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Eutrophication of the shallow Szczecin Lagoon (Baltic Sea): modelling, management and the impact of weather

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Abstract

The Oder estuary, especially the large, shallow Szczecin (Oder) Lagoon (687 km^2, average depth 3.8 m) suffers from severe and ongoing eutrophication due to heavy loads, mainly by the Oder river. Poor water quality nowadays is a main obstacle for further touristic development around the lagoon. Long-term nutrient concentrations show a high interannual variability and a decline during recent years. Using a simple eutrophication box model and comparing dry, warm years (1989-1991) with colder, wet years (1986-1988) we analyse the impact of inter-annual and short-term weather conditions on the eutrophication process.

Internal nutrient cycling processes in the lagoon are mainly driven by short-term weather conditions. During rare and short calm summer periods a stratification and oxygen depletion above the sediment is likely. Coarse model-based estimations indicate an anoxic P-release from sediments of up to 10 µmol P $m^{-3}d^{-1}$ or up to 400-600 t P for the entire lagoon. These situations are restricted to several days and occur only in a few years. Wind with a daily average velocity above 2-3 m/s cause mixing and put an end to anoxic P-release. Compared to a monthly summer load of 100-150 t P by the Oder river, internal eutrophication in the lagoon is important, but has no pronounced effect on biology.

In wet years the P and N load with the Oder river can be up to twice as high compared to dry years. Discharge and load by rivers control the nutrient dynamic in the Szczecin Lagoon, to a high degree. The observed reduction in nutrient concentrations in early 90's is an effect of the warm, dry years and cannot be attributed to anthropogenic nutrient load reductions. Management implications are discussed.

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1 Problems and management challenges in the Oder estuary

The large Oder-catchments is located at the German-Polish border. With a surface area of 120,000 km^2 and a population of about 13 Mio inhabitants it is responsible for the heavy nitrogen and phosphorous load of the Oder river. In recent years, about 63,000 t total N/a and 3,500 t total P/a were transported with the Oder towards the Baltic Sea. The river therefore is the most important source of eutrophication and pollution for the south-western Baltic Sea. The respective coastal zones, especially the Szczecin (Oder) Lagoon, suffer from severe eutrophication, heavy algal blooms of potentially toxic species, high water turbidity and even hygienic quality problems [1].

The Szczecin Lagoon is a key element of the Oder river estuary. It is a large (687 km^2) and shallow (average depth 3.8 m) coastal flow lake. The lagoon consists of two main parts - Kleines Haff on the German side and Wielki Zalew located on Polish territory (Fig. 1). The Wielki Zalew comprises about 60 % of the lagoon area and volume. A theoretical water exchange time of the entire water body is about 2 months, but its western part (Kleines Haff) receives only between 10 % and 20 % of the Oder water [2].

