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Coastal eutrophication management: Lessons learnt from long-term data and model simulations

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Abstract

River basins have to be taken into account in ICZM approaches and are imperative for coastal water and coastal sea management. To analyse and assess the impact of the Oder river basin on coastal water quality during the last 40 years, we apply a spatially integrated, large-scale model approach covering the entire river basin – river – coastal water – sea system. For this purpose the river basin model MONERIS is linked to the three-dimensional ecosystem model of the Baltic Sea (ERGOM). The preliminary results of the Oder/Odra lagoon eutrophication history clearly indicate that river basin management alone will not be not sufficient, to reach a "good water quality" according to the Water Framework Directive. Additional internal management measures in the lagoon, like mussel farms, are necessary to remove nutrients and to improve the water quality. Comprehensive, cost-efficient water quality management has to take economic and social aspects into account, as well. Water transparency is assumed to be a suitable indicator for water quality (status of eutrophication) and serves as the major link between ecology and economy. In a draft conceptual model we consider nutrient emission trading as the major funding mechanism for management measures. This funding is supported by tourism and the sale of mussel farming products. Some consequences for coastal water management are discussed.

1 Introduction, background and objectives

The Baltic Sea is one of the world‘s 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 million. According to the Baltic Sea Action Plan (HELCOM 2007), "eutrophication is a major problem in the Baltic Sea, caused by excessive inputs of nitrogen and phosphorus which mainly originate from inadequately treated sewage, agricultural run-off and airborne emissions from shipping and combustion processes. Eutrophication leads to problems such as intensified algal blooms, murky water, oxygen depletion and lifeless sea bottoms. The plan's objectives for eutrophication include: concentrations of nutrients close to natural levels, clear water, natural levels of algal blooms, natural oxygen levels, and natural distributions and abundance of plants and animals."

HELCOM (2007) assumes that for a good environmental status (clear water objective), the maximum allowable annual nutrient inputs into the Baltic Sea would be 21,000 tonnes of phosphorus and about 600,000 tonnes of nitrogen. Over the period 1997-2003, average annual inputs amounted to 36,000 tonnes of phosphorus and 737,000 tonnes of nitrogen. Therefore, annual load reductions of 15,000 tonnes of phosphorus and 135,000 tonnes of nitrogen would be necessary.

Managing eutrophication in the Baltic Sea ecosystem requires a large scale approach, integrating watersheds, coasts and sea. This knowledge is already reflected in the European Water Framework Directive (WFD) and was adapted by the Baltic Sea Action Plan (HELCOM 2007), which asks the

Baltic Sea to "develop national programmes, by 2010, designed to achieve the required reductions. Each country will be given enough flexibility to choose the most cost-effective measures, which can also be incorporated into River Basin Management Plans", to "implement specific measures to improve the treatment of wastewater, including increasing phosphorous removal from 80 % to 90 %, and substituting phosphorous in detergents…", and to "implement measures to drastically reduce agricultural inputs, including changes in manure handling and fertilisation practices".

Today, phosphorus is regarded as the key nutrient for Baltic Sea management. Over 90 % of phosphorus enters the Baltic Sea via rivers and over 50 % of the loads enter along the south coast of the Baltic Sea (Helcom 2005). Therefore, large rivers like the Oder (Polish: Odra), Vistula and Daugava in the southern Baltic region are of outstanding importance for Baltic Sea management. The southern Baltic coast is characterised by sediments and a complex pattern of land and sea. Usually rivers do not enter the Baltic Sea directly but discharge their nutrient load into coastal estuaries, bays and lagoons. The quantitative role of these coastal waters, with restricted water exchange, for Baltic Sea management is, in detail, not well known. They serve as converters for nutrients, sinks and retention ponds and control the amount and composition of the nutrients entering the Baltic Sea.

One of the most important polluters along the southern Baltic coast is the Oder River with its complex and heavily eutrophied coastal waters. Especially during summer, eutrophication effects like algae blooms or fish kills can cause serious economic damage to the tourism industry. Therefore water quality is a major management issue, and the Oder case study can serve an example for management problems, threats and challenges.

