

Water Pollution VI

Modelling, Measuring
and Prediction

Editor: C.A. Brebbia

 WIT PRESS

Water Pollution VI

Modelling, Measuring and Prediction

Edited By

C.A. Brebbia

Wessex Institute of Technology, UK

WIT*PRESS* Southampton, Boston



2001

ISBN 1-85312-878-1

ISSN 1462-6513

Cost-effective versus proportional nutrient load reductions to the Baltic Sea: Spatial impact analysis with a 3D-ecosystem model

T. Neumann & G. Schernewski

Baltic Sea Research Institute, Warnemünde, Germany

Abstract

A 3D-biochemical model of the Baltic Sea was deployed to investigate the effects of two different 50 % nitrogen and phosphorus load reductions scenarios on the Baltic Sea. The first scenario, according to the Helsinki Commission, assumed a proportional 50 % load reduction in all riparian countries. The second was based on a cost-effective optimal approach by Gren [1], with significant regional differences in load reduction. The comparative simulations covered a period of 16 month (January 1980 - May 1981).

In the central Baltic Sea a 50 % load reduction caused a decrease in inorganic nitrogen concentration by 39 % and inorganic phosphorus declined by 8.3 % in the upper water layer (30 m). Chlorophyll-a, as an indicator for algae biomass, was reduced by 9 %. The comparison between the two 50 % reduction scenarios revealed pronounced differences mainly in coastal waters. Near large rivers in the southern Baltic, like the Oder and the Vistula, the cost-effective scenario showed a further decrease of chlorophyll-a concentrations by more than 5 %. Altogether the water quality in southern Baltic Sea, especially in Germany, Poland and the Baltic states clearly benefits from a cost-effective approach.

Along the south coast of the Baltic Sea, bathing and summer tourism is most intensive, a major economic factor and high coastal water quality is essential. This is especially true for the intended further growth of tourism. Especially the German coast has a high net economic benefit from improved water quality of Polish rivers. Therefore, from an ecological and economical viewpoint it is reasonable that Germany invests money in improved Polish water treatment measures.

Nutrient load to the Baltic Sea: status and target

The Baltic Sea is the world wide largest brackish water body (412.000 km²) with a water residence time of about 25-30 years. Freshwater supply is maintained by the inflow of several large rivers. The sea is connected to the North Sea, where an estuarine circulation with an outflow of brackish surface water and inflow of saline water close to the bottom takes place. The drainage basin covers 1,734,000 km² with a population of about 85 millions in 14 states [2]. About 38,000 – 46,000 t/a phosphorus and 640,000 – 660,000 t/a nitrogen were discharged into the Baltic Sea in the early 90's [3]. The result is ongoing eutrophication, with intensive blue-green algae blooms and an endangered flora and fauna, especially in the coastal waters. Already in 1974, the nine riparian states (Denmark, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland and Germany) signed the Helsinki Convention. To improve water quality, the states agreed to undertake all appropriate measures to minimise land-based pollution to the Baltic Sea. Goal of the Ministerial Declaration of 1988 was a reduction of the nitrogen and phosphorous load by 50 %. The interim status report on implementation of suitable measures revealed that no country had achieved the promised 50 % nutrient reduction until 1995. Especially agriculture, the largest anthropogenic source of nutrient input, causes serious problems. Due to the transition as well as structural and economic problems in the eastern European countries, the use of fertilizer dropped in the early 90ies and caused significant N-load reduction to the Baltic Sea. The following recovery of the economies increased fertilizer use again. It is therefore doubtful whether a 50 % reduction of nutrient load from agriculture can be reached even until 2005.