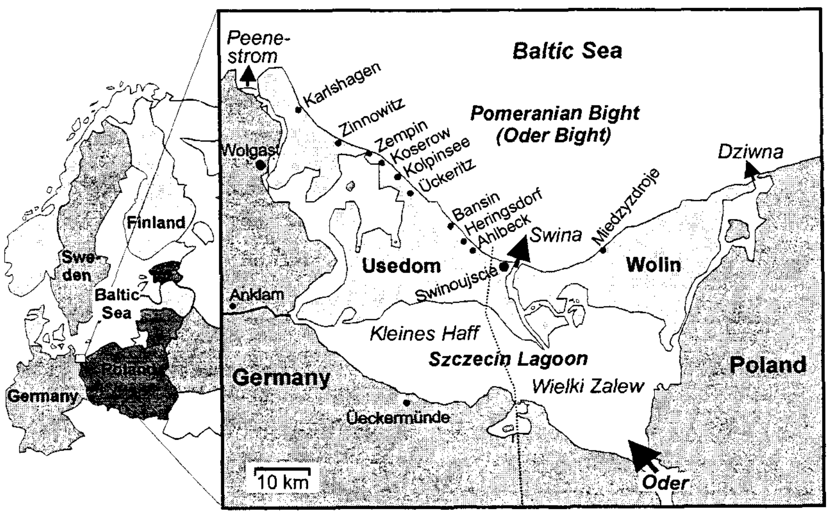

Figure 1: The Oder estuary at the German/Polish border

Along the southern Baltic Sea coast and especially on the islands of Usedom and Wolin located in the Oder estuary, bathing and summer tourism has a long tradition and is the most important economic factor, both on the German and Polish side of the border. The island of Usedom, for example, registered over 5 Mio guest nights in 2000 [3]. At the same time this remote region suffers from severe economic problems, with a high rates of unemployment e.g. above 20 % on the German side. Further growth in tourism industry is desired and regarded as the most important measure to abate the economic problems. Therefore considerable efforts are undertaken to extend tourism towards the hinterland and to develop the coasts of the lagoons. Especially the shallow Szczecin (Oder) Lagoon with its high water temperatures (often above 20° already in May) is generally suitable and competitive for bathing. Right now, severe signs of eutrophication and insufficient water quality are a main obstacle for further tourism development around the lagoon and a sustainable economic development.

Against this background, the requirements resulting from the implementation of the EU-Water Framework Directive Water as well as the needs of the integrated management plan of the Oder estuary, water quality management tools are urgently needed.

We show the course of the long-term eutrophication in the lagoon and present and apply a simple eutrophication box model, that is suitable to tackle water quality management problems. The goals are to show the impact of interannual and short-term weather conditions on water quality and the eutrophication process by comparing dry, warm years (1989-1991) with colder, wet years (1986-1988) and to answer the question what extent the lagoon is driven by internal and external processes.

2 The eutrophication box model

The first step of the modelling approach resulted in a simple dynamic model, that considers the two parts of the lagoon as two separate boxes, since they differ distinctly in water retention time. Modelling of the eastern part (Wielki Zalew) which is the first recipient of the Oder river waters was done as first step in development of the lagoon box model.

The model at this stage consists of 7 state variables, namely: DIN, PO_4, detritus (suspended organic matter) nitrogen and detritus phosphorus as well as nitrogen and phosphorus in the sediment and one phytoplankton group (Fig. 2). The phytoplankton state variable is expressed only in nitrogen units which can be converted to phosphorus using the Redfield N:P-ratio of 16:1. The model covers the dominant internal nutrient transformation processes in the estuary: nutrient uptake by phytoplankton, mineralisation, sedimentation, denitrification of nitrogen from water and sediment and loss to the atmosphere as well as burial of nutrients in sediment. The model is driven by external forces such as the seasonal changes of light and temperature, the nutrient loads discharged with the Oder river and from point sources in the immediate lagoon drainage area. In order to make long-term simulations possible, the internal time scale of the model is one day. The model does not take into account temporary, local inflows of Baltic Sea water.

Primary production is driven by solar radiation as well as phosphorus and nitrogen uptake. Temperature dependency of phytoplankton growth is based on a modification of the Epply expression by Savchuk and Wulff [4]. Zooplankton was considered to be of minor importance in the lagoon. The maximum phytoplankton growth rate was limited to a value of 1 d^{-1} to mimic limited increase in its biomass in summer months, when grazing might take place. Light dependency of phytoplankton growth is based on the modified Steel's equation from

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Savchuk and Wulff [4]. Nutrient uptake is described by Michaelis-Menten formula. Sedimentation of phytoplankton and detritus to the bottom is assumed to takes place at the same low rate of 0.07 d^{-1}. The shallow, large lagoon is characterized by high turbulence and intensive wind induced mixing that prevents material from settling. The algae mortality transfers organic nutrients to the detritus pool in water. Mineralisation of nutrients, both in water and sediment is described by the same temperature dependent process. Regenerated nutrients, both from water and sediment, directly enter the dissolved pool in water. Denitrification in water and sediment depends on temperature in a similar manner like mineralisation. Despite high availability of nitrate as substrate in water, denitrification in sediment is quantitatively more important, because the necessary low oxygen concentrations are prevailing in the sediment more often than in water column. Burial of nutrients in the sediment is proportional only to the amount of nutrients available in the sediment.

