ravinteet pääsevät helposti takaisin tuottavaan pintakerrokseen kiihdyttäen planktontuotantoa. Kuormituksen sekä rannikon topografian yhteisvaikutus näkyy monin paikoin kohonneena rehevyystasona. Koko Suomenlahden rannikkovesialue, Saaristomeren sisäosat ja osia keskisestä Saaristomerestä, Uudenkaupungin saaristo, Merenkurkun saaristo, Kokkolan-Pietarsaaren lähivedet sekä koko koillisen Perämeren rannikkovesialue Raahesta Tornioon ovat laajimmat Suomen rannikkovesien rehevöityneet vesialueet. Myös Kokemäenjoen edusta on rehevöitynyt. Edullisten sekoittumisolojen vuoksi voimakkaasti rehevöitynyt alue kuitenkin rajoittuu melko suppealle alueelle joen saaristoiselle estuaarialueelle, huolimatta rannikkovesiemme suurimmasta paikallisesta ravinnekuormasta. Itäisen Suomenlahden ulkosaaristossa ja ulappa-alueella rehevöityminen johtuu lähinnä Nevan ja Pietarin ravinnekuormasta.

Estuaarit sekä muut rannikkovesien vedenvaihdoltaan osittain suljetut altaat säätelevät niiden läpi kulkevia ravinnevirtoja sekä kvantitatiivisesti että kvalitatiivisesti. Yleensä maalta peräisin olevat epäorgaaniset ravinteet sitoutuvat biomassaan kesäaikana jo saaristovyöhykkeessä. Tällöin kuormituksen suoraan aiheuttama rehevöityminen rajoittuu lähinnä rannikkovesiin. Välillisesti rehevyystaso voi kuitenkin nousta myös kauempama rannikosta kun esimerkiksi voimakkaiden tuulten seurauksena pohjanläheisiin vesikerroksiin ja pohjalle vajonneet ja sittemmin mineralisoituneet ravinteet pääsevät uudellen levien ulottuville. Pietarin ja Nevan ravinteet aiheuttavan keväisin välitöntä rehevöitymistä aina Suomen vesialueilla saakka (150 km jokisuulta). Kesäisin rehevöitynyt alue yleensä rajoittuu Nevan estuaariin Koivisto-Seiskari linjan itäpuolelle. Tietyissä sääoloissa Nevan estuaarin rehevä vesi voi virrata myös kesäisin Suomenlahden pohjoisrantaa seuraten aina Suomen puoleiseen saaristoon asti.

Useat rannikkovesiekosysteemin sisäiset prosessit toimivat saman suuntaisesti siten, että huolimatta maalta peräisin olevan kuorman suuresta biologisesti käyttökelpoisen typen ja fosforin suhteesta (3.4-kertainen verrattuna perustuotannon optimiin), typestä kuitenkin näyttää muodostuvan perustuotannon minimitekijä keski- ja loppukesällä. Ilmiö tulee selkeästi esiin itäisellä Suomenlahdella. Nevan lahdessa, Pietarin tulvapadon sisäpuolella on alueen kuormituksen seurauksena aina levätuotannon kannalta huomattava ylimäärä epäorgaanista typpeä. Padon ulkopuolella tilanne vaihtelee fysikaalisten olojen (lähinnä sekoittuvan pintakerroksen paksuuden) mukaan: typpi, fosfori tai kummatkin rajoittavat perustuotantoa. Itäisen Suomenlahden ulappavesille tultaessa ravinnesuhde kääntyy kuitenkin lähes poikkeuksetta typen puutetta indikoivaksi.

Estuaareissa ja rannikkovesialueilla, joilla topografia edesauttaa kaksisuuntaista virtaussysteemiä (pintavirtaus merelle, syvä virtaus jokisuuta kohden) tai pysyvän tiheyskerrostuneisuuden muodostumista ja lisäksi veden viipymä on riittävä, biologiset ja mahdollisesti myös geokemialliset prosessit pidättävät osan maalta peräisin olevista ravinnevirroista. Nevan estuaari ja itäinen Suomenlahti suodattavat (sedimentaatio ja denitrifikaatio) taselaskelman mukaan 34 % typen ja 38 % fosforin kokonaisinputista (maalta, läntiseltä Suomenlahdelta ja ilmakehästä). Mikäli otetaan huomioon vain maalta peräisin oleva kuorma ja laskeuma ilmakehästä, pidätysprosentit ovat 69 % typelle ja 100 % fosforille. Kymijoen estuaarin tulokset viittaavat siihen, että Etelä- ja Lounais-Suomen saaristoiset ja melko syvät rannikkovedet kykenevät pidättämään ravinteita ja vähentävät siten ulappa-alueille joutuvaa ravinnekuormaa. Sen sijaan Selkämeren ja Perämeren rannikkovedet ovat tähän liian avoimia ja/tai matalia.

Suomen rannikkovesien rehevyystason alentaminen voi tapahtua vain ravinnekuormaa pienentämällä. Erityisesti maatalouden ja asutuskeskusten typpikuormaa rannikkovesiin tulisi vähentää. Suomenlahdella pelkät kansalliset toimenpiteet eivät riitä. Pietarin-Nevan alueen ravinnekuorman selkeä pienentäminen parantaisi ensisijaisesti itäisimmän Suomenlahden tilaa, mutta suotuisat vaikutukset yltäisivät todennäköisesti myös laajemmin tälle merialueelle. Huolimatta siitä että Suomessa on viime vuosikymmeninä onnistuttu merkittävästi vähentämään rannikkovesien fosforikuormaa, tulisi tämän ravinteen päästöjä rajoittaa erityisesti maataloudesta ja teollisuudesta (kalankasvatus mukaanlukien).

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