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# Total Phosphorus Distribution over the Baltic Sea Sub-regions

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**Abstract**—A quantitative relation has been revealed between the input and concentration of total phosphorus in different sub-regions of the Baltic Sea. This relation has been used to calculate the total phosphorus content of water in the Baltic Sea in 1990, 1995, 2000, and 2006.

**Keywords:** The Baltic Sea, eutrophication, total phosphorus.

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The HELCOM Extraordinary Ministerial Meeting held on November 15, 2007, in Krakow (Poland) adopted the HELCOM Baltic Sea Action Plan (BSAP) which represents a long-term strategy directed toward reduction of marine pollution and restoration of good environmental state of the Baltic Sea by 2021. The BSAP includes four main segments: eutrophication, hazardous substances, biodiversity and nature conservation, and maritime activities.

The main environmental problem of the Baltic Sea is eutrophication. Anthropogenic eutrophication causes many detrimental consequences from the viewpoint of water use and consumption, in particular algae blooms, water quality deterioration impairment, oxygen depletion, structural degradation of biocenoses, and disappearance of many hydrobionts species, including valuable commercial fishes. In addition, blue–green algae blooms produce very strong toxins (alkaloids, low-molecular-weight peptides, etc.) that are not consumed by the algae but are hazardous to living matter and humans. These toxins may cause hepatocirrhosis and dermatitis in humans, as well as poisoning and death of animals.

In aquatic ecosystems, the role of limiting elements belongs most frequently to such biogenic elements (BEs) as nitrogen and/or phosphorus. Nitrogen is a constituent of cellular proteins, while phosphorus is the key element in cellular energy transfer [1, 2]. Biogenic elements occur in living matter at strictly definite ratios; an appreciable variation of these ratios could lead to loss of viability of living organisms. For instance, the nitrogen-to-phosphorus ratio for phytoplankton is on the average 16 : 1. This ratio is called Redfield ratio, and it roughly characterizes nitrogen and phosphorus consumption by algae. The Fleming–Redfield ratio [3] describes the ratio of carbon, silicon, nitrogen, and phosphorus for phytoplankton as C : Si : N : P = 106 : 3 : 16 : 1, and the corresponding ratio for diatoms whose cells are enclosed within a silica frustule is 90 : 35 : 10 : 1, though other values were also reported, e.g., Si : N : P = 16 : 16 : 1 [4]. The concept of "limiting biogenic element" is based on the assumption that phytoplankton biosynthesis implies extraction from water and intake of BEs at the above listed or similar ratios.

Limits can be set for the following three parameters:

(1) Growth rate of some algae species population;

(2) Net primary production or final biomass yield;

(3) Net ecosystem production.

Both nitrogen and phosphorus in the Baltic Sea are involved in biogeochemical cycling processes developing both in the bulk water and sediments. Apart from such transport processes as advection, diffusion, and gravity sedimentation of dispersed particles, the concentration and distribution dynamics of BEs in the Baltic Sea is determined by the following chemico-biological processes:

(1) Photosynthetic assimilation of inorganic forms of BEs by phytoplankton in the upper water layer that is sufficiently illuminated;

**Table 1.** Nutrient balance in the Baltic Sea

| Item | Input, thousand tons/year | | | | | |
|---|---|---|---|---|---|---|
| | Nitrogen | | | Phosphorus | | |
| | total | mineral | organic | mineral | $P_{min}$ | $P_{org}$ |
| River runoff | 508 | 242 | 266 | 45.4 | 15.6 | 29.8 |
| North Sea exchange | 133 | 9 | 124 | 10 | –[a] | –[a] |
| Submarine discharge of groundwater | 21 | 19.6 | 1.5 | 0.8 | 0.74 | 0.05 |
| Atmospheric precipitation | 88 | 88 | – | 0.4 | –[a] | –[a] |
| Wastewater discharge | 66 | 33 | 33 | 14 | –[a] | –[a] |
| Total | 816 | 392 | 424 | 70.6 | –[a] | –[a] |
| Составляющие баланса | Output, thousand tons/year | | | | | |
| Outflow to the North Sea | 230 | 27 | 203 | 11 | –[a] | –[a] |
| Release to the atmosphere | 3 | 3 | – | – | –[a] | –[a] |
| Withdrawal by fishery | 27 | – | 27 | 4.5 | –[a] | –[a] |
| Residue in the sea | 556 | 362 | 194 | 55.1 | –[a] | –[a] |
| Total | 816 | 392 | 424 | 70.6 | –[a] | –[a] |

[a] No data.

