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The PIONEER-Project in the Odra Lagoon – Modelling the Ecosystem with ERSEM

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Abstract

Article deals with the implementation and testing of short term forcast systems as well as the application of data assimilation schemes on ecosystem models. The goal is to forcast the hydrodynamical and bio-chemical conditions within two areas. These two areas - the Ebro delta and the Odra lagoon and river respectively are characterized by different hydrodynamical and climatological conditions as well as their present anthropological impact.

1. Motivation

Within PIONEER – a MAST-III project which is funded by the EU's 4th framework – techniques for the day-to-day monitoring, analysis and short-term prediction of nutrient and related suspended matter distributions in estuaries (Odra and Ebro) are developed. Point observations together with a "best guess" are processed in data assimilation schemes. As a by-product, the project will offer estimates of the predictability of the estuarine ecosystems on time scales of days and weeks. The project integrates presently available technology and methodology in data management, geostatistical and dynamical data assimilation and numerical modelling in co-operation between scientific institutions, management authorities and commercial companies.

The following article focuses on the application of an ecosystem model within the Odra Estuary. The work described hereafter is part of the PIONEER project. First results are discussed, showing different aspects of the implementation of a generic ecosystem model in this area.

2. Integration of ERSEM within a Modelsystem

In the following components of a modelsystem applied to the Odra Lagoon will be discussed as far as they belong to the ERSEM ecosystem model in that sense that they deliver relevant boundary or intial data to this model.

The modelsystem consists of three major components – a hybrid shallow water model HYPAS, which is deployed in order to calculate the time dependent local wave field within the Odra Lagoon. TRIM3D is used to simulate the current and water field within the lagoon using as boundary informations the local wind field, sea level information at the entrances into the Southern Baltic Sea and the discharge rates of the Odra river itself. The development of the ecosystem of the Odra Lagoon is simulated with the generic ecosystem model ERSEM which is implemented for several compartment configurations.

2.1. Implementation of the Hybrid Shallow-water Wave Model HYPAS

HYPAS – a hybrid parametrical shallow-water wave model of the 2nd generation (Günther, Rosenthal 1983, Günther et al. 1984, Winkel 1994) – was set up in the lagoon on a numerical grid having $\Delta x = 500$ m. The time step for the model was $\Delta t = 60$ s. The model was run with 4449 active sea points giving a ratio between real and CPU time of $T_{real}/T_{CPU} \approx 30$ and a "turnaround" ratio of $T_{real}/T_{ta} \approx 10$ on a CRAY-C90. The directional discretization of the wave model was chosen to be $\Delta\Theta = 15°$, with having a nonequidistant resolution on the frequency axis, such that F_i = 0.1250, .1350, .1625, .1875, .2125, .2375, .2625, .3125, .4075, .4400, .4800, .5200, .5600, .6000, .6400, .6800, .7200 s^{-1}. The model calculates both integrated wave field parameters and the full 2-dimensional wave spectra.

HYPAS has been tested and validated successfully under a wide range of conditions and is in operational use by several governmental services in the area of the North Sea and the Baltic Sea. A comparison of performance and accuracy with other wave models can be found for shallow-water applications within the SWIM-report (SWIM 1985) and for deep-water conditions in the SWAMP-report (SWAMP 1985).

2.2. The Hydrodynamical Model TRIM3D

In the area under investigation, several projects were launched in the past, which already gave a large amount of information about the complex hydrological behaviour of the Odra Lagoon. The implementation and application of a baroclinic three-dimensional model in the lagoon and the response to severe storm events were given in (Jasińska, Nöhren 1988) and (Nöhren et al. 1992). The importance of different physical processes and their impact on the hydrodynamics of the water were investigated by (Pfeiffer, Walkowiak 1988) and (Jasińska et al. 1992). Water exchange processes between the lagoon and the Baltic Sea have been the subject of different investigations (Correns 1973, HELCOM 1986, Rosenthal et al. 1998). Exchange balances based on 2-dimensional hydrodynamical modelling were given for a few years by the GOAP-project Buckmann 1996.

For the present study, the hydrodynamical model TRIM3D (Casulli, Cheng 1992, Casulli, Cattani 1994) has been implemented in the area on a three-dimensional grid with a spatial resolution of $\Delta x = 250$ m and 15 vertical layers giving a total number of 85000 active model points. The model was run in baroclinic mode with a time step of $\Delta t = 60$ s.