From interpolated monthly flow and monthly nutrient concentrations, the Oder river nutrients inputs are calculated on a daily basis. The difference between total and dissolved nutrient forms is regarded as detritus. This means, that a die off is assumed. It is supported by observations, that the phytoplankton composition changes when the river enters an estuary. The nutrient output towards the Baltic Sea is calculated from riverine inflow and nutrient concentrations in the lagoon. Since the entire lagoon is regarded as one box, there is no time lag between inflow and outflow.

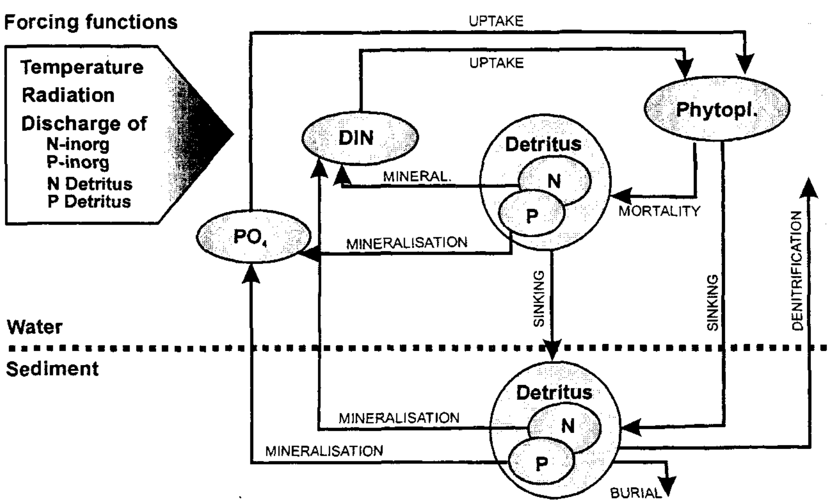

Figure 2: Conceptual model of the Szczecin Lagoon.

Oder river nutrient concentrations used in the model were obtained from the Westpomeranian Inspectorate of Environmental Protection in Szczecin/Poland, data about the monthly Oder River flow were taken from the IMGW [5] and daily average values of light were obtained from NOAA http://www.cdc.noaa.gov/.

3 Long-term eutrophication of the Szczecin (Oder) Lagoon

The lagoon is directly and heavily effected by the nutrient load of the Oder river due to its location and morphometry. Chlorophyll a-concentrations are about 5 times, inorganic nitrogen concentrations 3 times and phosphate concentrations 2 times higher compared to the adjacent coastal Baltic Sea near Ahlbeck [3].

