IHP/OHP-BERICHTE

SONDERHEFT 13
KOBLENZ 2002

Low-lying Coastal Areas – Hydrology and Integrated Coastal Zone Management

International Symposium, Bremerhaven, Germany
9-12 September 2002

DEUTSCHES IHP/OHP-NATIONALKOMITEE

INTERNATIONALES HYDROLOGISCHES PROGRAMM DER UNESCO
OPERATIONELLES HYDROLOGISCHES PROGRAMM DER WMO
IN DER BUNDESREPUBLIK DEUTSCHLAND

International Symposium on Low-lying Coastal Areas
Hydrology and Integrated Coastal Zone Management

Bremerhaven, Federal Republic of Germany
9-12 September 2002

Will algal blooms in the Baltic Sea increase in future? Model simulations with different eutrophication combat strategies

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Summary

During the last decade, harmful algal blooms in coastal waters became an increasing problem world-wide. Often, the increase in harmful algal blooms has been addressed to increased loads of nitrogen and phosphorus into coastal waters. This eutrophication of coastal and marine waters causes ecological and economical problems and became a major issue for Integrated Coastal Zone Management (ICZM). Eutrophication is large scale problem that requires large scale management approaches as well as large scale modeling tools. We present applications of a biogeochemical model linked to a three-dimensional flow model that serves as a decision support tool in ICZM. The model covers the entire Baltic Sea and allows an efficiency-analysis of different eutrophication combat strategies in the Baltic Region.

The scenario-simulations suggest that a 50 % nutrient load reduction into the Baltic Sea causes a spring bloom reduction (diatoms and dinoflagellates) of about 30 %. The effect on cyanobactreia blooms in summer is opposite. In some regions, especially of the Polish and Lithuanian coast, decreased nutrient loads increase the nitrogen limitation in summer and favour very strong and harmful cyanobacteria blooms. Intensified summer blooms compensate lower spring bloom and the effect of a 50 % nutrient load reduction on average annual chlorophyll concentrations is only minor. The scheduled measures to abate eutrophication in the Baltic Sea therefore might fail and generate even undesirable effects.

The comparison of a cost-effective (nutrient load reduction where it is cheapest) with a proportional load reduction approach (every country reduces by 50 %) generally gives similar results. The cost-effective approach shows slightly increased cyanobacteria blooms in the south-eastern Baltic Sea, but altogether it is not very important where the nutrient load reduction is carried out.

1 Algae blooms in the Baltic Sea

The first algal bloom in the Baltic Sea in spring is characterized by varying portions of dinoflagellates and diatoms. These blooms can form a high algal biomass, reduce water transparency and potentially toxic species can be involved. Despite that, the main concern are algal blooms during summer, when human leisure activities along the coasts are most intensive.

In the central Baltic Sea cyanobacteria (blue-green algae) blooms are a common feature in summer. Due to their ability to fix atmospheric nitrogen, cyanobacteria are favored under prevailing nitrogen limited conditions in the central Baltic Sea. Potentially toxic species of *Aphanizomenon, Anabaena* and mainly *Nodularia* are dominating and can cause large accumulations and foam on the water surface. In 1982, 1983 and 1984 more than 30,000 km² water surface were covered by algae foam accumulations. In 1991, 1992 or 1993 between 40,000 km² and more then 60,000 km² (Kahru et al. 1994) or up to 30 % of the central Baltic Sea area, the Baltic Proper, were affected. 1994, 1996, 1997 and 1999 were more recent years with intensive blue-green algae blooms. In coastal regions, especially in river plumes, the availability of nitrogen is higher and phosphorus sometimes plays a key role as a limiting element. Therefore, cyanobacteria are often less dominant in coastal regions, but pronounced differences between regions exist. Due to a generally better availability of nutrients, the algal biomass in coastal waters is higher (Wasmund 2002).

Drifting surface accumulations of algae, especially of toxic cyanobacteria, nowadays are not only a nuisance but a real threat for coastal areas and beaches in the entire Baltic Sea. They can cause human health problems and a poisoning of marine and terrestrial animals (birds, fish, cattle etc.) was reported several times for the Baltic Sea. Over 50,000 cases of human poisoning by toxic algae were estimated worldwide (Edler et al. 1996).