(2) Extracellular excretion by phytoplankton of intermediate photosynthesis products as readily oxidizable nitrogen- and phosphorus-containing compounds;

(3) Excretion of mineral (as ammonium and phosphates) and readily mineralizable organic (uric acid, urea, amino acids, lipids, etc.) zooplankton catabolism products. In summer, i.e., at the acme of zooplankton community, excretion is one of the most important sources of BEs, primarily of nitrogen, necessary for maintaining primary phytoplankton production in the depleted near-surface water layers;

**Table 2.** Total phosphorus concentrations and inputs and morphometric parameters of different Baltic Sea sub-regions (1997–2003)

| Sub-region | TP, μM | $Q_{TP}$, t | $V$, km$^3$ | $H_{av}$, m | $H_{max}$, m |
|---|---|---|---|---|---|
| Gulf of Riga | 1.00 | 2200 | 406 | 22.7 | 51 |
| Gulf of Finland | 0.94 | 7100 | 1098 | 37.2 | 123 |
| Danish Straits | 0.62 | 1400 | 287 | 14.3 | 38 |
| Kattegat | 0.57 | 1600 | 515 | 23.1 | 109 |
| Baltic Proper | 0.55 | 17900 | 13045 | 62.1 | 459 |
| Bothnian Sea | 0.35 | 2500 | 4889 | 61.7 | 294 |
| Bothnian Bay | 0.32 | 2600 | 1481 | 40.8 | 156 |

(4) Mineralization (ammonification and phosphatization) occurring everywhere as a result of both autolysis of senescent or dead algal cells and biochemical degradation of organic matter promoted by aerobic and anaerobic microorganisms.

The main sources of biogenic elements entering into the Baltic Sea are the following:

(1) Land-based point sources (treated and untreated wastewater from industrial, municipal, and agricultural enterprises);

(2) Land-based diffuse sources (drainage water from urban, agricultural, forest, and other areas). Unlike point sources, the nutrient load from diffuse sources is largely determined by the underlying terrain properties and hydrometeorological factors;

(3) Atmospheric precipitation;

(4) Release from sediments.

The contribution of different countries to the overall nutrient input strongly depends on the catchment area, population, agricultural intensity, wastewater treatment quality, and other factors. According to the HELCOM data, in 2001–2006 the annual average input of nitrogen and phosphorus to the Baltic Sea from land-based sources was 641000 and 30200 tons, respectively [5].

Over the observation period, repeated assessments of both entire BE balance and its particular constituents were made with subsequent refinement as new data accumulated [6–12]. It may be concluded that since 1960 till present the BE balance of the Baltic Sea changed mainly as a result of continuous growth of BE input from continental runoff and that the other balance sheet items changed insignificantly. The BE balance of the Baltic Sea according to the data of [9] is given in Table 1.

It is seen that the main BE input item (>60%) is provided by river runoff, which is typical of a sea located in a damp zone and characterized by limited water exchange with the ocean. Next follows water exchange with the North Sea from which about 10–15% of BEs comes. It should be emphasized that the outflow of BEs from the Baltic Sea to the North Sea considerably exceeds the reverse inflow.

The total phosphorus and nitrogen contents of the Baltic Sea water were analyzed since the early 1970s, whereas the data on the water transparency (Secchi depths) are available since the beginning of the past century. Correlations between the Secchi depths and total nitrogen and phosphorus concentrations were constructed on the basis of the modern experimental data, and these correlations were used to perform retrospective analysis of nutrient concentrations before 1940, when the Baltic Sea was obviously oligotrophic [13].

Unfortunately, no mathematical models describing the input and concentration of nutrients in different sub-regions of the Baltic Sea have been reported. In view of the aforesaid, the goal of the present study was to reveal a quantitative relation between the input ($Q_{TP}$) and concentration of total phosphorus (TP) in different sub-regions of the Baltic Sea.

**Table 3.** Statistical parameters of correlation (1)

| Parameter | Value |
|---|---|
| Number of sub-regions $N$ | 7.00 |
| Correlation coefficient $r$ | 0.88 |
| Determination coefficient $r^2$ | 0.77 |
| Standard deviation, $s_{Y(X)}$ | 0.14 |
| Calculated F-test value $F_c$ | 16.39 |
| Reference F-test value $F_r$ | 6.61 |

## MATERIALS AND METHODS

The above problem was solved on the basis of a hypothesis according to which the concentration of total phosphorus in a given basin $(TP)_i$ depends on the phosphorus input $(Q_{TP})_i$, water volume $(V)_i$, and average $(H_{av})_i$ and maximal depths $(H_{max})_i$, i.e. $(TP)_i = f[(Q_{TP})_i, V_i, (H_{av})_i, (H_{max})_i]$. The values of the corresponding parameters are given in Table 2. The initial total phosphorus concentrations were taken from [14], and the morphometric parameters, from [15].