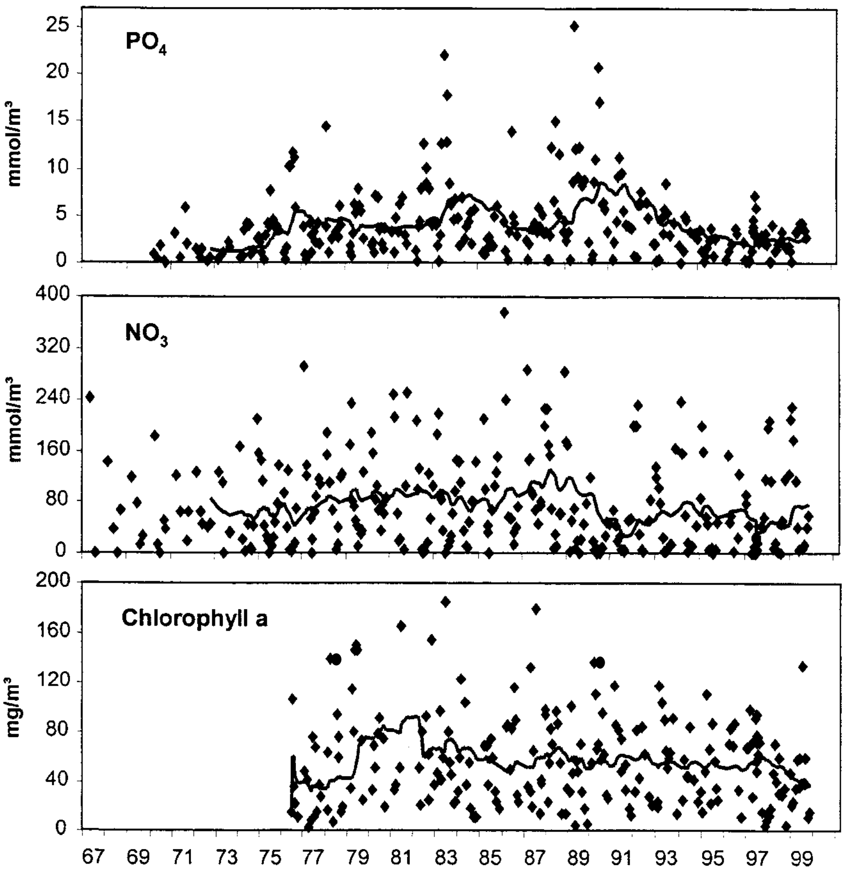

Figure 3: Near surface concentrations of PO_4-P, NO_3-N and Chlorophyll a in the central Szczecin (Oder) Lagoon (at the Polish/German border) between 1967 and 1999. The solid line indicates the moving average (compilation of data supplied by StAUN, Ueckermünde and LUNG, Güstrow).

The long term monitoring observations indicate, that phosphate concentrations in the lagoon increased in the 70's, reached their maximum in the early 90's and decreased afterwards (Fig. 3). In the late 80's a significant temporal drop of the concentrations was observed. Between 1989 and 1991 several PO_4-values were exceptionally high and exceeded 15 mmol/m³.

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The long-term trend in inorganic nitrogen concentrations is less pronounced (Fig. 3). Already in late 60's high values of about 70 mmol/m³ were observed. The concentrations increased until the late 80's and declined in the 90's. Between 1977 and 1997 the concentrations of Chlorophyll a (Fig. 3), as an indicator of algae biomass, are more or less stable. In recent years a decline is implied. Characteristic is the high variability of the values.

4 Impact of weather variability on eutrophication

We compared the impact of cold, wet years and warm, dry years on water quality and trophic parameter in the lagoon on the basis of data and model simulations. By comparing two periods differing significantly in weather conditions we tried to find out if other internal processes, not included in the model, might play an important role in nutrient cycling in the lagoon.

The long-term phosphorus concentrations in the lagoon (Fig. 3) and to a minor degree nitrogen concentrations, too, showed significant differences between the periods 1986-1988 and 1989-1992. Between 1989-1992, the average annual concentrations of total phosphorus in the Oder river (15.3 mmol/m³) were slightly higher compared to the previous period (12.8 mmol/m³) [6]. Between 1986 to 1988 the years were wet with an average annual Oder discharge of 620 m³/s compared to 340 m³/s in the following years. This large discrepancy explains the decline of the phosphorus loads by about 40 % (Fig. 4). Differences in nitrogen load were even more pronounced and decreased by more than 50 %. The reason are the higher average annual nitrogen concentrations in the late 80's of 290 mmol/m³, compared to 250 mmol/m³ in the following period.