In this study we link economic and natural scientific approaches and show the value of a complex model as a tool in environmental management. Two 50 % nutrient reduction scenarios are used as an input for a 3D-coupled physical-bio-chemical model of the Baltic Sea. The first scenario assumes a proportional 50 % nutrient reduction in every riparian country, as suggest by HELCOM. The second scenario is based on existing socio-economic calculations by Gren [1] and Turner et al. [2] suggesting an optimal cost-effective 50 %-nutrient reduction. Our goal is a regional differentiated effect-analysis of these two 50 %-nutrient load reduction scenarios on nitrogen, phosphorus, chlorophyll-concentrations in the Baltic Sea. Finally, we evaluate the results with respect to tourism and coastal management.

Nutrient reduction scenarios for the Baltic Sea

The riparian countries around the Baltic Sea show pronounced differences in land use, economy, intensity of agriculture, population density and especially the quality and efficiency of sewage treatment. The agreed proportional 50 %-load reduction from the territory of every country is a political goal without taking the total costs for the measures into account. The alternative approach [1, 2] has the goal to meet the 50 %-nutrient load reduction at minimum total costs. This im-

plies, that nutrient load reduction takes place in countries and drainage basins where it shows its highest cost-efficiency.

Background for the calculation of the cost-effective scenarios is the awareness, that the marginal costs of abatement measures are not equal between the riparian states. Marginal cost are defined as the increase in costs to reduce the nutrient load of nitrogen and/or phosphorus to the Baltic Sea by 1 kg. To calculate the scenario Gren [1] identified all reduction options and their location, quantified the reduction effect on nutrient loads to the Baltic Sea and calculated the marginal costs for all options.

The marginal costs of different measures reducing the nitrogen load to the Baltic Sea, for example, vary very much between different types of sources. To reduce the N-load from agriculture in Germany costs between 20-122 SEK, from sewage plants 24-60 SEK from wetland 27 SEK and from atmospheric deposition 210-3576 SEK. Similar variations are obvious between different countries. For a reduction of the nitrogen load by 50 % wetlands, agriculture and sewage plants have to contribute about the same share. This is different for phosphorus, where improvements of sewage plants are most important and alone can contribute 80 % to the reduction. Most pollution takes place from the territory of the eastern European countries and in general it is cheapest to reduce the nutrient load there. The optimal reduction of nitrogen and phosphorus causes only 23 % of the costs of a proportional reduction and has therefore serious economic benefits [1]. The two scenarios have different consequences for the Baltic Sea. The intensity of the load reduction varies between the regions and imply significant regional differences with respect to water quality in the Baltic Sea.

3D-ecosystem model and simulation period

A 3D-flow and circulation model with biochemical module was applied for the simulations. The circulation model is based on the Modular Ocean Model MOM2.2 and covers the entire Baltic Sea. A horizontally and vertically telescoping model grid with high horizontal resolution in the southwestern Baltic (3 nautical miles) and increasing grid size towards north and east was applied. The first 12 vertical layers possess a width of 2 m. The width of deeper layers increase with depth. Towards the North Sea (Skagerrak) an open boundary condition is applied. An atmospheric boundary layer model derives the ocean surface fluxes from measured and calculated meteorological data. For detailed model description and applications refer to Fennel & Neumann [4, 5].

The chemical-biological model consists of 10 state variables (ammonium, nitrate, phosphate, 3 phytoplankton groups, detritus, zooplankton, oxygen and sediment). Altogether 11 processes are taken into account (N-fixation, denitrification, nitrification, atmospheric input, algae respiration, algae mortality, nutrient uptake by algae, zooplankton grazing, mineralization, sedimentation and re-suspension) In most parts of the Baltic Sea, nitrogen has to be regarded as the limiting element for phytoplankton production. The model therefore is focused on a proper description of the nitrogen cycle.