River discharge of the Odra was described by discharge rates at the southern tip of Jezioro Dabi (Dammscher See). The seaward boundaries of the numerical model were described by water levels at the inflow locations of the three outlet channels – Peenestrom, Świna and Dziwna – into the Pomeranian Bight. The boundaries of the outlets were controlled by water levels of water gauge Koserow. Via these three branches the lagoon is connected with the water level variations in the open sea (Hela 1944, Wuebber, Krauss 1979) which affect the water levels in the lagoon with a time delay of a few hours and exert an important influence on the flow and water-exchange regime within the lagoon.

2.3. The Ecological Model ERSEM

The ecological part of the model consists of a number of sub-models of the ERSEM-II model (Baretta-Bekker et al. 1995) which are interlinked and which describe the biological and chemical processes in the water column and in the benthic system (Blackford, Radford 1995). The dynamics of the biological functional groups are described by physiological processes (ingestion, respiration, excretion, egestion etc.) and population processes (growth, migration and mortality). Biological variables in the model are phytoplankton, variables related to the microbial loop, zooplankton and benthic fauna (Varela et al. 1995, Ebenhöh et al. 1997, Baretta-Bekker et al. 1995, Baretta-Bekker et al. 1997, Broekhuizen et al. 1995, Ebenhöh et al. 1995, Blackford 1997). The nutrients dynamics are fully coupled to the biologically driven carbon dynamics. Early diagenetic transformations and fluxes of organic matter and nutrients in the sediment are included in the model (Ruardij, van Raaphorst 1995)

Based on size and ecological properties, the total phytoplankton pool is subdivided into four functional groups, which are diatoms, flagellates, picophytoplankton and in-edible phytoplankton (see Fig. 1). Picophytoplankton rapidly grows and is grazed by heterotrophic flagellates. Despite their larger size diatoms grow faster than flagellates (Ebenhöh et al. 1997). In-edible phytoplankton is a slow grower due to the fact that the maintenance of its inedibility is an energy consuming process. All phytoplankton groups contain internal nutrient pools and thus have dynamically varying C:N:P:(Si) ratios. The nutrient uptake by phytoplankton is controlled by the difference between the external nutrient concentration and the internal nutrient pools. The growth rate is dependent on the internal quota (Droop 1973). The pelagic consumers consist of five groups also based on their ecological function and size (see Fig. 1). In the benthic system is divided in a oxic and an

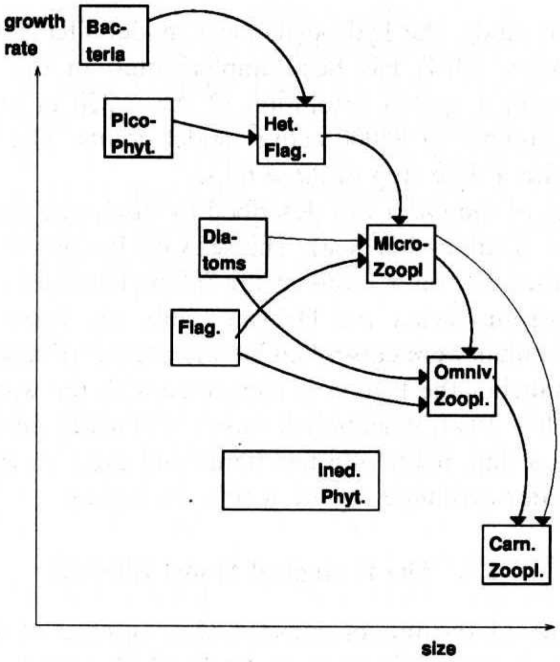
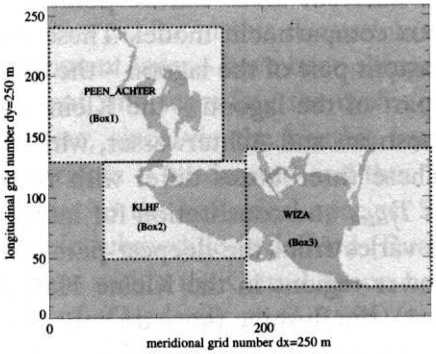


Fig. 1. Schematic food web of ERSEM

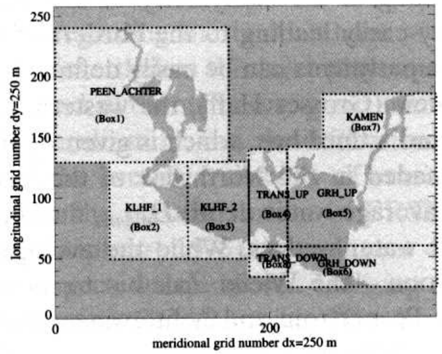
anoxic layer. The thickness of this layer is controlled by the oxygen consumption in the benthic system. In the oxic layer 5 consumers groups are distinguished: meiofauna, deposit feeders, filter feeders, epibenthic predators and internal predators. They all depend directly or indirectly on the carbon input which arrives in the system by sedimentation or filtering. In each layer a group of bacteria are present and they play an essential role by digesting the detritus and being available as food for the other consumers. Each consumer group in this model by eating food regenerate nutrients which on its turn is available again for uptake by the primary consumers.