The objective of this study is to assess the water quality objectives and the measures suggested in the Baltic Sea Action Plan. Can "clear water" in the Baltic Sea be reached with the recommended nutrient load reductions? For this purpose, we focus our analysis on the Oder River basin – coast – sea system. We reconstruct the pollution history of the Oder River, and analyse the consequences on the Oder Estuary between 1960 and 2000. What were the consequences of different riverine nutrient load levels on nutrient availability and limitation as well as algae biomass in the estuary? How fast does the estuary respond to changes in loads? Did the structure and function of the Oder Lagoon change and if yes, what are the consequences for the Baltic Sea?

Based on the results, we develop a conceptual model for the comprehensive management of the river basin - coast- sea system and reflect on the consequences of management of the Baltic Sea.

2 Location and Methods

The Oder (Polish: Odra) Estuary is located on the German/Polish border. It consists of the Oder Lagoon (Szczecin Lagoon) and the Pomeranian Bay (a part of the Baltic Sea) (Figure 1). The lagoon is large (687 km^2) but shallow (average depth of 3.8 m) and can be subdivided into an eastern bay (Wielki Zalew) on the Polish territory and the Kleines Haff in the west, on the German side. Three outlets link the lagoon with the Pomeranian Bay. The entire estuary is controlled by the discharge of the Oder River into the lagoon. With a length of 854 km, a river basin of 120,000 km^2, an annual discharge between 9.5 km^3 (1990) and 25 km^3 (1980) and an average discharge of 17 km^3 (530 m^3 s-1) the Oder is the third largest river in the Baltic region. About 89 % of the river basin is located in Poland, 6 % in Czech Republic and 5 % in Germany. The Odra contributes at least 94 % to the lagoon's water budget and dominates the nutrient budgets, as well.

Data for the entire last decades are incomplete especially for the 1960's and 1970's. To be able to analyse, assess and evaluate the impact of the Oder River basin on coastal water quality during the last 40 years we apply a spatially integrated, large-scale model approach covering the entire river basin – river – coastal water – sea system. For this purpose the river basin model MONERIS has been linked to the three-dimensional ecosystem model of the Baltic Sea (ERGOM).

ERGOM is an integrated biogeochemical model linked to a 3D circulation model covering the entire Baltic Sea. The circulation model is an application of the Modular Ocean Model (MOM 3) and includes an explicit free surface, an open boundary condition to the North Sea and freshwater discharge with rivers. The biogeochemical model consists of nine state variables. The nutrient state variables are dissolved ammonium, nitrate, and phosphate. Primary production is provided by three functional phytoplankton groups: diatoms, flagellates and cyanobacteria (blue-green algae). Neumann (2000) provides a detailed model description and Schernewski & Neumann (2005) as well as Neumann (2007) present model applications and details about the data requirements as well as possibilities and limits of the model. However, it can be regarded as a reliable tool for water quality simulations.

MONERIS was applied to calculate the nutrient inputs and loads in the entire Oder River basin. The model calculates the annual nutrient load into the coastal waters, resulting from point and various diffuse sources. MONERIS is based on a geographical information system (GIS), which includes various digital maps and extensive statistical information. Details about the model, processes and validations are given in Behrendt & Dannowski (2005).

ERGOM simulations not only take the nutrient load of the Oder River into account, which contributes more than 90 % of the total load into the lagoon, the contribution of all small rivers is quantitatively taken into account, but allocated spatially and quantitatively to the Oder river. Wet deposition of nitrogen is considered as an independent diffuse source. ERGOM does not consider the total load of N and P, but only the bio-available fractions. With respect to phosphorus, the soluble reactive phosphate (SRP), or dissolved inorganic P (DIP), plus 30 % of the sum of dissolved and particulate organic fractions is used as input. With respect to nitrogen, dissolved inorganic N (DIN) serves as input.