Discharge [m³/s]	559.8	685.1	622.6	393.7	299.6	324.4	360.0
DIN [t/a]	64,100	86,600	75,200	42,500	27,900	34,400	42,200
TP [t/a]	7,000	7,300	7,400	6,000	4,800	4,700	4,000

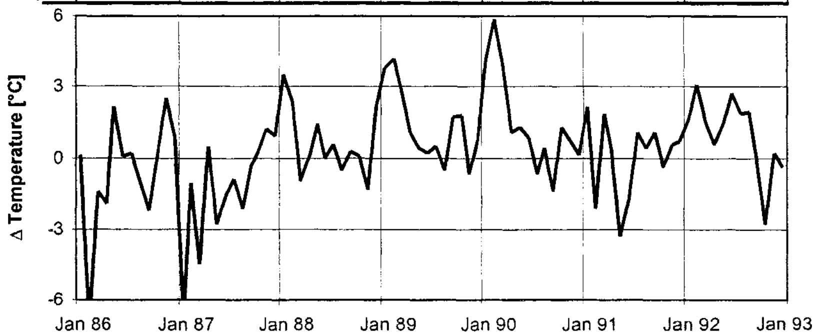

Figure 4: Table: average annual Oder discharge, dissolved inorganic nitrogen (DIN) and total phosphorous (TP) load between 1986 and 1992 near Schwedt, 116 km river upstream. Data by Behrendt et al. [6]. Figure: Monthly differences in air temperatures during the period 1986 and 1993 compared to the long-tern average (1975-2000). Data source: Deutscher Wetterdienst (DWD).

With respect to air temperatures, the years 86/87 showed an annual average of 1° C below the 25 years average. 89/90 on the opposite, are 1.3 °C warmer than the long-term average. In both years, warm winter and spring temperatures contributed a great deal to the increased average annual temperatures. This is different in 1992 where unusual high summer temperatures were recorded.

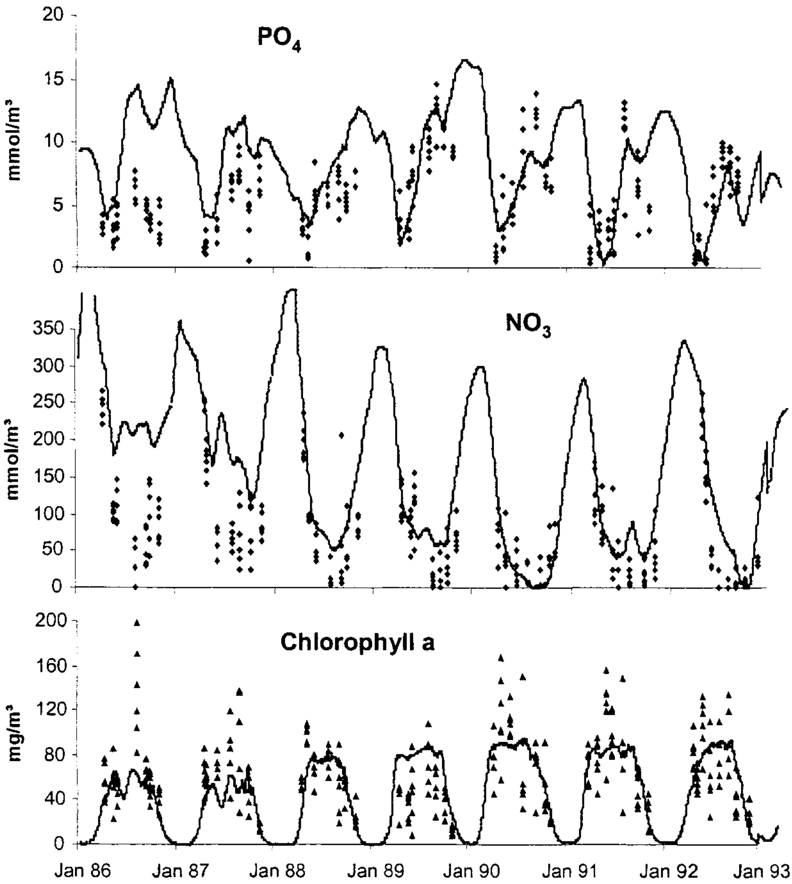

Figure 5: Comparison between data (sub-surface measurements in central Wielki Zalew, data from Westpomeranian Inspectorate of Environmental Protection Szczecin) and model simulations (solid lines).