3. Implementations of ERSEM within the Odra Lagoon

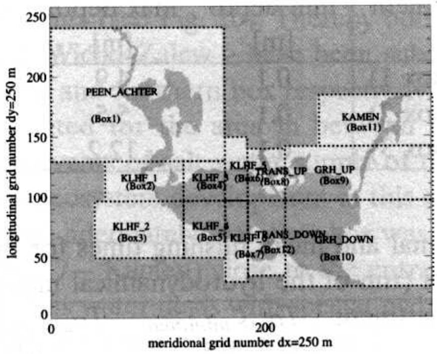
ERSEM is implemented within the lagoon using different subdivisions of the water body, which were defined according to a set of topographical, sedimentological and hydrodynamical arguments (see Fig. 2). The goal is to moderate between the requirements and inherent limitations of an ERSEM implementation which arise due to the big number of prognostical variables and the application of the model within data assimilation schemes of the Ensemble Kalman Filter (EnKF) type on one hand and the aim to take into account the locally changing environmental conditions and their influence on the ecosystem on the other hand.



(a) 3-box model



(b) 8-box model



(c) 12-box model

Fig. 2. Three compartment models of ERSEM within the Odra Lagoon. Compartment borders have been defined according to topographical, sedimentological and hydrodynamical arguments respectively

Especially the application of the EnKF data assimilation technique gives strong limitations to the number of applicable boxes, since the numerical efforts increase linearly with the number of boxes going quickly beyond the possibilities of available computer systems.

Therefore within the lagoon three different compartment models of increasing complexity – a 3-box, a 8-box and a 12-box model – were defined (see Fig. 2).

3.1. The 3-box model – Topographical Arguments

A first compartment model was defined according to findings of the topography (see Fig. 2a). Except for the implementation of a 1-box model (Fennel 1999), this 3-box model is the most simple adequate representation of the water. While looking at the bathymetry of the area three different areas can be pointed out very easily leading to the borders of the 3-box compartment model. These three compartments can be easily defined by the eastern part of the lagoon – the Wielki Zalew (Grosses Haff), the western smaller part of the lagoon – the Kleine Haff – and a third box, which is given by the Peenestrom and Achterwasser, which are situaded in the Northwest of the lagoon. These three boxes differ with respect to average water depth D_{mean}, flushing times T_{flush} and constitution for intruding salt water wedges. While the average depth varies from the deepest part of the lagoon – the Wielki Zalew – to more shallower regions in the Kleine Haff and the Peenestrom and Achterwasser (see Table 1), the flushing times do vary as well (see Table 2).

Table 1: Depths and volumes for the compartments of the 3-box model (horizontal resolution of the original depth field ΔX=250 m)

Compartment	min depth [m]	max depth [m]	mean depth [m]	volume [km^3]
PEEN_ACHTER (Box 1)	0.1	4.9	2.2	0.357
KLHF (Box 2)	0.1	5.5	3.4	0.833
WIZA (Box 3)	0.1	12.2	3.6	1.635

Table 2: Minimal, maximal and mean flushing times for the compartments of the 3-box model (run of the hydrodynamical model for 1997)

Compartment	$T_{flush,minimum}$ [d]	$T_{flush,maximum}$ [d]	$T_{flush,mean}$ [d]
PEEN_ACHTER (Box 1)	8.7	26.3	16.9
KLHF (Box 2)	10.1	38.7	27.4
WIZA (Box 3)	7.7	29.6	18.6

The flushing times – the times which are necessary to replace the whole volume of a compartment box by inflowing water – give an indication how long the water will reside within this single compartment box and how fast the nutrient reservoirs could be filled up and replaced by other water masses coming from other parts of the lagoon or the Odra river itself. Therefore flushing times are important parameters to determine, whether the influence of outer boundaries will prevail the environmental conditions of the box itself or vice versa, thus whether the development of the ecosystem in the compartment box under investigation will be dominated by exterior or interior factors and conditions.