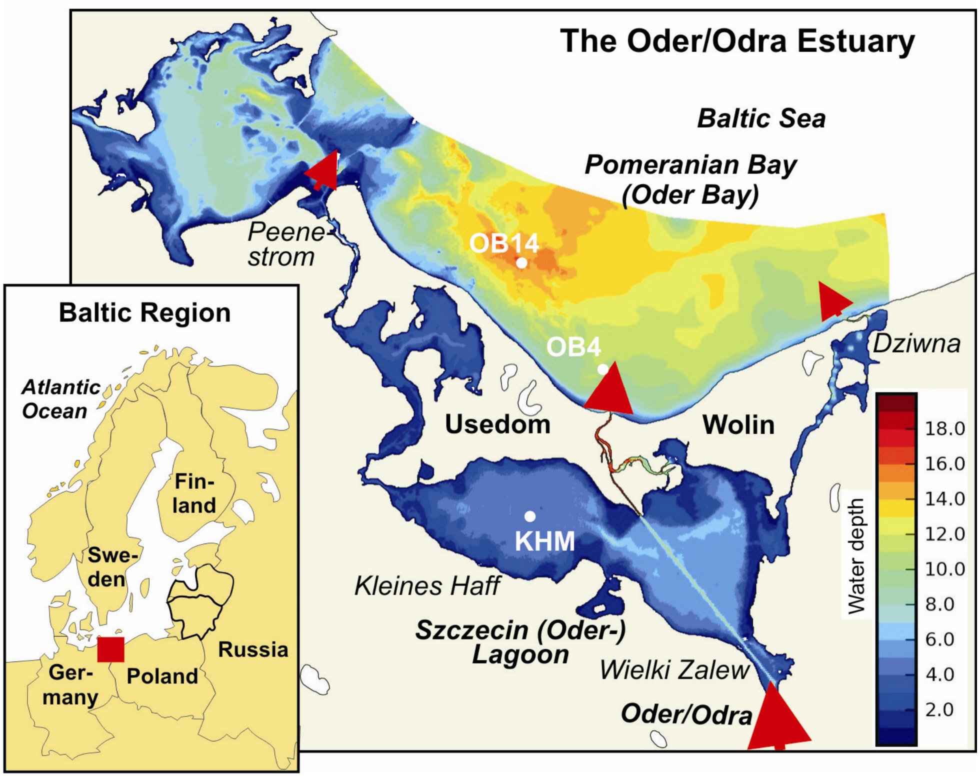

Figure 1: The Oder/Odra Estuary

3 Long-term eutrophication history

3.1 Nutrient loads and concentration between 1960 and 2002

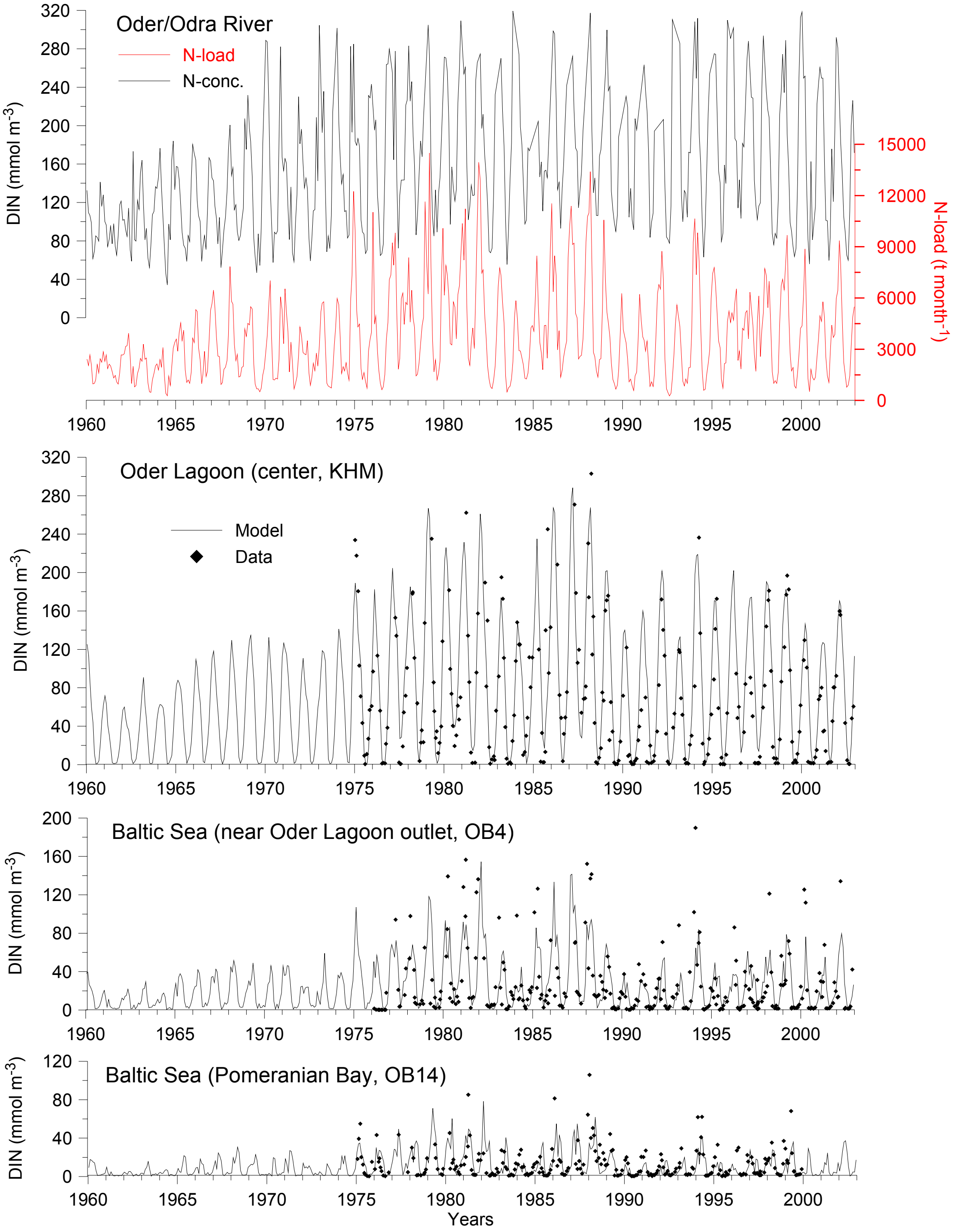

Figure 2: Nitrogen (Dissolved Inorganic Nitrogen, DIN) loads and concentrations in the Oder/Odra River and estuary. The labels and years indicate the 1st of January. Oder/Odra River loads are based on MONERIS model simulations. In the estuary, concentrations simulated with the ERGOM model are aggregated to monthly averages, while the measured data represents single samplings near the water surface (from Schernewski et al. in prep, data source: LUNG).

The riverine nutrient loads are based on MONERIS model simulations, which are in agreement with monitoring data (Behrendt, in pep.). Data is only available back to the 1980's but the model simulations make it possible to trace back the nutrient load development until 1960. The total annual nitrogen loads (5 year averages) increased from nearly 50,000 t in the early 1960's up to over 110,000 t in the mid 1980's and declined to slightly below 100,000 t in 2000.

