ENVIRONMENTAL MAPPING OF THE BALTIC SEA USING GIS*

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In order to assess the degree of anthropogenic impact on the water area of continental sea and its ecological situation, a procedure of environmental mapping using GIS technologies was developed for the largest unique continental basin such as the Baltic Sea.

The Baltic Sea is the largest unique continental sea in the north of Europe. It has always played an important part in the life of the population in that it helps maintain the socio-economic conditions by washing the coasts of Sweden, Finland, Russia, Denmark, Germany, Latvia, Lithuania, Poland. The human activities and the anthropogenic impact on the environment inevitably brought about the pollution of the Baltic Sea and ecological stress, which affect the functioning of this important sea system. The geographical and oceanological singularities of the Baltic Sea make it especially vulnerable to the potential impact of anthropogenic pollutants. The sea is shallow-water (51 m deep on the average, with the maximum depth of 470 m), virtually closed, with very limited water transfer, characterized by a strong effect of fresh-water runoff and inflow of transformed North Sea water and by a very long shoreline. It is land-locked, and only in the south-western part it is communicated with the Atlantic Ocean via narrow and shallow Danish straits which change to the Kattegat and Skagerrack, deep and wide straits belonging to the North Sea. A characteristic feature of the Baltic Sea is that it is a combination of basins such as the Gulf of Bothnia, the Sea of Bothnia, the Sea of Archipelagos, the Gulf of Finland, the Gulf of Riga, the Baltic proper, Western Baltic, the Sound, the Kattegat.

In the last decade, anthropogenic pollution has become an important environmental factor in the ecosystem of the Baltic Sea. The main sources of pollution include:
1. The delivery from the shore and with river water of solid and liquid matter which contains organic nutrients, inorganic compounds, and microorganisms.
2. The delivery of nitrogen and sulfur by atmospheric transfer, mainly, from Europe, with rainfall.
3. The pollution with petroleum products due to navigation both in a regular way and because of accidents and catastrophes.
4. Deliberate burial in the sea of harmful waste, chemical weapons (1945-1947).
5. The sea pollution caused by mining on the continental shelf.
6. Pollution as a result of violation of the existing rules and regulations because of intensive development of tourism in some coastal areas.

For the purposes of environmental mapping, we analyzed the findings of international monitoring published in the annual reports of the Helsinki Commission (HELCOM) [3-5]. The program of investigation of the Baltic Sea as a unified environmental object was proposed in 1973. However, starting in 1980 (which was taken to be the base reference point), a new stage of international monitoring was begun with a view to studying the tendencies of many years in the variation of the state of the sea medium (water, grounds, ecosystems), caused by the anthropogenic factors, by means of systematic observations according to standardized procedures in certain areas of the open part of the sea and the gulfs.

One hundred and thirty two "environmental hot spots" were selected within the watershed area of the Baltic sea by the HELCOM experts for study and analysis of the ecological situation of the Baltic Sea; these spots include industrial enterprises and populated areas identified by the results of monitoring of pollution for several years. For each one of those "environmental hot spots", the data on pollutants delivered with river, industrial, and municipal wastewater and as a result of atmospheric transfer for the period of 1991-1997 [3-5] were treated.

In the case of systems approach that is typical of environmental studies, one must usually proceed from the numerous characteristics of the environment, as a result of which rather diverse information is treated. In so doing, a simple accumulation of data is not sufficient; the data must be readily accessible and systematized in accordance with the needs of the researcher. For the purposes of integrated geographical analysis, it is important that one should be capable of relating different data with one another, comparing, analyzing, and simply viewing them in a convenient and illustrative form, as well as of using those data to develop necessary maps, tables, schemes, and diagrams. Best suited for these purposes are the present-day GIS technologies, the very concept of which is based on the possibility of acquisition, integration, and analysis of any data distributed in space or referenced to a concrete spot [2].

The software support for the investigation of the ecological situation of the Baltic Sea was provided GIS systems ARC/INFO version 8.0.2 and ARCVIEW 3.2 by ESRI. The choice of these software products was governed by adequate functional support they provide to the solution of diverse problems, relative ease of operation, possibility of extension by additional modules, wide capabilities of operating the attributive information and its representation, and the possibility of operation using data formats of other software products.

The ARC/INFO system was used to produce mainly base topological layers (coatings) of spatial information. Subsequent work (visualization, editing, combining and analyzing different layers of information, construction of models, creating and editing legends and attribute tables, construction of charts, layouts, etc.) was done in GIS ARCVIEW.