3.2. The 8-box model – Sedimentological Arguments

In the discussion of previous section 3.1 topographical arguments have been stressed in order to give reasons for a subdivision of the water into compartments according to their environmental conditions and their exposure to exterior influences. So far in this discussion arguments regarding the benthic layer – say the sediment layer – have been skipped totally. Nevertheless this layer plays a very important rule regarding the cycles of carbon and nutrients in any given marine ecosystem, since via the benthic layer the mineralization and denitrification of the nutrients is moderated and thus influences the overall availability of nutrient resources to the biological species. Since within the present version of ERSEM a benthic submodule is defined (Ruardij, van Raaphorst 1995) the sediment distributions within the Odra Lagoon have been inspected more closer. Utilizing the results of (Osadczuk et al. 1996) and the foregoing GOAP project (Osadczuk, Wawrzyniak-Wydrowska 1998) several possibilities became obvious regarding the subdivision of the lagoon with respect to the underlying sediment layer. Having in mind the strongly limited number of boxnumber due to foregoing described application requirements another subdivision of the lagoon was defined according to sedimentological arguments (see Fig. 2b). Thereby both central compartments – the Kleine Haff and the Wielki Zalew – have been subdivided into an western and eastern and a northern and southern box respectively. Moreover additionally boxes have been implemented for the area in between these two main basins. Thereby special intrusion events of salt water supply of the Southern Baltic Sea and their influence on the ecosystem development in this special area are likely to be taken into account more adequately. Another box was defined for the area of the Zalew Kamieński (Box 7 – Kamen) close to the entrance of the Dziwna into the Southern Baltic Sea. This water deals with special hydrodynamical conditions, low water depths and very small water exchange rates.

3.3. The 12-box model – Hydrodynamical Arguments

Regarding the hydrodynamical conditions within the Odra Lagoon we can notice that the current patterns and the water level are governed by the discharge of the Odra river, the local wind field, the water level elevations at the entrances of the lagoon into the Southern Baltic Sea and the Seiche modes of the water itself. Ecosystem development always is connected with the actual environmental and especially hydrodynamical conditions in the water which determine advection and supplys of nutrients and fresh water, the exchange and transport of biological active components and the anorganic constituents. Looking at the strong limitations which are given for the ERSEM implementation it is obvious that the number of compartments has to be kept strictly small. Since the application of data assimilation tools is time consuming these restrictions apply. Obviously it is not possible to present the complex hydrodynamics of this water with a more or less crude subdivision of the water. Nevertheless looking at different wheather situations it turned out, that the current pattern within the lagoon change quickly and will show only small persistency in time. Watching those fast changes in the current regime the patterns as eddies and streams seem to give an 'smearing out' effect regarding different water bodies and gradients of nutrients or salt. In contrary to the situation found in the open Baltic Sea, where eddies e.g. in the Gotland Sea will maintain there structure for weeks and will govern the interaction between the biological entities and nutrient supply during e.g. spring bloom, the patterns in the Odra lagoon will not exert such a big influence, regarding the formation of special conditioned water bodies under which the ecosystem evolves. Thus a box-model or compartment approach seems to be justifiable by these characteristics of the water also with respect to the hydrodynamics.

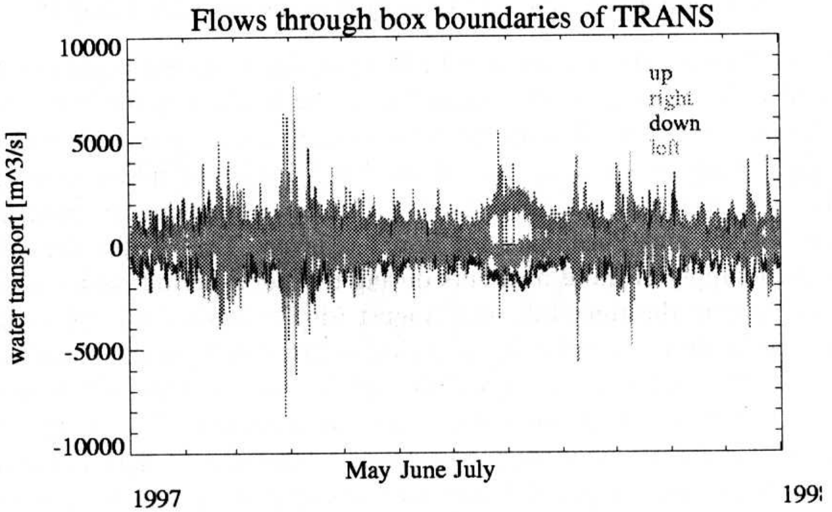
Nevertheless a compartment model can not represent the hydrodynamical current pattern adequately the attempt has been made to take into account at least a few major features which are known to occur during various wheather conditions. Thus the 'Kleine Haff' has been subdivided in a northern and a southern part, where in which the current system can often be distinguished (see Fig. 2c).