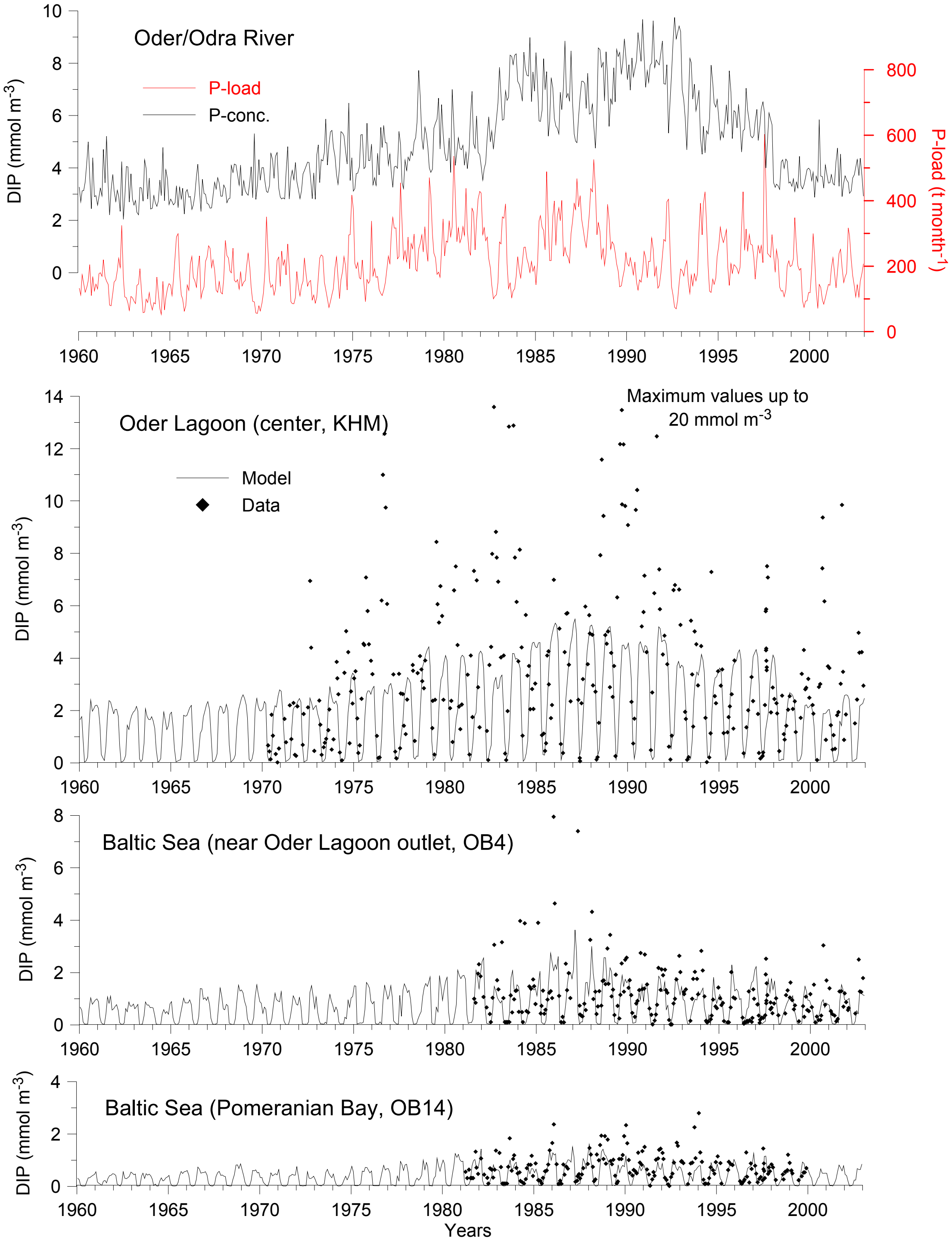

Figure 3: Phosphorus loads (bio-available P) and concentrations (Dissolved Inorganic P, DIP) in the Oder/Odra river and estuary. The labels and years indicate the 1st of January. Oder/Odra river loads are based on MONERIS model simulations. In the estuary, concentrations simulated with the ERGOM model are aggregated to monthly averages, while the measured data represents single samplings near the water surface (from Schernewski et al. in prep, data source: LUNG).

To analyse the effect of nitrogen loads on coastal waters, the Dissolved Inorganic Nitrogen (DIN) concentrations, instead of total loads, were used in the model simulations (Fig. 2). Long-term monthly data shows a strong annual cycle, with high loads during winter and low loads during the summer months. Further, the inter-annual variability is very high. Despite much higher total annual loads, today's nitrogen loads during summer do not differ much from the 1960's. This is reflected in the DIN-concentrations in the central lagoon (KHM). In most years nitrogen is depleted in late summer and can be regarded as a limiting element. Only between mid 1977 and 1997, do several years show excess nitrogen during summer. Uptake, sedimentation and denitrification cause a decline of nitrogen availability towards the Baltic Sea, which is easily visible at the stations OB4 and OB14 (Fig. 2). With respect to nitrogen, model simulations are well in agreement with the data.

The annual total phosphorus loads (5 year averages) increased from nearly 6,000 t in the early 1960's up to over 15,000 t in the mid 1980's and declined to below 9,000 t in 2000. Compared to the 1960's the recent loads are still 50 % higher. In the Baltic Sea, phosphorus is and always was a potentially limiting element in spring during the last 40 years. Model results and data are in agreement and support this statement. In general, phosphorus has its lowest abundance in the Oder lagoon in spring, as well. However, in the lagoon, serious differences between model and data occur in summer. One reason is that data are single samplings, while the model results are aggregated to monthly values. However, this explanation is not sufficient. Dissolved Inorganic Phosphorus (DIP) concentrations in July and August can reach extreme values of up to 20 mmol m^{-3} as a result of anoxic P-release from the sediments (Schernewski & Wiegat 2001). This is not well reflected in the model results. However, it does not have ecological consequences because phosphorus is available in abundance during summer and fast precipitation as $Fe^{III}PO_4^{3}$ obviously removes P from the water column again after these short anoxic periods.

