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Impact of river basin management on the Baltic Sea: Ecological and economical implications of different nutrient load reduction strategies

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ABSTRACT

Water quality and the eutrophication of the Baltic Sea depend on the nutrient load in rivers. Therefore, nitrogen and phosphorus management in river basins is at the same time management of the Baltic Sea. We compare the impact of two 50 % nutrient reduction strategies on the Baltic Sea using a 3D-coupled physical-bio-chemical model of the Baltic Sea (Neumann 2000). The first strategy assumes a proportional 50 % nutrient reduction in every riparian country, as suggest by HELCOM. The second approach is based on existing socio-economic calculations by Gren (2000) suggesting an optimal cost-effective 50 %-nutrient reduction. In this cost-effective approach the nutrient reduction measures in the river basin are realised in countries like Poland, Russia, Lithuania, Latvia and Estonia, where the costs per reduced ton of N and P are lowest. The consequence is a reduction of the nutrient loads by more than 50 % in the southern and south-eastern Baltic countries and less reduction in Scandinavia. In previous studies the general impact of a 50 % nutrient reduction (Neumann et al. 2002) and the short term effects on the Baltic coastal waters (Neumann & Schernewski 2001) were analysed. In this study we focus on the different effects of the two approaches in different regions of the Baltic Sea in a longer perspective and refer to consequences for river basin management.

The model takes into account the real meteorological conditions of the 1980's and we assumed an immediate nutrient load reduction by 50 %, starting in winter 1980. The reduction has immediate effects on all coastal waters. A reduced nutrient availability and shifts between the utilisation of nitrogen and phosphorus are visible in the Arkona, Bornholm and Gotland Sea already in the first summer. After 3 years the mean annual phosphorus and more intensive, the nitrogen concentrations are reduced in the south-eastern Baltic Sea. The reduction in chlorophyll a, an indicator of algal biomass, shows only a decline of about 10 %. The model suggests that the 50 % reduction of the nitrogen as well as the phosphorous load, favours blue-green algae blooms in the south-eastern Baltic Sea. In the cost-effective approach, blooms of the potentially toxic blue-green algae become even more pronounced.

Referring to our simulation results, the scheduled measures to abate eutrophication in the Baltic Sea will partly fail and generate undesirable side effects. A more pronounced reduction of the phosphorous loads might prevent an increase in blue-green algae blooms. The cost-effective approach shows, compared to the proportional load reduction approach, clear positive effects in the western, German part of the Baltic Sea and no serious differences along the Swedish coast. Due to an increase of blue-green algae blooms, there are negative implications for the south-eastern Baltic regions. Altogether the cost-effective approach reaches the same objective with one fourth of the costs and is strongly recommendable. It makes a reallocation of water quality investments between the countries in the Baltic necessary.

Eutrophication abatement in the Baltic Sea

The Baltic Sea is one of the world wide largest brackish water bodies (412.000 km²) with a water residence time of about 25-30 years, a drainage basin of 1,734,000 km² and a population in the drainage basin of about 85 millions. In the late 80's about 70,000 t/a phosphorous and 917,000 t/a nitrogen were discharged into the Baltic Sea (FEI 2002). The result was a severe eutrophication, especially of 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 %. 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 phosphorous. 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 phosphorous 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 yet meet high water quality standards and have already realised load reductions during the early 1980's. Therefore alternatives are under discussion.

Nutrient load reduction strategies: Cost effective versus proportional approach

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 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 between 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.

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 1 kg N-load from agriculture in Germany costs between 3-15 Euro, from sewage plants 3-8 Euro from wetland 3.5 Euro and from atmospheric deposition 24-450 Euro. 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 (Gren 2000). The two approaches have different consequences for the Baltic Sea. The intensity of the load reduction varies between the regions and implies regional differences with respect to water quality in the Baltic Sea.

ERGOM: A 3D-ecosystem model of the Baltic Sea

A 3D-flow and circulation model with biochemical 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. A horizontally and vertically telescoping model grid with high horizontal resolution in the south-western 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 vertical thickness of deeper layers increases 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 refer to 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) 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 represent 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 favourable 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 remains 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 (2000).

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 4 years (January 1980 – December 1983) was simulated for both nutrient reduction strategies 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 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 (2000) 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. Due to differences in methodology and the data basis some differences occurred.