Another aspect is the publicity effect of an algae bloom. A recent example was a algal bloom (cyanobacteria and diatoms) off the Danish coast in Juli 2001. The algal foam accumulated on the water surface and drifted into Lübeck Bight, were a beach had to be closed for several days. The algae accumulation covered only several hectares and was not a serious problem, but it became an important issue in the local news. Tourism industry was concerned, that bathing and tourism along large parts of the German Baltic Sea coast might be negatively affected simply by the bad news. Therefore, algal blooms can cause serious economic losses not only in fish farms and aquaculture.

2 Baltic Sea eutrophication combat strategies

To improve the water quality of the Baltic Sea, the bordering states Denmark, Sweden, Finland, Russia, Estonia, Latvia, Lithuania, Poland and Germany 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 phosphorus load by 50 %. In a recently published report, the Finnish Environment Institute (FEI 2002) evaluated the nutrient load reductions into the Baltic Sea between the late 80's and 1995. Altogether the total nitrogen as well the phosphorus load was reduced by 35 %. A fast reduction was observed mainly in countries with a transitional economy. Poland and Russia alone contributed about 155,000 t or nearly 50 % of the total load nitrogen reduction into the Baltic Sea. The same is true with respect to phosphorus. Russia and Poland reduced their P-load by about 11,900 t or nearly 50 %, as well. Despite that, Poland remained by far the most important N and P pollutant for the Baltic Sea.

The first 35 % reductions of nitrogen and phosphorus were achieved within a period of only 7 years. The experience in other regions shows that further reductions are much harder to obtain. There are already doubts, whether a 50 % reduction of nitrogen especially from diffuse sources in the Baltic can be reached even until 2005. To obtain the 50 % nutrient load reduction is especially problematic for all countries, which already meet high water quality standards and have realised load reductions during the early 1980's, before the declaration was signed. Therefore alternatives are under discussion.

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. We call it the proportional reduction approach. The alternative approach suggested by Gren (2000), has the goal to meet the 50 %-nutrient load reduction at minimum total costs. This implicates, that nutrient load reduction takes place in countries and drainage basins where it shows its highest cost-efficiency. We call this the cost-effective approach.

Background for the calculation of the cost-effective approach is the awareness, that the marginal costs of abatement measures are not equal among the riparian states. Marginal costs 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 (2000) 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. 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 (Gren 2000).

A 3D-flow and circulation model with biogeochemical module was applied for the simulation of the impacts of the two strategies. The circulation model is based on the Modular Ocean Model MOM2.2 and covers the entire Baltic Sea (Neumann 2000). 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 resuspension) (Neumann et al. 2002)

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 (Neumann & Schernewski 2001).

3 Nutrient load reduction effects on algae

The Baltic Sea and especially the coastal regions show a fast reaction on the 50 % nutrient load reduction. After four years, the annual average nitrogen (dissolved inorganic N) concentrations in the south and south-east Baltic Sea are reduced by nearly 50 %. Near Sweden, the reduction of the nitrogen concentrations is below 10 %. Phosphate reduction is less pronounced. A 20 % reduction is observed only directly in the mouth of the large rivers. Reduced nutrient loads and concentrations in the Baltic Sea cause an average decline of chlorophyll concentrations, which is an indicator for algae biomass. With about 15 % the highest decline in chlorophyll concentrations is observed in the south-eastern Baltic Sea. Nearly no effect is visible along the Swedish coast. In average, the chlorophyll concentrations are reduced by less than 10 %. Altogether, the 50 % nutrient load reduction does not cause a similar reduction of the algae biomass. The poor effect of the nutrient load reduction is to a large degree a result of the different behaviour of the three algae groups in the model. They are called diatoms, flagellates and cyanobacteria.

The three algae groups are functional groups with certain properties. These functional groups can only partly be addressed to taxonomic groups. In the model one group is called diatoms. This group represent large cells which depend very much on high nutrient concentrations. They develop early in the season and, depending on regional differences in water temperature, form the first algae bloom in spring. The functional diatom group in the model has a relatively high sinking velocity and needs turbulence to stay in the water column. The functional diatom group reflects early diatoms and dinoflagellates in the Baltic Sea. The small diatom species in summer show properties closer to the functional flagellate group. In the simulations, the diatom bloom in spring is very much affected by the 50 % nutrient reduction. The average annual biomass along the entire south-eastern Baltic Sea shows a decline by more than 30 % (Figure 1).