The model simulation is well in agreement with measured nitrate, phosphate and chlorophyll-concentrations during these seven years. As mentioned before, the chlorophyll-concentrations show a strong variability, especially during the summer month. The summer phytoplankton in the lagoon is dominated by blue-green algae, which have a strong floating ability and show sub-surface accumulations and often strong scum formation on the surface. The model assumes one water layer and calculates depth-averaged values. It therefore cannot account for this kind of temporary, vertical heterogeneity within the water column. The model reflects the changing DIN to PO_4 ratio in the lagoon corresponding to the nutrient ratio of the inflowing riverine waters [7]. Like other temperate zone estuaries [8], the lagoon tends to nitrogen limitation in summer. Phosphorus plays a role as a limiting element only in spring, indicated by low PO_4 values between April and June (Fig. 5). However, especially in the eastern part of the lagoon even intensive phytoplankton blooms during summer usually do not deplete nutrients. The reason is the constant nutrient supply by the Oder. Due to self-shading effects and high water turbidity as a result of sediment resuspension light becomes a scare resource.

In the following, we focus on the high phosphorus concentrations that are visible at single dates in the summer of 1989, 1990 and 1991 in the Kleines Haff (Fig. 2) and are even more pronounced in Figure 5 in the Wielki Zalew. The general performance of the model during summer month is satisfying, but the model fails to simulate these short-term situations in a proper manner. Processes that are not taken into account might have played an important role at that time. We studied the phosphorus budget of the Kleines Haff, because the data shows that internal processes have a more pronounced impact in the Kleines Haff, due to longer retention times of the riverine waters than in the Wielki Zalew.

During the interval between 8.6.1989 and 11.7.1989, the PO_4-concentrations in the entire Kleines Haff increased by 4 times from about 5-6 mmol/m^3 to 20-25 mmol/m^3. This increase was observed at 5 stations in the German part of the lagoon (Fig. 6). In 1990 a doubling to 16-24 mmol/m^3 was observed between 11.7.90 until 16.8.90 and in 1990 another very strong increase by in average 8 mmol/m^3 was found in a 4 weeks interval until 16.7.91. It is nearly impossible to address differences in nutrient concentrations measured on a monthly basis to defined short-term processes, because processes causing additional P-release are superposed by mineralisation and riverine input. We therefore don't compare the measurement dates, but the high measured value with the prediction of the model. The model simulation takes increased mineralisation due to high water temperatures as well as the impact of the Oder river into account. The Oder river load during summer is more or less constant and significant effects on short-term alterations of the concentrations in the lagoon were not observed. Comparing simulated PO_4-concentrations with measured values yields an average underestimation of about 6.7 mmol/m^3 (1989), 10.6 mmol/m^3 (1990) and 3.6 mmol/m^3 (1991). For the Kleines Haff, with a surface of 277.3 km^2 and a volume of 1.026 km^3, 221 t P (1989), 347 t P (1990) and 117 t P (1991) were obviously additionally released into the Kleines Haff by other processes during short-terms in summer.

All three periods in July 1989, August 1990 and July 1991 show similarities with respect to the weather conditions before the sampling date. Between 5.7.89 and 10.7.89 sunny days with high radiation, unusual daily maximum air temperatures between 25°C and 33 °C and low wind speed (daily averages between 1-2 m/s) prevailed. On 10.7.89, one day before sampling date, stronger wind (daily average 4.2 m/s) was observed. The period from 10.8.90 until 15.8.90 as well as the period 10.7.-15.7.91 showed maximum air temperatures between 23-27°C resp. 21-26°C and always average daily wind speeds below 2 m/s with several entirely calm days. Both sampling days showed higher average wind speeds of 3.3 m/s resp. 4.5 m/s. It is very likely, that during all three periods a stable stratification developed for several days and caused fast oxygen depletion near the sediments. Stronger winds on the sampling days and one day before put an end to these calm conditions and caused entire mixing.