4. Simulation Runs

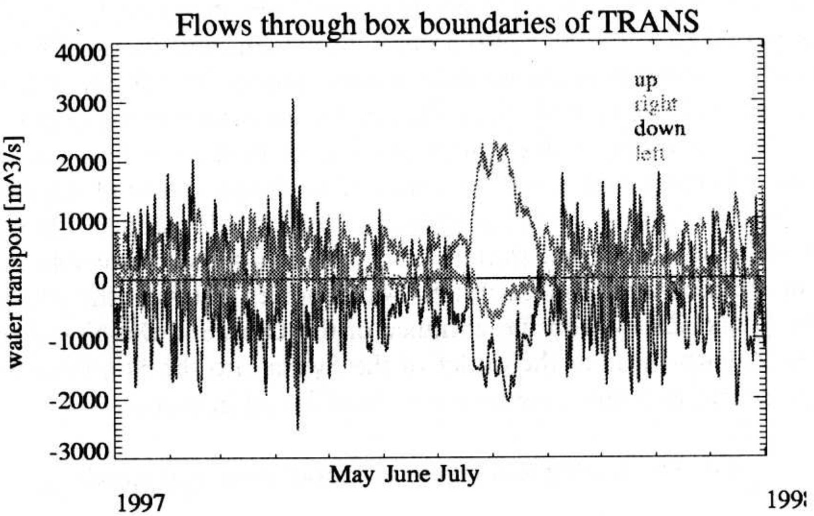
4.1. Run of the Hydrodynamical Model

The hydrodynamical model TRIM3D (section 2.2) has been applied for the year 1997 in order to reckon the water exchange rates for the different box-model configurations which have been described in section 3. Closer investigations on these water exchange time series have been carried out thus giving also a hint on the time scales on which these processes take place and the periodical behaviour across special compartment borders, which are located along the east-west axis of the lagoon. In figure 3 the time series of the water exchanges are given for a central box of the 8-box model (see Fig. 2b), which is situated in the transition between the Kleine Haff and the Wielki Zalew (Grosses Haff). In figure 3a the water exchanges can be seen for the unsmoothed hourly output values of the hydrodynamcial model, whereas in figure 3b these time series are given for smoothed values, were smoothing has been carried out for 24 hours. Whereas the overall inflow $V_{original}$ for the unsmoothed time series sums up to $V_{original} = 36.1$ km^3 the smoothed time series give a smoothed water inflow to this box $V_{t_s=24h} = 24.8$ km^3. Thus a important part of the overall water exchange between some boxes is governed by periodical processes which are shifting water back- and forward, with periods near to the eigenmodes of the water (Rosenthal et al. 1998).

For a simulation period of one year – 1997 – the output of the hydrodynamical model TRIM3D has been processed in order to get the water exchange between the different compartments of the ERSEM configurations (see chapter 3). For the compartments of all 3 configurations the water exchanges and the accumulative water exchange have been reckoned, corrigated and exported into files which were prepared for usage within the ecosystem model. First runs were made with the 3-box model of ERSEM, which showed up interesting features and results.



(a) T_{smooth} = 0 hours



(b) T_{smooth} = 24 hours

Fig. 3. Water exchanges via the borders of the central compartment TRANS of the 8-box model (Fig. 2b)