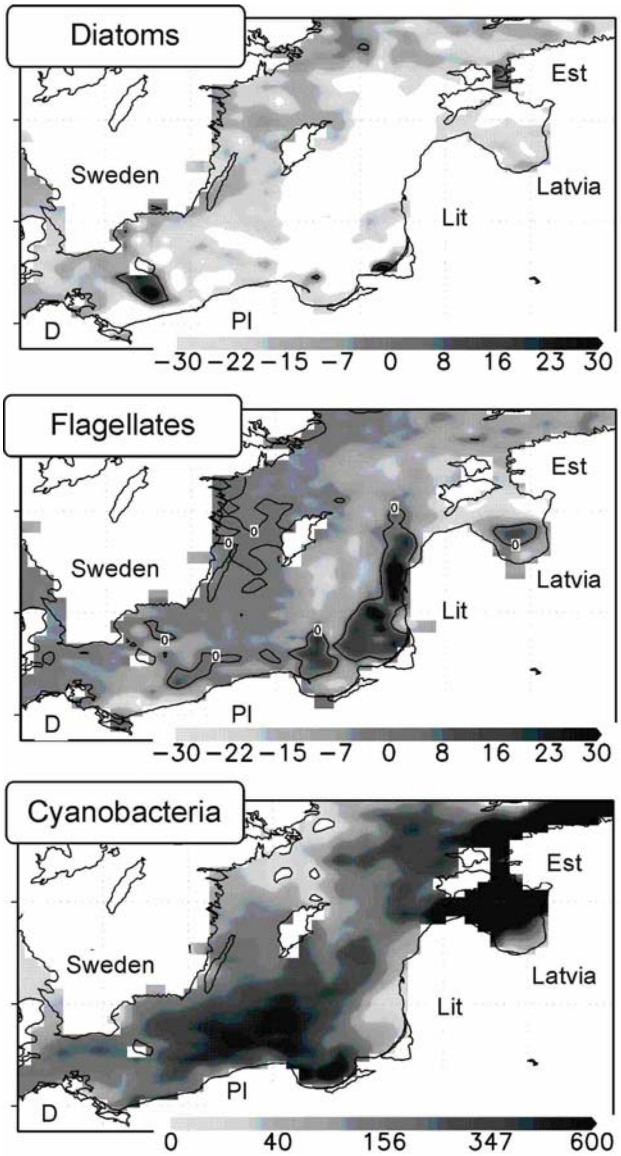

Figure 1: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] decrease of chlorophyll a concentrations in the 3 functional phytoplankton groups (diatom, flagellate and cyanobacteria (Blue-green algae)). On the basis of a cost-effective reduction of N and P load by 50 % (diffuse and point sources). The simulation started in January 1980. The results display the average annual concentrations in 1983.

In the model a general group of small flagellates succeeds the diatoms in early summer. They need higher temperatures and are able to use nutrients in an efficient manner. Their reaction to the 50 % nutrient load reduction is less pronounced. A chlorophyll reduction of about 10 % in average is observed.