Phytoplankton is divided into three generalized functional groups: flagellates, diatoms and blue-green algae. Diatoms represents large phytoplankton and flagellates smaller phytoplankton. Both groups utilize dissolved nitrate and ammonium. The blue-green algae have the ability to fix atmospheric nitrogen and act as a nitrogen source for the system. Phosphate is included to limit the growth of blue-green algae and is linked to nitrogen within organic matter via the Redfield ratio. The primary production is driven by solar radiation and uptake of nitrogen as well as phosphorus. Different physiological parameters allow different ecological optima for the algae groups, depending on available nutrient concentrations, temperature and sinking velocity. The chlorophyll-a concentrations are calculated from the biomass of all three phytoplankton groups. Generally diatoms dominate new production in spring whereas flagellates prevail during regenerated production. Low nitrate and ammonium concentrations are favorable for blue-green algae.

Grazing converts phytoplankton nitrogen into zooplankton and mortality of phytoplankton and zooplankton controls the nitrogen flux into detritus. The recycling process of detritus to nutrients provides an ammonium flux. Depending on oxygen conditions, ammonium is nitrified to nitrate. Oxygen demand and oxygen production is coupled to nitrogen conversion and controls the recycling path (oxic or anoxic) of dead organic matter (detritus). At the bottom, an additional sediment layer is introduced where sinking detritus accumulates. Suspension and resuspension of detritus is taken into account and occur if the currents near the bottom exceed critical values. In the sediment layer detritus can be mineralized and may be released as ammonium. Denitrification of 50 % of the mineralized nitrogen takes place within the sediments around a hypothetical redoxcline as long as the water above the sediments remain oxic. Under oxic conditions the sediment is regarded as a sink for phosphorus (precipitation with iron). The chemical-biological model code is embedded as a module in the circulation model and linked via the advection-diffusion equation. For a detailed model description and applications of the 3D-ecosystem model see Neumann [6].

Fresh water supply and nutrient load of the fifteen largest rivers with their proper spatial location are taken into account as an model input. The rivers are regarded as point sources, which carry not only the measured river nutrient load itself, but represent additional diffuse and smaller point sources of the surrounding area. The 15 rivers therefore cover the entire diffuse and point source load to the Baltic Sea. Atmospheric deposition is kept separately. A period of 16 month (January 1980 - May 1981) was simulated for both nutrient reduction scenarios as well as a control run with no nutrient reduction. The choice of this period was due to the availability of a comprehensive and reliable data set of river loads as well as atmospheric deposition for the entire Baltic Sea. The calculated time period was restricted by available machine time. Data were provided by the Baltic Environmental Database of the University of Stockholm. Meteorological data was supplied by the ERA 15 project. Initial distributions of temperature and salinity were derived from climatological data set provided by Janssen [7]. A problem was the lack of biochemical Baltic Sea data with a sufficient spatial resolution. To overcome this problem, the existing measured data was used as an initial

condition for a separate, preliminary model run over 4 years. The calculated spatial distributions of the biochemical data after these 4 years were used as starting condition for the two nutrient reduction simulations.

Table 1: River loads 1981 [kt/y] used as input in the 50 % optimal, cost-effective and proportional reduction simulations.

River system	Country	Phosphorus		Nitrogen	
		Opt.	Prop.	Opt.	Prop.
Kemijoki	Finland	1.4	1.1	11.8	10.0
Lulealv	Sweden	0.6	0.5	5.9	5.1
Angermansalv	Sweden	1.0	0.8	16.1	13.8
Umealv	Sweden	0.7	0.4	15.6	13.5
Kokemäenjoki	Finland	0.9	0.7	11.0	9.3
Narva	Est./Rus.	0.8	0.5	10.2	10.7
Neva	Russia	1.1	1.4	26.3	27.4
Oder	Poland	3.4	3.9	56.8	59.2
Vistula	Poland	2.4	2.7	77.8	81.0
Nemunas	Lithuania	1.7	1.7	24.9	26.0
Helgean	Sweden	0.1	0.1	2.8	2.4
Eman-Motal	Sweden	0.4	0.3	5.7	4.9
Maelaren	Sweden	0.0	0.0	0.4	0.3
Daugava	Latvia	2.3	2.6	45.9	53.4
Goetaaelv	Sweden	0.6	0.5	16.4	14.1