Effect of 50 % nutrient load reduction on the Baltic Sea

After four years, the comparison of the simulation without any nutrient load reduction with the 50 % cost-effective nutrient load reduction simulation shows pronounced differences. The annual average nitrogen (dissolved inorganic N) concentrations in the south and south-east Baltic Sea are reduced by nearly 50 % (Figure 1). 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 concentration are reduced by less than 10 %. Altogether the 50 % nutrient load reduction does not cause a similar reduction of the algae biomass. The different algae groups behaved in a different manner.

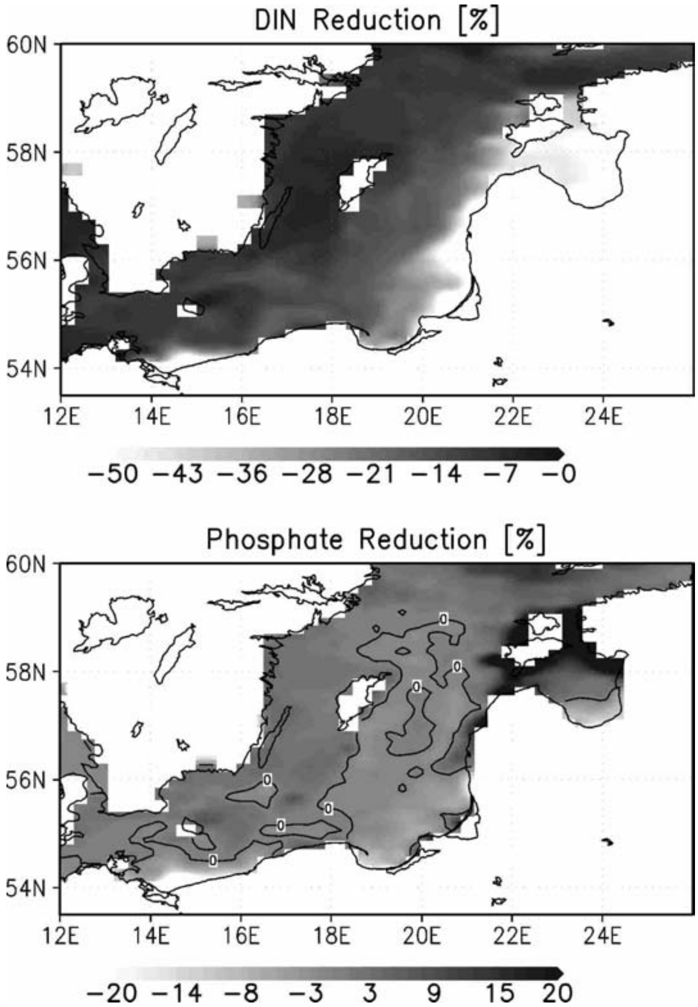

Figure 1: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] decrease of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations after a cost-effective reduction of N and P load by 50 % (diffuse and point sources). The simulation started in January 1980. The results display the average annual concentrations in 1983.

Diatoms show a strong respond to nutrient reduction. The diatom biomass along the entire south-eastern Baltic Sea shows a drop of more than 30 %. The situation with respect to blue-green algae is opposite. Reduced nutrient loads favoured 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 2).

Effects of the cost-effective versus the proportional approach

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, 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. The simulation of the cost-effective approach shows even more pronounced blue-green algae developments in the south-eastern Baltic Sea.