4 Eutrophication management - challenges, possibilities and limits

4.1 River basin management - limits and future threats

Estuaries or coastal waters linked to large rivers cannot be managed independently. These coastal ecosystems depend on processes, utilisations, structures and management in the river basin. But is river basin management sufficient? Can we reach a "good" water quality status in coastal waters according to the Water Framework Directive with optimal river basin management? Recently, suggestions for reference conditions, for a very good water quality status, in coastal waters have been made (Brockmann et al. 2005). For oligohaline inner coastal waters, like the Oder Lagoon, the reference concentrations are 7.5 (0.2-0.3) mmol m^{-3} NO3 (PO4) and 15 (0.8-0.5) mmol m^{-3} for total nitrogen (total phosphorus). The Pomeranian Bay belongs to the mesohaline outer coastal waters with reference concentrations of 7.5 (0.25-0.4) mmol m^{-3} NO3 (PO4) and 14-18 (0.9-0.6) mmol m^{-3} for total nitrogen (total phosphorus). According to Brockmann et al. 2005 a good water quality can be 1.5 times higher than the reference value. The concentrations are average concentrations between November and February. For the Oder River 15 (0.45) mmol m^{-3} total nitrogen (total phosphorus) are under discussion. Nutrient concentrations are only supporting elements in the European Water Framework Directive. The Directive focuses on biological elements like phytoplankton, macrozoobenthos and macrophytes. With respect to phytoplankton, chlorophyll a is used as an algae biomass indicator. Concentrations below 1.9 mg m^{-3} chl.a in the Pomeranian Bay and below about 2 to 20 mg m^{-3} in the lagoon during the summer season can be considered as a good status (Sagert pers. com.). All values are still under discussion. In the early 1960's, the nitrate (phosphate) concentrations between November and February in the lagoon were in the range of 50 (2) mmol m^{-3} and around 9 (0.5) mmol m^{-3} in the Pomeranian Bay. All values are far above the suggested values for a good water quality.

Behrendt et al (2005) show that load reduction in the river basin above 35 % for nitrogen and 60 % for phosphorus are not realistic. The P-loads could be reduced from 12,180 t a^{-1} to 4,650 t a^{-1}. Basis for this calculation is the average load between 1993 and 1997. This is slightly below the loads of the early 1960's. The nitrogen loads can be reduced to the level of the late 1960's.

A lack of systematic changes in the nutrient limitation and ecosystem behaviour of the estuary between 1960 and 2002, and the suggested very low nutrient concentrations according to the Water Framework Directive clearly indicate that a nutrient load reduction significantly below the level of 1960 is required. The scenarios by Behrendt et al (2005) show that this will be very difficult. Phosphorus mainly stems from point sources which can be efficiently managed. For nitrogen load reductions diffuse sources have to be tackled. This is much more complicated and during recent years, the loads from diffuse sources did not show a decrease. To the contrary, a slight increase of nitrogen from diffuse sources is observed. The improvements during recent years were fairly easy to reach and at reasonable costs. Further nutrient load reductions face increasing marginal costs and increasing costs might hamper ongoing efforts. Further, Poland's membership in the European Community might lead to a growing economy and intensified agriculture. The result could be an increased nitrogen load from diffuse sources, which would counteract load reduction measures. Therefore, it is uncertain whether a reduction of 35 % will be possible for nitrogen. These results call for additional management measures in the coastal waters.

4.2 Internal eutrophication management in coastal lagoons

Especially in the Oder lagoon, several measures are possible to combat eutrophication, to remove nutrients and improve ecosystem quality:

- Mussels farms, managed mussel beds and enlarged natural mussel beds,
- algal farms,
- increased reed belts (supported by pile rows) and extended submersed macrophyte areas and
- dredging of sediment and dumping on land.