The first simulation assumed a proportional reduction of every load by 50 %. The second simulation was based on the optimal cost-effective nutrient reduction scenario. In both cases the absolute load reduction of nitrogen and phosphorus to the Baltic Sea was similar, but the spatial distribution of the nutrient load differed. Gren [1] suggested the following allocation of cost-effective reductions of phosphorus and nitrogen: Denmark 60 % P / 46 % N, Estonia 10 % / 54 %, Finland 32 % / 41 %, Germany 55 % / 15 %, Latvia 55 % / 66 %, Lithuania 52 % / 58 %, Poland 58 % / 59 %, Russia 65 % / 57 %, Sweden 19 % / 42 %. This information was used to calculate the rivers loads (Table 1). Due to differences in methodology and the data basis some deviations occurred.

Simulation results

Already after one year the proportional reduction scenario showed a significant effect on winter and spring nutrient concentrations compared to the control run (Figure 1). In the Baltic Proper, the central Baltic Sea, a general reduction of 39 % for dissolved inorganic nitrogen (DIN), 8.3 % for dissolved inorganic phosphorus (DIP) was observed in the upper water layer (30 m). The most pronounced effects took place in the Arkona Sea and in the Gotland Sea. These regions are strongly effected by large rivers (Oder, Vistula, Daugava, Nemunas) and their high nutrient loads enter the Baltic Sea from the south. About 42 % of the total nitrogen load and 38 % of the phosphorus load are discharged by the rivers Oder and Vistula draining mainly Polish territory. Gradients in nutrient concentrations from the river mouth towards the open Sea are obvious but significantly modified by the prevailing flow field. Even in the central Baltic Proper

an effect of the nutrient reduction on algae biomass was observed. Chlorophyll-a concentrations, as an indicator for algae biomass, declined by 9 %. In April, diatoms are the dominating algae group. The spatial pattern of chlorophyll-a showed similarities to the distribution of nitrogen, the main limiting nutrient for algae growth. Large scale variations in chlorophyll-a concentrations are due to spatial differences in water temperature, too. Especially in spring, temperature is an important factor for algae growth.

A general feature of the cost-effective scenario is an increased reduction of nutrient loads from countries with transitional economies, Poland, Lithuania, Latvia, Estonia and Russia. To keep the balance, nutrient loads from Scandinavia and Germany were reduced to a minor degree. The additional reduction of loads from large rivers entering the Baltic Sea along the south coast, like the Oder and the Vistula in Poland, caused slightly reduced concentrations in the central Baltic Proper (41 % for DIN, 9.0 % for DIP and 9.6 % for chlorophyll-a) compared to the proportional reduction scenario. Most pronounced differences were observed in coastal waters, especially in the vicinity of the estuaries. In these locations chlorophyll-a and phosphorus showed decreased concentrations above 5 %.

Implications for coastal eutrophication and tourism

Altogether the water quality at the southern Baltic Sea and especially the coast along Germany, Poland and the Baltic states clearly benefits from a cost-effective approach. What are the practical and economical implications? Intensive tourism along the Baltic Sea coasts is linked to water temperatures of at least 17 °C in summer. Bathing tourism is profitable when tourist beds are rented for at least 90 days per year [8]. This means that water temperatures have to remain high during several months or other attractions have to ensure a sufficient average utilization of the tourist beds. Due to these circumstances, intensive bathing tourism is concentrated along the south coast of the Baltic Sea, mainly in Germany and Poland. The number of beds in official accommodations along the German Baltic coast was close to 200,000 with about 20 Mio overnight stays in 1998 [9]. In many coastal regions, tourism accounts for over 50 % of the annual income and is the most important economic factor. The situation along the Polish coast is similar. The two coastal regions Pomorskie and Zachodniopomorskie possess a tourist bed capacity of 172,000 with more than 19 Mio overnight stays in 1999 [10]. Many well-known tourist regions are located in the estuaries of the rivers Vistula and Oder. One example is the island of Usedom in the Oder estuary. The population of Usedom is about 31,500. During peak-season in August about 40,000 guests and additional daily visitors are on the island, stressing the infrastructure and crowding the Baltic beaches at a length of about 40 km. The number of overnight stays nowadays exceeds 5 Mio [11].