The 1:10 000 000 Digital Chart of Europe of the Nasha Zemlya (Our Earth) electronic atlas compiled at the Data+ Company on the basis of ARC/INFO and ARCVIEW software products by ESRI was used as the base map for spatial location and modeling of distribution of the point data about pollution of the water area of the Baltic Sea.

The ARCVIEW system was used to create tables in DBF format, containing data on the concentration of different pollutants in different years at different points of the Baltic sea watershed being investigated.

This resulted in the compilation of a series of ecologo-geographic maps for the water area of the Baltic Sea for the period of 1991-1997:

1. Loading with organic matter (according to BOD7 in MGO2/lit) delivered with river water and from point sources.
2. Loading with biogenic elements, namely, total phosphor and total nitrogen, delivered with river water and from point sources.
3. Delivery of sulfur oxide and nitrogen dioxide to the atmosphere from point sources.

An analysis of the thus compiled maps and charts helped trace the changes and regularities in the distribution of sources and flows of pollutants in the watershed of the Baltic Sea.

The pollution of the Baltic Sea is largely due to waste water from public utilities and agricultural enterprises, because they are highly saturated with biologically active organic substances subject to decomposition.

The delivery of the latter substances causes an increase in the biogenic elements in the sea, as well as in the amount of oxygen-consuming substances. The "loading" of the sea with waste water is most commonly defined in terms of "the biochemical oxygen demand for a period of five or seven days" (BOD5 or BOD7), i.e., the amount of oxygen which is spent during five or seven days for decomposition of organic substances contained in one liter of water. Tables 1 and 2 give the total runoff of organic matter supplied with river and littoral water, as well as with urban and industrial sewage, in the year of 1997 to separate basins of the Baltic Sea from countries in the territory of its watershed.

According to the data of 1997, the total amount of organic matter delivered to the Baltic Sea basin with river, littoral, urban, and industrial runoffs is 1.140 mln t, of which 80% comes with river and littoral runoffs, 10% with urban runoffs, and 9% with industrial runoffs. A comparison of the overall values of runoffs of organic matter delivered by river water and from point sources to the Baltic basin from the countries in the territory of its watershed reveals that most of the runoffs come from Poland (288.6 thou. t/yr), Russia (228.1 thou. t/yr), and Sweden (218.7 thou. t/yr). Most of pollutants come with the runoffs of the major rivers flowing through the most populated regions of the watershed: the Vistula (164.6 thou. t/yr), the Oder (86.6 thou. t/yr), and the Niemen (91.9 thou. t/yr). A large fraction of organic matter (237.3 thou. t/yr) comes to the Baltic Sea from the Gulf of Finland (125.9 thou. t/yr), with the water from the Neva (45 thou. t/yr), and with the urban and industrial runoffs from St. Petersburg and from the towns of the Leningrad Province.

The highest load of organic matter flowing with urban and industrial runoffs (81%) per unit area falls on the Sound basin (1858 kg/km2) and on the western part of the Baltic Sea (1521 kg/km2), and the lowest load falls on the Gulf of Bothnia (475 kg/km2) and the Gulf of Riga (521 kg/km2), with the average value for the entire Baltic Sea being 689 kg/km2 (Table 1).

Thanks to its advantageous geographical location and peculiar natural conditions, the Baltic Sea plays an important part in the fishing potential of the countries located on its shores; in spite of the general scarcity of species, this sea is regarded a body of water highly productive for fishing.

Table 1.

Organic matter, N_{total}, P_{total} load going into the Baltic Sea of Riverine and direct point in 1997

Subregions of the Baltic Sea	Total drainage area load in 10^3 km^2	Total BOD_7 load in 10^3 t/a	Area specific BOD_7 load in kg/km^2	Total N_{total} load in 10^3 t/a	Area specific N_{total} load in kg/km^2	Total P_{total} load in 10^3 t/a	Area specific P_{total} load in kg/km^2
Bothnian Bay (Finland, Sweden)	251,9	119,6	475	44,9	178	2,9	11
Bothnian Sea (Finland, Sweden)	209,4	128,1	612	46,8	224	2,3	11
Archipelago Sea (Finland)	8,9	5,8	648	7,0	784	0,5	54
Gulf of Finland (Estonia, Finland, Russia)	404,7	237,3	586	132,9	328	8,2	20
Gulf of Riga (Estonia, Latvia)	135,0	70,4	521	86,6	642	2,2	16
Baltic Proper (Estonia, Lithuania, Latvia, Germany, Denmark, Russia, Poland, Sweden)	537,3	492,9	917	316,2	589	17,8	33
Western Baltic (Germany, Denmark)	19,7	30,0	1521	41,6	2110	1,2	61
Sound (Denmark, Sweden)	4,1	7,7	1858	13,1	3153	0,9	220
Kattegat (Denmark, Sweden)	83,3	48,3	581	71,6	860	1,8	22
Total Baltic Sea	1654,3	1141,1	689	760,7	460	37,890	23

The productivity of a sea is defined by the amount of nutrients (biogenic elements) entering the biogeochemical cycle. The concentration of biogenic substances in the surface layer defines the level of development of phyto- and zooplankton.