Mussel farming might serve as an example of the efficacy of these measures in the Oder lagoon. *Dreissena polymorpha* forms mussel beds in the lagoon with an estimated biomass according to Fenske (2008) of about 8,000 t in the western lagoon (Kleines Haff) und about 60,000 t in the eastern part, the Maly Zalew (Woźniczka & Wolnomiejski 2005). In the Kleines Haff, 6.56 km² (2.4 % of the area) are covered with mussel beds, the average abundance in beds is 4000 mussels per m² (varying between 864 – 10,444 mussels m^{-2}), and a filtration rate of 1,0831 l m^{-2} d^{-1} has been observed (Fenske 2008). Taking a volume of 1,026 km^3 (only Kleines Haff), the existing mussel beds need 144 days to filter this water volume. This total filter capacity can be increased by supporting measures.

One example is the supply of hard substrate to increase the natural development and spatial extent of mussel beds. About 30 % of the Kleines Haff (western bay) is covered by sandy substrate and is suitable for mussel beds. If these 83 km^2 would be covered with mussel beds, the water volume could be filtered in only 11.4 days. In natural mussel beds, only a very limited amount of nutrients is fixed permanently in the sediment. A regular dredging of mussels and a utilization of the harvested mussels on land would be an option to remove more nutrients from the system.

Mussel farming on horizontal nets, fixed above the sediment (according to Fenske), or farming based on a vertical line system (Lindahl et al. 2005) are alternative options. *D. polymorpha* settles well on horizontal nets and can reach a density of 15,000 mussels per m^2 (Fenske 2005). The existing mussels beds together with additional mussel nets covering 10 km^2 could filter the Kleines Haff volume in 21.5 days. Vertical line systems can even reach higher filtering rates and are more efficient in the utilization of the available phytoplankton, because a fast depletion of the food resource in the immediate surrounding is less likely.

According to Lindahl et al. (2005) the annual harvest of blue mussels along the Swedish west-coast is 40 kg m^{-2}. Assuming an annual harvest of only 5 kg mussels m^{-2} a^{-1} (Fenske 2008) in the Oder lagoon (due to lower depth, less turbulence and simplified net structures), an area of 20 km^2 in the entire lagoon (Kleines Haff and Maly Zalew) and a concentration of 0.06 % P and 1 % N in the mussels (Lindahl et al. 2005), we would get a removal of 1,000 t nitrogen and 142 t phosphorus for the entire lagoon. This removal would take place mainly during summer months. Compared to a recent monthly total N (total P) Oder river load for July of 2,200 t N (250 t P) mussel cultivation could play a major role in eutrophication management.

Internal management measures in the lagoon cannot replace river basin management, but might be an important supplement. Different management measures have to be combined to reach a good water quality in the Oder estuary.

4.3 Towards a comprehensive management approach

The Oder/Odra example shows that nutrient management between land and sea requires a comprehensive approach, has to link external and internal management measures and has to follow guiding principles. Firstly, the application of nutrients on terrestrial systems and their loss to the sea has to be minimized. Secondly, nutrient cycles have to be established and/or strengthened. Figure 4 shows an example: Nutrients are used as fertilizer in agriculture and are partly lost to ground and surface waters and end up in the river and finally in the sea. The application of fertilizer and agricultural practice has to be optimized, to reduce this loss. Measures in the river basin can increase the retention of nutrients. Denitrification in wetlands and tile drainage systems is one example. Vegetated strips along watercourses to reduce runoff and sediment input are another example. Measures in coastal waters, like the mentioned mussel or algal farms are another option. With the mussel or algal harvest, the nutrients are removed back to the land and end up as fertilizer in agriculture. The cycle is closed and protects the coastal waters and the sea from eutrophication.