About 17 km³ of polluted water enter the large shallow Oder lagoon (687 km² surface area, average depth 3.7 m) with the Oder river per year before reaching the Baltic Sea. The result are intensive algae blooms, hygienic water problems, a poor water transparency and a reduced attractiveness of the beaches for swimming [11].

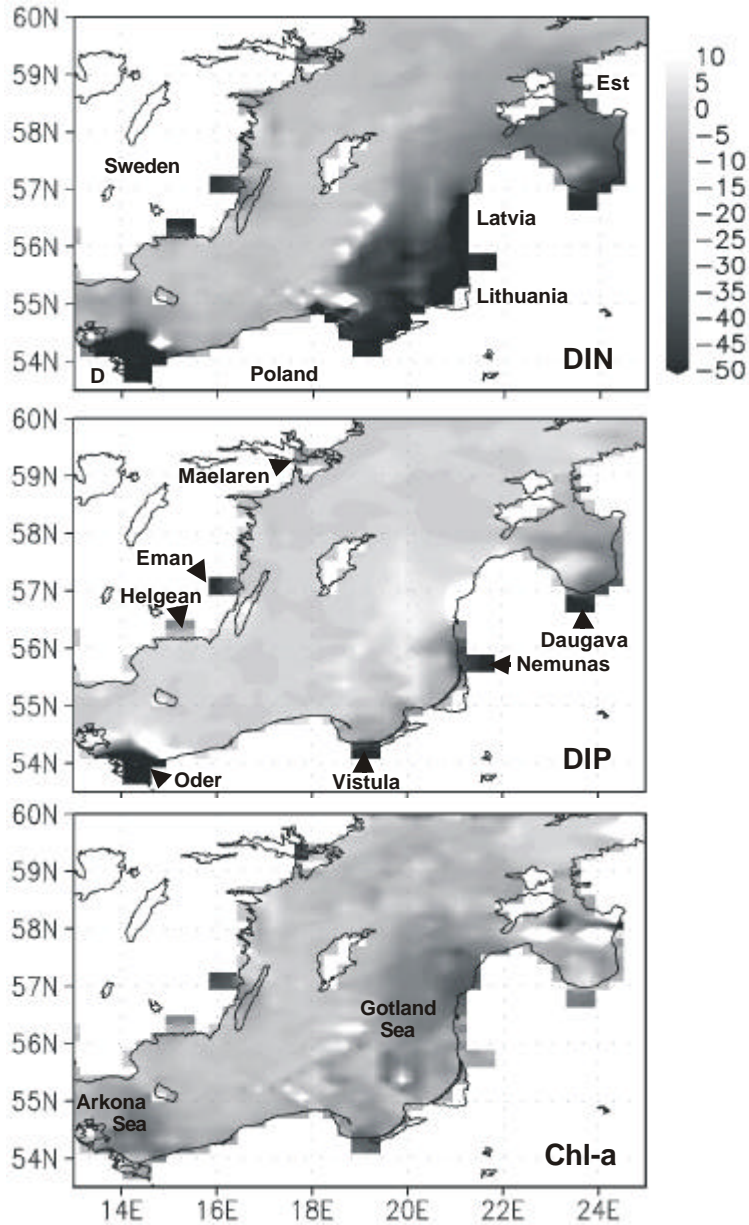


Figure 1: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] decrease of dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and chlorophyll-a concentrations after a proportional reduction of N and P load by 50 % (diffuse and point sources). The simulation started in January 1980. The results display the effects in April 1981, after 16 month.