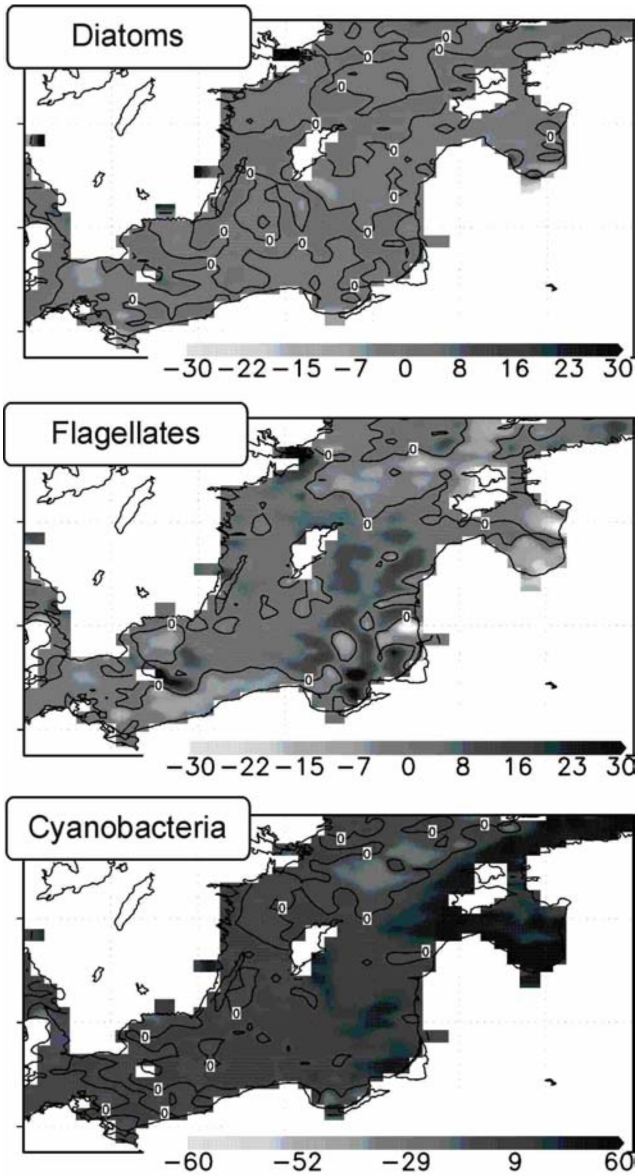

Figure 2: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] decrease of chlorophyll a concentrations in the 3 functional phytoplankton groups (diatoms, flagellates and cyanobacteria (Blue-green algae)). Differences between the cost-effective and the proportional reduction of N and P load by 50 %. Positive values indicate higher concentrations in the cost-effective approach. The simulation started in January 1980. The results display the average annual concentrations in 1983.

Cyanobacteria (blue-green algae) show a very different behaviour. The functional cyanobacteria group in the model is able to fix atmospheric nitrogen and represents the taxonomic group to a comparatively high degree. Reduced nutrient loads favour the development of blue-green algae in the entire Baltic Sea. In some parts of the southern and eastern Baltic Sea an increase up to 600 % is observed (Figure 1).

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 are slightly higher compared to the proportional approach. The additional reduction of loads from large rivers entering the Baltic Sea along the south coast, like the Oder and the Vistula in Poland, causes slightly reduced nutrient concentrations in the river mouths and especially in the Riga bay in winter when compared to the proportional load reduction approach (Fig.2). The simulation of the cost-effective approach shows even more pronounced blue-green algae developments in the south-eastern Baltic Sea.

With exception of blue-green algae development, the differences between both approaches are not very pronounced. The concentration of all positive and negative effects of the nutrient load reduction in the south-eastern Baltic Sea is a result of the prevailing current systems. In average an anti-clockwise circulation pattern dominates in the central Baltic Sea. The water and the nutrient load of the Odra and the Vistula river is transported along the Polish coast towards east. In front of the shores of the Baltic States, in the south-eastern Baltic Sea, the nutrient load reduction effects accumulate.

4 Discussion

Nodularia blooms, as an example for bloom forming cyanobacteria, need a sufficient availability of phosphorus and water temperatures above 16°C as starting conditions (Kahru et al. 1994). A 50 %-reduction of nitrogen and phosphorus increases the nitrogen limitation in central parts of the sea. Low nitrogen concentrations allow a dominance of cyanobacteria because competing algae cannot overcome the nitrogen shortage and cannot develop. Phosphorus concentrations are slightly reduced in the 50%-reduction scenario, too, but phosphorus is exclusively available to cyanobacteria and therefore allows an increased bloom. The model results therefore are reasonable.

High blue-green algae concentrations in the water do not automatically mean an intensive surface accumulation. Surface accumulations need low wind conditions, too, but the likelihood of a scum formation is increased and with it the likelihood of problems for the coasts.

Increased cyanobacteria blooms with increased N-fixation would increase the nitrogen load to the Baltic Sea and counteract the eutrofication combat measures. On the other hand, this extra nitrogen might lower the nitrogen limitation and might favour other species again. This example shows that the interactions are complex. The model takes several interactions into account, but cannot represent the complexity of the Baltic Sea ecosystem. Therefore, the model results should be regarded as competent hints for further research and not as true facts.

A box-modelling approach for several basins of the Baltic Sea shows a fast reaction of the system when a 50 % load reduction is applied (Wulff 2000). During the first 10 years the nitrogen and phosphorus concentration were reduced by about 25 % in the Baltic Proper. Due to sediment processes and a lack of loss term like denitrification, the decline of phosphorus concentrations shows a higher intertia than nitrogen concentrations. Our model results are in agreement with the results of Wulff (2000). We presented our results after four years of simulation and it is likely that at that time, the Baltic Sea is not in a balance again. To get an impression of the full impact of a nutrient load reduction an extension of the simulation time might be needed.

The results suggest far-reaching consequences with respect to eutrophication combat strategies in the Baltic region. Before concrete recommendations are possible, further analysis and evaluations of the model results as well as additional simulations are necessary.

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