4.2. Comparison of Water Quality Parameters with ERSEM

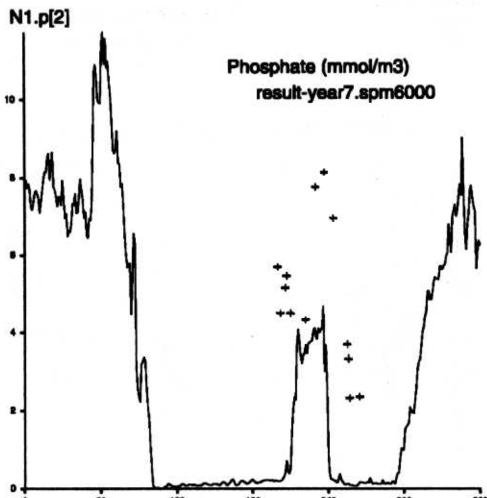
Nevertheless the model structure and the flux rates between the single components of the food web has been chosen according to the findings in the North Sea, the model showed within the first applications already good agreement with several parameters. Comparisons have been made for a variety of different parameters as can be seen in figure 4. In Fig. 4a, b the comparison between modelled and measured Nitrate and Phosphate for box 2 is given. The model simulates well the increased supply of these nutrients during the flood period, which took place in this year during the time July and August (day $\approx 200 - 240$). Also the decay and 'renormalization' after the flood period is fitted well by the simulations. In Fig. 4c the comparison made for the Chlorophyll-a can be seen, which shows also reasonable results for these simulations. Essential prerequisite for an adequate description of a marine ecosystem is a proper definition of light conditions. In Fig. 4d simulated and measured Secchi depths are plotted, which show the close values of both – measured and modelled values.

4.3. Spatial Gradients for Nutrients

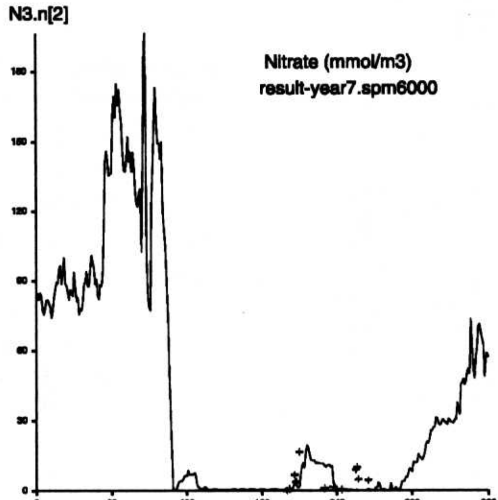
The model does also give structural information about the distribution and concentrations of the prognostical variables of the model in the different compartments of the lagoon. In figure 5a, b the spatial gradients in between the three compartments for Nitrate and Phosphate respectively are given. Especially during the flood period (day $\approx 200 - 240$) a decay in the concentrations of Nitrates and Phosphates is obvious between the three compartments. This decay of the concentrations seems to be reasonable. Since the main contributor to the overall nutrient budget – the Odra river – does enter the lagoon in the southern tip of Box 3, the highest concentrations should be expected in the area around the entrance of the river into the lagoon. Later on uptake processes will diminish the content of available nutrients. Nevertheless this scenario seems to be reasonable and also a descent in the measured concentrations was reported between the southern part of the the Wielki Zalew with the entrance of the Odra and the Northern part of the Wielki Zalew – near to the outlet of the Swina into the Southern Baltic Sea – this concentration pattern seems not to hold for all instances.

4.4. Oscillating Behaviour at Lower Trophical Levels

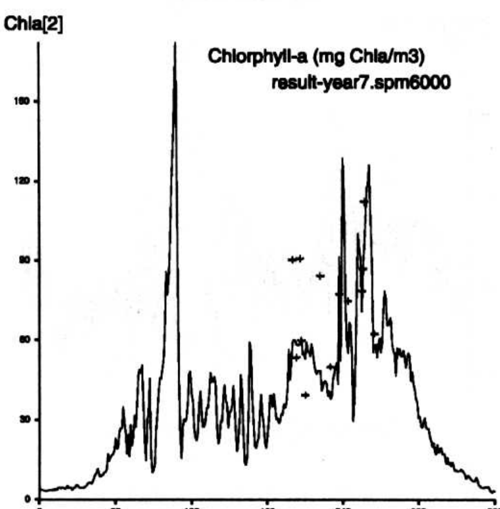
Another interesting result is found while looking closer to the behaviour of the functional groups at the lower trophical levels (see Fig. 6). Time series for bacteria, heteroflagellates respectively are given in Fig. 6. They show a strongly oscillating behaviour at days $\approx 100 \ldots 150$, which resamples the times of typical spring blooms. From observations in nature predator-prey and competitor relations are known, giving oscillating behaviour as well (Joergensen, Patten 1995, Joergensen