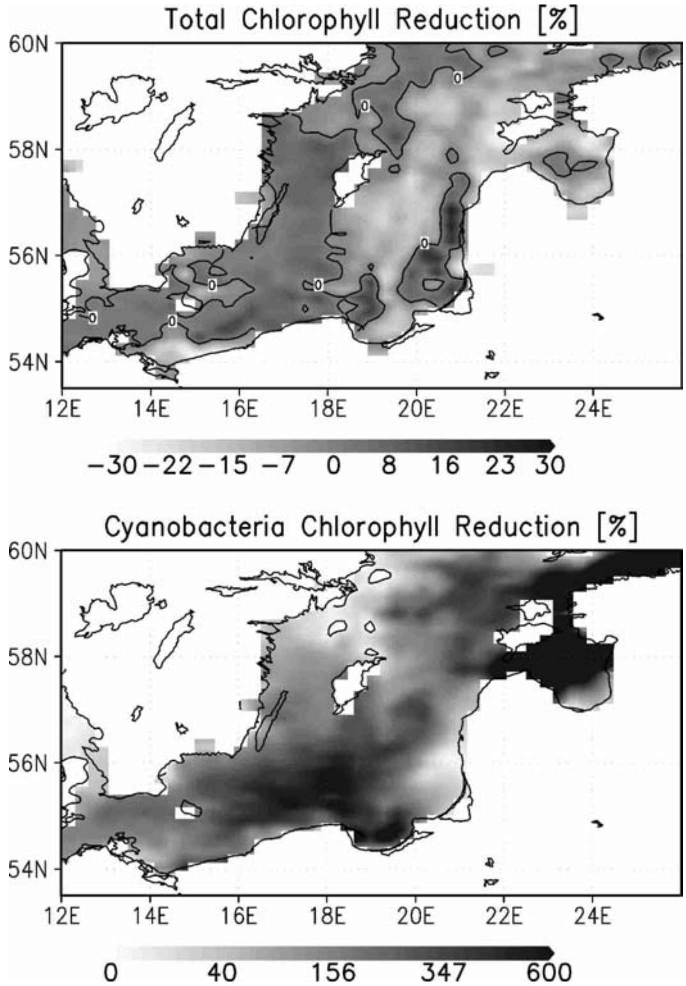

Figure 2: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] decrease of total chlorophyll a (indicator of algal biomass) and cyanobacteria (Blue-green algae) chlorophyll a concentrations after an cost-effective reduction of N and P load by 50 % (diffuse and point sources). The simulation started in January 1980. The results display the average annual concentrations in 1983.

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.