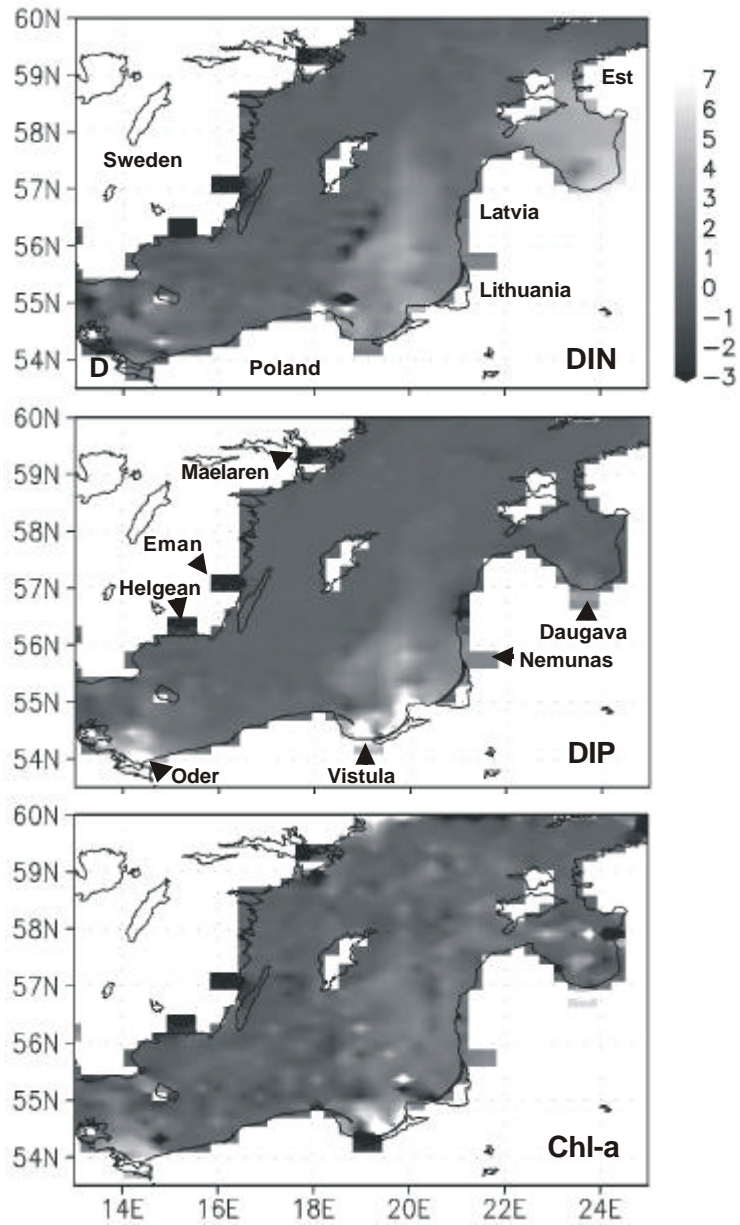


Figure 2: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] differences in dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and chlorophyll-a concentrations between the proportional and the cost-effective reduction of N and P load by 50 % (diffuse and point sources). The simulation started with data of January 1980. The results display the effects after 16 month (April 1981).

Around the Oder Lagoon insufficient water quality is a problem for further touristic development. With respect to the EC bathing water directive, the water quality along the beaches towards the Baltic Sea can be regarded as good or very good. Depending on the wind conditions, the Oder river plume can significantly reduce water transparency on Baltic Sea beaches of Usedom and algae blooms as well as intensive makroalgae growth and accumulations along the beach are a common phenomena in these coastal water, too (Picture 1). It is very likely that eutrophication by the Oder river at least contributes to these problems. The competition for tourists became harder during the last years and environmental quality, especially high water quality, is an increasing ecological and economic factor for the spas along the Baltic Sea. Against this background the differences between the two 50 % reduction scenarios gain importance and the cost-effective scenario is favorable with respect to tourist industry.