## REZULTS AND DISCUSSION

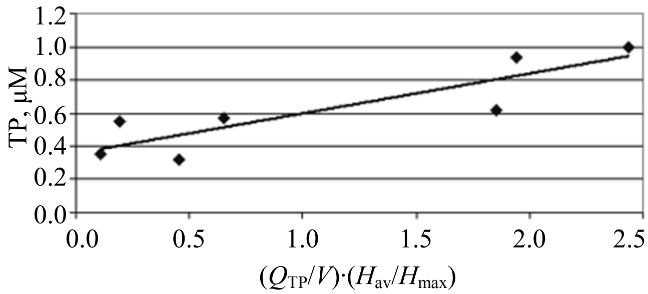
Mathematical and statistical analysis revealed the following statistically significant correlation (see figure):

$$TP = 0.358 + 0.241(Q_{TP}/V)\cdot(H_{av}/H_{max}), \qquad (1)$$

where TP is the total phosphorus concentration, μM, $Q_{TP}$ is the phosphorus input, t/year, and $H_{av}$ and $H_{max}$

**Table 4.** Approximate total phosphorus contents of different sub-regions of the Baltic Sea

| Sub-region | 1990 (PLC-2) | 1990 (PLC-2) | 1995 (PLC-3) | 1995 (PLC-3) | 2000 (PLC-4) | 2000 (PLC-4) | 2006 (PLC-5) | 2006 (PLC-5) |
|---|---|---|---|---|---|---|---|---|
| | $Q_{TP}$, t | | $Q_{TP}$, t | | $Q_{TP}$, t | | $Q_{TP}$, t | |
| Gulf of Riga | 3389 | 1.26 | 2165 | 0.94 | 2210 | 0.95 | 2660 | 1.07 |
| Danish Straits | 2787 | 1.25 | 2121 | 1.03 | 1270 | 0.76 | 1190 | 0.74 |
| Gulf of Finland | 11790 | 1.13 | 8161 | 0.90 | 6030 | 0.76 | 5010 | 0.69 |
| Kattegat | 2729 | 0.63 | 1791 | 0.54 | 1810 | 0.54 | 1820 | 0.54 |
| Baltic Proper | 17807 | 0.40 | 17799 | 0.40 | 16050 | 0.40 | 13040 | 0.39 |
| Bothnian Sea | 2262 | 0.38 | 2256 | 0.38 | 2770 | 0.39 | 1780 | 0.38 |
| Bothnian Bay | 2345 | 0.46 | 2870 | 0.48 | 3450 | 0.50 | 2270 | 0.45 |




Plot of the total phosphorus concentration in the Baltic Sea sub-regions versus phosphorus input (load) and morphometric parameters.

are, respectively, the average and maximal depths of the basin, m.

The statistical parameters of model (1) are given in Table 3. In keeping with the Chaddock scale [16], these data indicate a high correlation ratio ($r$ = 0.7–0.9). In addition, the validity of the proposed model was confirmed by the Fisher's ratio test which exceeded the reference values ($F_{calc} > F_{ref}$) [17].

Correlation (1) was used to roughly estimate nutrient content of the Baltic Sea sub-regions in different years on the basis of the results of HELCOM Pollution Load Compilations PLC-2, PLC-3, PLC-4, and PLC-5 (Table 4). The average concentrations of total phosphorus in different sub-regions of the Baltic Sea over a period of 1990–2006 are as follows (in descending order): Gulf of Riga, TP = 1.06 (0.82–1.30) > Danish Straits, TP = 0.95 (0.57–1.33) > Gulf on Finland, TP = 0.87 (0.56–1.18) > Kattegat, TP = 0.56 (0.49–0.63) > Bothnian Bay, TP = 0.47 (0.44–0.50) > Baltic Proper, TP = 0.40 (0.39–0.41) > Bothnian Sea, TP = 0.38 (0.30–0.46).

## CONCLUSIONS

(1) Equation (1) quantitatively describes the relation between the total phosphorus content and its input in different sub-regions of the Baltic Sea and is statistically significant; it can be used to roughly estimate the concentration of total phosphorus provided that the data on phosphorus load are available.

(2) Over a period of 1990 to 2006, the maximum concentration of total phosphorus was detected in the Gulf of Riga, and the minimum, in the Bothnian Sea.

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