In the opinion of many researchers, both phosphor and nitrogen may be regarded as the biogenic elements that limit the development of phytoplankton in the Baltic Sea [1]. The increase in the biogenic runoff from the land, observed during the last decade, caused an increase in the concentration of biogenic substances and, as a consequence, an increase in the biological productivity.

As a result of the increase in the amount of phytoplankton and zoobenthos, the rate of growth of plankton-eating species has accelerated. The increase in the amount of organic matter intensified the redox processes, which led to an increased consumption of oxygen and, as a result, an extension of the area of suffocation zones, especially, in abyssal basins.

The increase in the content of organic matter and biogenic elements in the Baltic Sea waters and the resultant eutrophication take the position of key importance in the present-day environmental studies [1, 3, 4, 5].

Every year, the Baltic Sea receives, from the watershed area of 1.654 mln km2, 760 thou. t of total nitrogen with river runoff (76%). with river and littoral runoff (14%), and with urban and industrial runoff (10%).

The river runoff prevails in the case of Lithuania and Poland (95%), Latvia (89%), Russia (68%), Germany and Finland (75%), and Sweden (64%). In so doing, the highest load of total nitrogen per unit watershed area falls on Denmark (2208 kg/km2) and Germany (1255 kg/km2), with the average load for the entire watershed being 460 kg/km2. The largest amount of total nitrogen comes to the Baltic basin proper (361.2 thou. t/yr) and to the Gulf of Finland (133 thou. t/yr) with river and littoral runoff (94%). A comparison of the values of total nitrogen load per unit area for each one of the Baltic Sea basins reveals that the Sound basin must be singled out, in which this value is seven times the average value for the entire water area, and Western Baltic, where the load is five times the average (Tables 1 and 2).

The total amount of the other biogenic element, namely, total phosphor, delivered to the water area of the Baltic Sea in 1997 is 37.9 thou. t, which is 20 times less than the delivery of total nitrogen. A large amount of total phosphor is also delivered to the sea by river runoff (71%) from the watershed of Russia, Poland, and Sweden - countries of intensive agriculture and forestry. The urban runoff from these countries amounts to 14%, littoral runoff to 10%, and industrial runoff to 5%.

The largest amount of total phosphor is delivered from the watershed to the Sound (220 kg/km2), which is ten times the average amount (23 kg/km2), to Western Baltic (61 kg/km2), which is three times the average amount, and to the Sea of Archipelago (54 kg/km2), which is 2.5 times the average amount (Tables 1 and 2).

Table 2.

Riverine and direct point source BOD_7, nutrient, phosphorus loads going into the Baltic Sea from the country's of catchment area in 1997

Countries	Total drainage area load in 10^3 km^2	Total BOD_7 load in 10^3 t/a	Area specific BOD_7 load in kg/km^2	Total N_{total} load in 10^3 t/a	Area specific N_{total} load in kg/ km^2	Total P_{total} load in 10^3 t/a	Area specific P_{total} load in kg/ km^2
Finland	231,1	125,5	543	66,1	286	3,6	15
Russia	302,7	228,1	754	84,6	280	7,1	23
Estonia	84,4	53,5	634	46,5	551	1,3	15
Latvia	131,5	67,4	513	91,1	692	2,2	17
Lithuania	98,9	96,4	975	36,8	372	1,4	14
Poland	331,2	288,6	871	214,7	648	14,2	43
Germany	17,0	19,9	1167	21,4	1255	0,6	34
Denmark	31,1	41,9	1348	68,7	2208	2,6	83
Sweden	426,4	218,7	513	130,9	307	4,7	11
Total Baltic Sea	1654,3	1140,0	694	760,8	460	37,7	23

Total phosphor is delivered to the Sound with littoral, urban, and industrial runoffs (96%), to Western Baltic - with littoral, urban, and industrial runoffs (55%) and river runoff (45%), and to the Sea of Archipelago - with river and littoral runoffs (76%).