Due to the shallowness and size of the lagoon a pronounced stratification is only temporarily and in spatial limited to the deepest regions. In some cases, H_2S was mentioned in deeper central water layers [Dahlke, pers com], indicating an anoxic sediment surface. Long-term monthly oxygen measurements 1 m above deeper sediments never showed an oxygen depletion [9]. The temporal resolution might have been too coarse to meet single short-term events, but this observation excludes longer oxygen depletion over periods of several weeks.

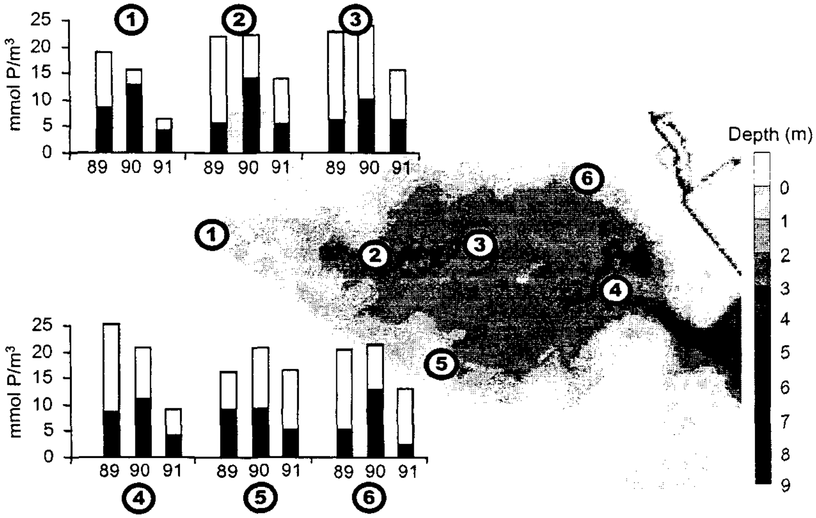

Figure 6: Sub-surface phosphorus concentrations at 6 locations in the Kleines Haff. The black bars indicate concentrations on 5.7.89, 11.7.90 and 10.7.91. The white bars indicate the increased values 4-5 weeks later (10.7.89, 16.8.90, 15.7.91). Data provided by LUNG, Güstrow.

It is well known, that oxygen depletion at the sediment surface can cause a strong release of phosphorous from the sediment into the water body, the so called internal eutrophication [10,11]. This is especially true if large amounts of phosphorous are bound to iron. This is the case in the lagoon, where Fe-concentrations between 2 % and 6 % were found in surface sediments [12] and Fe-redox processes can be expected to play a major role in P dynamics. Dahlke [pers. com.] measured several vertical pore water profiles in the sediments in 1994 and 1995. An increase in P-concentrations, from about 10 mmol P/m³ below the sediment surface to 20-40 mmol P/m³ in a depth of 10 cm, depending on the date, was found. These concentrations are about 2-3 times higher compared to the concentrations in the water body. About 13 t dissolved phosphorus are stored in the pore water of the upper 10 cm sediment layer of the Kleines Haff and are available for a fast release. The surface sediments (0-6 cm) of the Kleines Haff contain about 0.36 % P. This concentration decreases with increasing sediment depth. We can assume that at least 10.000 t P are stored in the upper 10 cm of the 61 % muddy sediment surface of the Kleines-Haff [12]. The opposite vertical gradients between pore water and particulate phosphorous suggest that dissolution from particulate phosphorus compounds maintain the pore water gradient and flux towards the surface. During this process the amount of particulate P in deeper sediments is decreasing with time. High amounts of P bound to iron and a fast P-transport from deep sediments are a feature often observed in iron-rich eutrophied lakes [10, 11]. We can assume, that large amounts of phosphorus in sediment are available for an anoxic release in the lagoon, too.