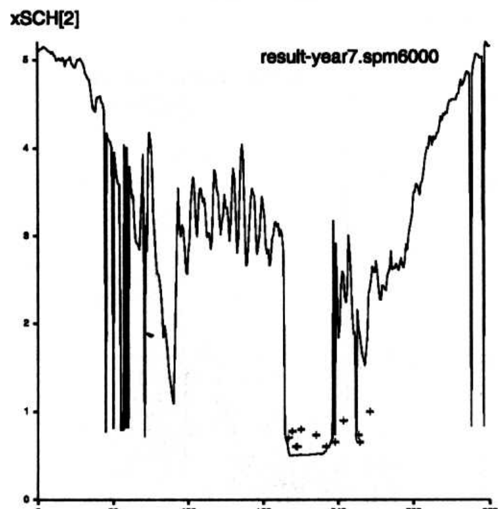
(a) Nitrate



(b) Phosphate

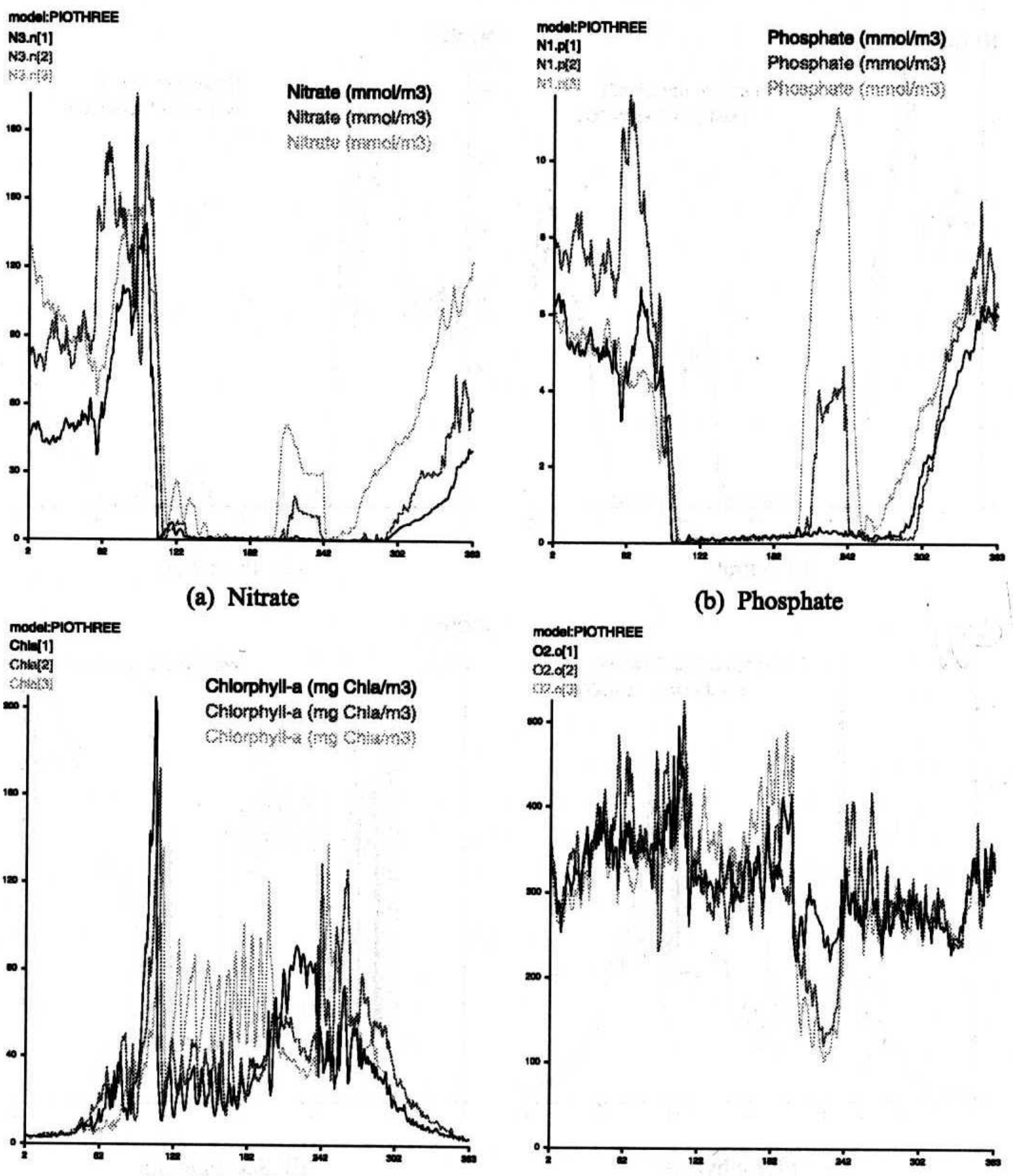


(c) Chlorophyll-A



(d) Secchi depth

Fig. 4. Comparisons between for different Phosphates, Nitrate and Chlorophyll-a and Secchi-depth in box 2 (Kleines Haff) of the 3-box model (Fig. 2a). Crosses refer to measurements, solid lines to model results