An analysis of maps leads to the following conclusions about the delivery of organic matter and biogenic elements for the period of 1991-1997. The delivery of organic matter from the territory of all countries within the watershed has decreased a little; however, large amounts of organic matter continue to be delivered with river water from the territories of Poland, Lithuania, and Estonia. The delivery of biogenic elements (nitrogen and phosphor) from the territory of Sweden, Finland, Estonia, Czechia, Russia, Belarus, and the Ukraine did not vary; a reduction of delivery form Denmark, Germany, Poland, and Lithuania was observed. The largest amounts of phosphor come from the territory of Poland, Lithuania, and Estonia (Fig. 1). The largest amounts of nitrogen are delivered to the water area of the Baltic Sea from Estonia, although its total amount over the last several years did not increase. Note that, thanks to the large-scale circulation of the sea waters and to the integrity of its biological structure, local anomalies in some part of the sea reflect, in the final analysis, on the characteristics of the state of adjacent regions and of the water area as a whole.

The Baltic Sea region is characterized by the nonuniform distribution of industrial enterprises, as well as by the density of population and of main transportation lines, which are the major sources of pollutants to the atmosphere. The water area of the Baltic Sea is the site of the main routes of powerful cyclones originating in the North Atlantic. They are accompanied by west and south-west winds, cloudy weather, rainfall. The cyclonic activities reach the highest intensity during the cold season.

The distribution of pollutants in the atmosphere of the Baltic watershed is governed by the general circulation of air masses. Based on the results of meteorological observations (HELCOM), one can identify the prevailing south-western direction of transport of air masses. An analysis of the compiled maps has revealed a tendency for increasing concentration of nitrogen in the atmosphere above the water area of the Baltic Sea in the south-western direction. The largest amounts of nitrogen are delivered to the atmosphere from the territory of Poland, Belarus, and Latvia. Most of sulfur oxides come from Estonia and Poland. The general tendency is that the emission of sulfur oxides from the territory of the Baltic countries for the period of 1991-1997 remained on the same level and that of nitrogen oxides increased due to emissions from the territory of Belarus.

In order to derive a full picture of environmental situation of the Baltic Sea, one needs to analyze the behavior of its ecosystems; still, the available series of compiled environmental maps makes it possible to draw preliminary conclusions about the degree of anthropogenic load on its separate basins by the amounts of pollutants delivered to those basins and to assess the impact made by each country within the watershed of the Baltic Sea.

Most of organic matter and biogenic elements are delivered with river water and from point sources to the Baltic proper, which has the largest watershed area (537.3 thou. km2) that includes the countries of Estonia, Latvia, Lithuania, Russia, Poland, Germany, and Denmark, as well as three major rivers, namely, the Vistula, the Oder, and the Niemen, and numerous smaller rivers. Almost 99.7% of the territory of Poland with the population density of 123 persons/km2 (with 62% urban and 38% rural population) is in the territory of watershed of the Baltic proper.

The same is true of Lithuania (83% of its territory) with the population density of 57 persons/km2 (with 53% rural population).

The results of comparison of the amounts of pollutants delivered to separate Baltic basins and calculated per unit area lead one to single out the Sound, Western Baltic, Baltic proper, and the Sea of Archipelagos.

In the Sound basin, the load of organic matter is three times, of total nitrogen - seven times, and of total phosphor - ten times, that calculated for the entire water area of the Baltic Sea. The area of the Sound watershed includes the territory of Sweden with 64% of agricultural land and high population density (240 persons/km2), and the territory of Denmark with arable land (50%) for grain cultures. The population density in this part of Denmark is the highest - 849 persons/km2.

Large amounts of pollutants are delivered to the Western Baltic basin mainly via small rivers flowing through the territory of Germany with agricultural land (80%) and with the population density of 159 persons/km2, and through the territory of Denmark with arable land for grain cultures (68%) and with the population density of 128 persons/km2.

The amounts of organic matter and biogenic elements delivered per unit area to the Baltic Sea proper with river water and from point sources are almost the same as those delivered on the average for the entire water area of the Baltic Sea (Table 1). The watershed of the Sea of Archipelagos is fully located in the territory of Finland that is largely covered with forests (61%), with only 30% of its area taken up by agricultural land.

The compiled environmental maps of the Baltic Sea and the results of analysis of the delivery of pollutants from the watershed to the water area of the Baltic Sea point to the special importance of GIS mapping of seas in developing the system of comprehensive environmental monitoring.

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