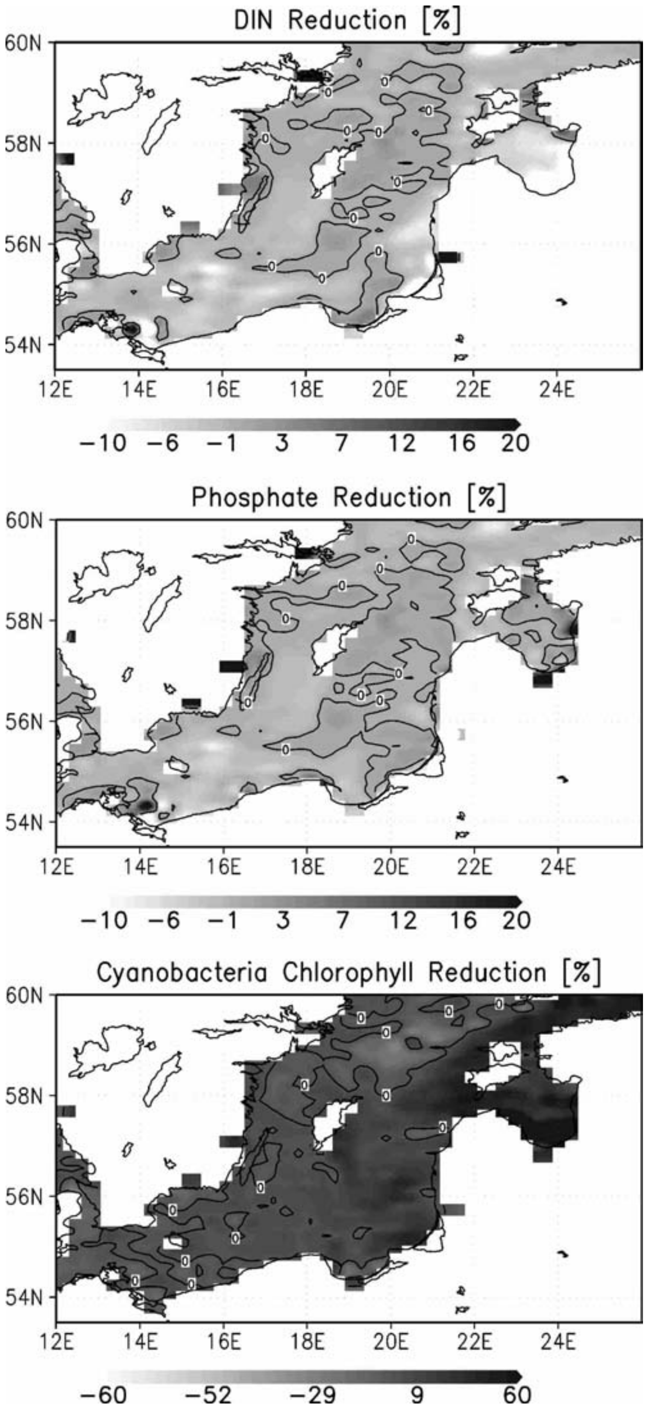

Figure 3: Simulation results with the 3D-ecosystem model of the Baltic Sea: Relative [%] differences in dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and chlorophyll-a concentrations between the proportional and the cost-effective reduction of N and P load by 50 % (diffuse and point sources). The simulation started with data of January 1980. The results display the average effects in August 1983.

Implications for river basin management

Reduced river nutrient load causes reduced nutrient concentrations in the Baltic Sea, but the effect on phytoplankton is not very pronounced. Due to lower nitrogen availability in the water, the spring development of diatoms is less intensive. In summer, the shortage of nitrogen has negative effects on all phytoplankton groups, with exception of blue-green algae. Blue-green algae are able to utilise atmospheric nitrogen and have the possibility to overcome a shortage of dissolved nitrogen components in the Baltic Sea water. In opposite, their development is favoured, because the development of competing groups is hampered. The reduced spring bloom due to reduced nutrient availability is compensated by an increased summer development of blue-green algae.

Blue-green algae blooms are a common feature in the Baltic Sea during summer month. Toxic species occur in the open sea (e.g. *Nodularia spumigena*) as well as in coastal waters (e.g. *Microcystis* sp.). Examples of potentially toxic species, toxic effects and incidents in the Baltic Sea are given by Wasmund (2002). Toxic blooms are not only harmful for men or animals, but have also high economic relevance for fish and shellfish farming as well as tourism.

The model simulations suggest, that a proportional reduction of nitrogen and phosphorous at the same time does not have the desired reducing effect on phytoplankton development in the open sea. The taken measures seem to be not suitable to abate eutrophication in the Baltic Sea. A possible solution can be an increased reduction of the phosphorous load. Phosphorous is an element that potentially limits the phytoplankton production in the Baltic Sea. In some regions of the Baltic Sea phosphourous is the most important limiting element. A shortage in dissolved phosphorous in the water cannot be compensated by algae. All groups are affected by a phosphorous limitation more or less in the same manner and the observed shift between different phytoplankton groups is less likely under P-limitation. Additional simulations have to prove, whether an intensified phosphorous load reduction management is a suitable way to abate eutrophication in a more efficient manner.

To a high degree phosphorous has its origin in point sources, like municipal sewage. The nutrient load from point sources can be reduced during a short period of several years. Usually, measures to reduce input from point sources are much cheaper compared to measures dealing with diffuse sources. The main source for nitrogen is the input by ground water. To reduce ground water nitrogen concentrations is expensive and takes decades. This is the reason, why phosphorous load reductions are usually obtained faster. Behrendt et al. (1999) calculated the load reduction of P and N from the German territory between 1993-1997 and 1983-1987. The aim was a 50 % reduction, too. A 60 % reduction was achieved for phosphorous during that period but only a 25 % nitrogen reduction took place. There is a certain likelihood that a similar development will take place in the Baltic region, too and that we automatically will get the suggested increased P-reduction in the future.

Söderqvist (2000) compared the costs and economic benefits from a cost-effective 50 % nutrient load reduction to the Baltic Sea. He applied the contingent valuation method basing on 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. The market economies in Scandinavia and Germany, on the contrary, have a positive net benefit of an improved Baltic Sea water quality.

The analysis did not take into account spatial implications of the cost-effective reduction scenario in different regions of the Baltic Sea. Our earlier results showed that improved water treatment along the rivers Vistula and Odra in Poland, for example, have an immediate effect on adjacent coastal waters (Neumann & Schernewski 2001). The river plume of the Odra 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 (2000).

In general the simulation results show that the spatial exchange of nutrients in the central Baltic Sea is fairly fast and that in a long-term perspective it is not important where nutrient reduction measures take place. Therefore the cost-effective 50 % nutrient reduction approach should be realised within the Baltic. It means that financial resources have to be reallocated among the Baltic riparian states.

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