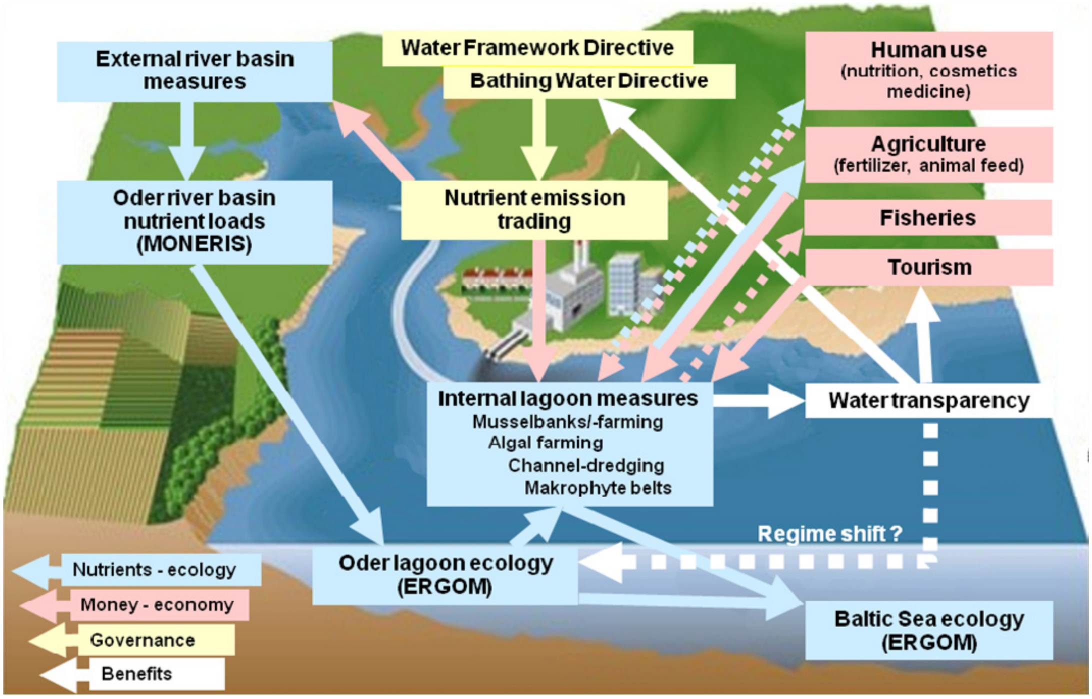

Figure 4: Conceptual model for comprehensive eutrophication management of the Oder estuary. Internal measures in the lagoon and external measures in the river basin are linked to economic and governance aspects (modified background picture after LOICZ, 2000).

Who covers the costs for internal (in coastal waters) and external (in the river basin) measures? The European Water Framework Directive (WFD) can be regarded as a major driving force for water protection. Its implementation requires cost-effective approaches. Lindahl et al. (2005) used the example of the Gullmar Fjord to compare the costs of external measures with mussel farms with respect to nitrogen removal. Mussel farming turned out to be a cost-effective method, but still requires subsidies. One solution to fund nutrient removal is a nutrient emission trading system. Polluters pay for the emission of nutrients and the money is used to fund cost-efficient internal or external removal measures. Additionally other beneficiaries could contribute to cover the costs for nutrient removal. In the case of the Oder/Odra estuary, the tourisms sector would especially benefit from improved water transparency.

However eutrophication management requires a comprehensive approach and has to consider governance and economic aspects beside ecology. The full conceptual model for the Oder/Odra estuary is shown in Figure 4.

Water transparency serves as the major link between ecology and economy. It is determined by the concentration of particles and dissolved substances and reflects the intensity of autochthonous primary production, the resuspension of sediment as well as the input of allochthonous materials. Elmgren and Larsson (2001) or Savchuk et al. (2006) show that water transparency is a suitable indicator for the state of eutrophication in Baltic coastal waters. Therefore it has been chosen as one of the environmental targets in the Swedish programme MARE and became the link between cost calculations and the nutrient modules in the MARE Decision Support System NEST (Wulff et al. 2001). In the Oder/Odra estuary this idea has been adapted.

5 Conclusions

The Oder river basin is an example of a southern Baltic river and can reveal general insights and transferable results. Other southern Baltic rivers like Warnow, Peene, Vistula, Pregola, Daugava and Nemunas are in similar situations and face similar problems. It is very likely that river basin management alone will not be sufficient to manage eutrophication in coastal waters and the Baltic Sea efficiently. Southern Baltic rivers usually do not enter the Baltic Sea directly but discharge their nutrient load into coastal estuaries, bays and lagoons. Especially large lagoons like the Oder (Szczecin), Vistula and Curonian lagoon serve as converters for nutrients, sinks and retention ponds and control the amount and composition of the nutrients entering the Baltic Sea. The analysis of internal eutrophication management measures in theses coastal systems will become a key task in the near future.

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