Picture 1: Problems along the eastern German Baltic Sea coast. a) Blue-green algae bloom (*Mycoysis*) at the coast of the Island of Rügen in Sept. 1999 (Greifswalder Bodden). b) Water turbidity due to makroalgae in Ahlbeck (Usedom) in Aug. 2000. c,d) Makroalgae accumulation including small amounts of seaweed near Binz (Rügen) in spring 2000.

Söderqvist [12] compared the costs and economic benefits from a cost-effective 50 % nutrient load reduction to the Baltic Sea. He applied the contingent valuation method with surveys and questionnaires. Individual people were asked about their willingness to pay for the realization of improved coastal water quality. The conclusion was, that the transition economies in eastern Europe have a negative net benefit. This means, the population is not willing to pay the high costs for

improved water quality. Whereas the marked economies in Scandinavia and Germany show a positive net benefit.

The analysis did not take into account spatial implications of the cost-effective reduction scenario in different regions of the Baltic Sea. Our results show that improved water treatment along rivers Vistula and Oder in Poland, for example, has not only a general impact on the Baltic Sea, but an increased effect along the coasts. The river plume of the Oder river directly effects larger coastal regions with intensive tourism in Germany which are depending on high water quality. Reduced river loads in Poland therefore have a much higher regional benefit for Germany than indicated in the analysis by Söderqvist [12]. This fact is hard to quantify, but leads to the conclusion, that German investments in improved Polish water treatment measures are, from an ecological as well as economical viewpoint, reasonable. The reallocation of financial resources among the Baltic riparian states to implement the cost-effective 50 % nutrient reduction will be a major problem and challenge for the future.

References

- [1] Gren, I.-M. Cost-effective nutrient reductions to the Baltic Sea. Gren, I.-M., Turner, K. & Wulff, F. (eds). *Managing a sea*. Earthscan Publ., London, pp. 43-56, 2000.
- [2] Turner, R.K., Adger, W.N. & Lorenzoni, I. (eds). *Towards integrated modeling and analysis in coastal zones: principles and practises*. LOICZ Reports & Studies No. 11, 1998.
- [3] HELCOM. *Second Baltic Sea Pollution Load Compilation*. Balt. Sea Environ. Proc. No. 54, pp. 66-117, 1993.
- [4] Fennel, W. & Neumann T. The mesoscale variability of nutrients and plankton as seen in a coupled model. *Ger. J. Hydrogr.* 48, pp. 49-71, 1996.
- [5] Fennel, K. & Neumann T. A coupled physical-chemical model for the Western Baltic. In: Harff, J. et al. (eds). *Computerized modeling of sedimentary systems*. Springer Verlag, Berlin, pp. 169-182, 1999.
- [6] Neumann, T. Towards a 3D-ecosystem model of the Baltic Sea. *J. Mar. Sys.* pp. 405-419, 2000.
- [7] Janssen, F., Schrum, C., Backhaus, J. A climatological dataset of temperature and salinity for the North Sea and the Baltic Sea. *German Journal of Hydrography*. Supplement 9, 245p.
- [8] Klug, H. Tourismus als Belastungsfaktor. Lozan et al. (eds). *Warnsignale aus der Ostsee*. Parey Verlag, Berlin, pp. 118-124.
- [9] Statistisches Bundesamt (eds). *Tourismus in Zahlen*. Metzler-Poeschel Verlag, Stuttgart, p. 309, 1999.
- [10] Institute of Tourism, <http://www.intur.com.pl/index.htm>, 1999.
- [11] Schernewski, G. & Sterr, H. Tourism and environment quality at the German Baltic coast: conflict or chance? Submitted.
- [12] Söderqvist, T. The benefit of a less eutrophicated Baltic Sea. Gren, I.-M et al. (eds). *Managing a sea*. Earthscan Publ., London, pp. 66-77, 2000.