Taking into account only the 4-5 calm days before the sampling dates in July 1989, August 1990 and July 1991, where oxygen depletion at the sediment surface was likely and a fast P-flux from the sediment possible, we get release rates between 2 μmol P $m^{-3}d^{-1}$ and 10 μmol P $m^{-3}d^{-1}$. The values show the range between the three dates and were calculated on the basis of the 6 sampling stations Figure 6 suggests spatial differences in the release rates, with increased values in the deepest parts of the lagoon, where muddy sediments, with higher P-content prevail [12,13]. Lowest values are found near the outlet, which is influenced by water from adjacent lagoons. The calculated release from sediment is not high when compared to eutrophic lakes [11]. P-contents in pore water are not sufficient to explain the total release from the sediment. Large amounts of P have to be contributed from solids and require a dissolution from particular Fe/P compounds first.

5 Discussion

Our calculations for internal P-release from the sediment have been made on a general basis and several processes as well as spatial differences between them remain to be investigated in detail. Problematic is this respect is that these events are rare and not easily predictable. However, the model proved to be a valuable tool for the analysis and interpretation of the data and several aspects with relevance for practical management can be stated. Internal anoxic P-release from Szczecin Lagoon sediments takes place only during short calm summer periods and up to 400-600 t P might be released from the sediment into the entire lagoon during several days. Data indicates that internal P-release from sediments is less pronounced in Wielki Zalew. Intensive mixing by the Oder river and intensive ships traffic might be the reasons. Average daily wind velocities above 2-3 m/s are sufficient to cause mixing down to the bottom, to transport oxygen towards the sediment and to put an end to anoxic release. Compared to a monthly summer load of 100-150 t P by the Oder river our calculations indicate that internal eutrophication in the lagoon is an important process. Different to most lakes, phosphorus does not play a role as limiting element for summer production and algae blooms in the lagoon. Additional phosphorus released from the sediment therefore is not taken up by algae and a release event and increased concentrations are visible even after weeks. The biological effect of the internal eutrophication in summer therefore is negligible. An important uncertainty is the unknown precipitation rate of P with iron and calcite.

Pronounced influences of warm or cold years on internal nutrient cycling processes in general were not observed. Internal nutrient cycling processes in the lagoon are influenced mainly by short-term weather conditions. Nevertheless, Schmidt [9] points out that cold and warm winters cause different annual phytoplankton successions. After cold winters the likelihood of blue-green algae blooms and scum formation is much higher. We can conclude, that the system is driven only to a minor degree by the impact of weather variability on internal processes. The lagoon depends on external factors, namely the load and discharge of the river Oder.

The example of the wet years 1986-1988 compared to the dry years 1989-1992 showed, that the phosphorus as well as the nitrogen load in wet years can be up to twice as high compared to dry year. For these comparisons, we used reliable long-term data by Behrendt et al. [6] for the station Schwedt, 116 km river upstream. The additional load entering the river downstream or entering the lagoon with other small rivers small accounts for additional several percent [14,15]. Weather conditions have a significant impact on processes in the large catchments area and the catchments area controls the Szczecin Lagoon. Interannual variability of nutrients loads caused by weather conditions superimpose changes caused by human activity. Due to the large catchment area and long retention times especially of nitrogen, anthropogenic load reductions are usually below 10 % per year. We therefore can state, that the loads reduction from the late 80's to the early 90's are a result of the wet resp. dry years This is true for other Polish rivers, too [16]. We neither can say that the recent decline in P-concentrations in the lagoon reflect improvements in sewage treatment in Germany and Poland. Nor can we say that the transition of agriculture starting at early 90's in Poland, with reduced use of fertilizer, is already visible in the lagoon [7]. To get a reliable interpretation of long-term trends, a differentiation between anthropogenic and weather influences is necessary.

Nutrient concentrations in the lagoon can only be reduced by measures in the catchment. The poor water transparency in the lagoon is a result of high primary production and sediment resuspension. To obtain a macrophyte dominated system, measures in the catmnent as well as in the lagoon itself are necessary.

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