(a) Nitrate

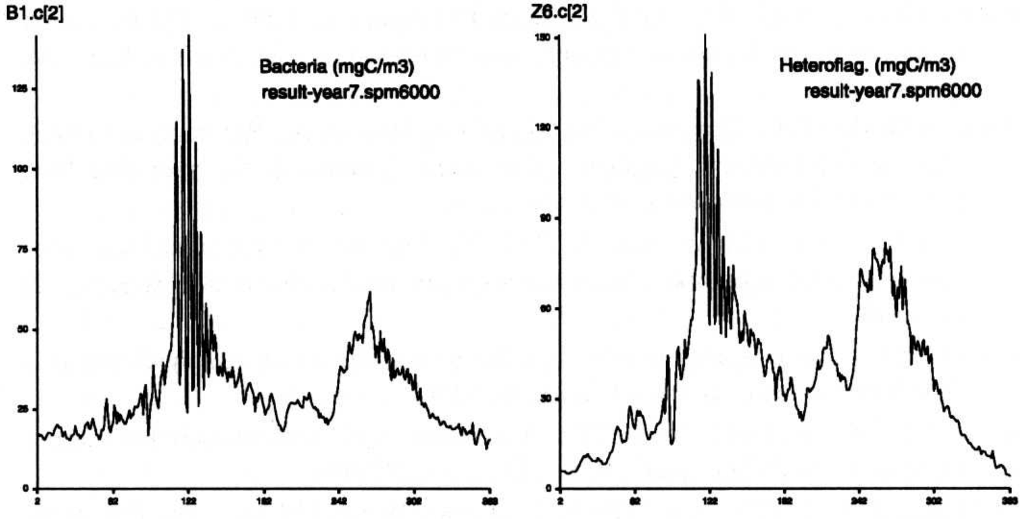
(b) Phosphate

(c) Chlorophyll-A

(d) Oxygen

Fig. 5. Distribution of Nitrate, Phophate, Chlorophyll and Oxygen in the three Compartments of the 3-box model. Box 1 belongs to Peenestrom and Achterwasser, Box 2 to Kleine Haff and Box 3 Wielki Zalew (Grosses Haff)

1992). Nevertheless these oscillating abundancies are part of natural systems, the question remains open, whether the oscillations observed in the model runs at the lowest trophical levels are real or solely model artefacts. Since all the natural abundancy of the functional groups are abstracted into few classes the feeding-grazing and competition relations become extremely simplified. Moreover the implementation of the ecosystem model in a box model configuration even more abstracts from the diversity and the transport phenomena taking place in one box at the natural scales of the water. Thus additive to the simplifying model formulation the processes of transport and supply of nutrients and species due to advective processes is stronlgy simplified as well if not to say neglected. Taking this into account the oscillations seem to be reducible to the model formulations, model abstraction of functional classes and smoothing, averaging and finally simplifying the whole area due to a compartment formulation of the model. Nevertheless a close review on nutrient as well abundancy measurements should be carried out to ensure and testify whether those oscillations could also occur in nature.



(a) Bacteria Compartment 2 **(b) Heteroflagellata Compartment 2**

Fig. 6. Oscillating behaviour of functional groups of lower trophical levels

5. Conclusions

Within the Odra lagoon a 3-dimensional hydrodynamical model TRIM3D was deployed for 1997. The output of the model was processed to derive water exchange rates for this year for three different compartment configurations of the water. The ecosystem model ERSEM was implemented on these box configurations. First runs were made with the ecosystem model using a 3-box configuration. Thereby the model has been compared with nutrient measurements, say Phosphate, Nitrate and Chlorophyll-a measurements carried out during measurement campaigns. The model gives good agreement between measurements and simulations. Open questions remain, looking at the spatial gradients in nutrient concentrations of the different compartment boxes as calculated by the model and the oscillating behaviour which is found in lower trophical levels. These oscillations have to be traced probably to model formulations as well as to the simplifications, which has been made due to the definition of abstract functional classes as well as averaging within big compartments. Nevertheles it should be clarified by measurements that oscillations of this type are solely model artefacts and do not occur in this form in the water under considerations, since those coupling effects between functional groups of the lower trophical levels would also determine the basic dynamical behaviour of the ecosystem as a whole.

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