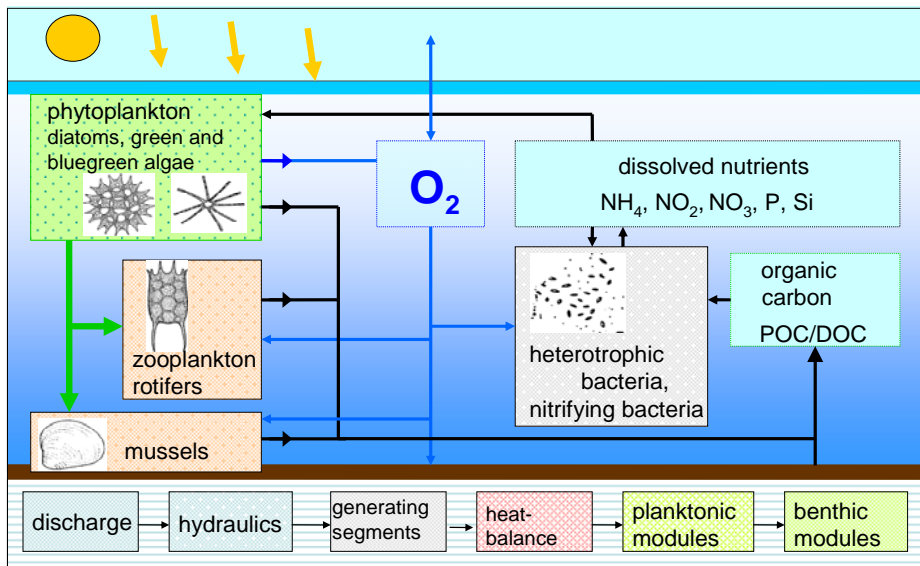


BFG-1788

Modelling the oxygen budget of the Elbe-Estuary – Scenarios concerning the impact of shallow water zones and reduced algal and detritus load

Contribution for TIDE-Project - WP3



QSim – the water quality model of the Federal Institute of Hydrology (BfG)

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edited by:

Federal Institute of Hydrology (BfG)

Division Ecology,
Department: Ecological Interactions:

Andreas Schöl
Birte Hein
Volker Kirchesch

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1. Introduction

The Elbe estuary is a partially mixed mesotidal estuary located at the southern coast of the North Sea. The total length is about 140 km from its upper boundary at the weir of Geesthacht (km 586) down to the North Sea at Cuxhaven (km 727). The expanded freshwater region reaches from Elbe km 586 to km 655 including the Hamburg Harbour. The tidal range at the gauge St. Pauli (km 620) is about 3.6 m. In summer, the freshwater region of the Elbe estuary is loaded by high inputs of algal biomass from the highly productive middle reach of the river Elbe. In the Hamburg Harbour area a strong decline of algal biomass can be observed. In parallel, a strong depletion of oxygen lowers the ecological state of the Elbe estuary dramatically. Due to this algal load and the related load of organic degradation compounds, the Elbe estuary is dominantly heterotrophic throughout its freshwater and mesohaline section and regularly develops an oxygen deficit in summer.

The recent state and different scenarios concerning the oxygen budget of the Elbe Estuary are calculated with the water quality model QSim (Kirchesch & Schöl 1999, Schöl et al. 2002, Becker et al. 2010, Quiel al. 2011). The modelled section reaches from middle reach of the river at the Czech/German border (Schmilka, km 0) to the outer part of the estuary (Cuxhaven, km 727). Different scenarios are calculated in order to get an idea whether and to what extent potential adaptations of the morphological characteristics or a reduction of input of algae from upstream could positively influence the oxygen budget in the harbour area and downstream, where the oxygen deficiency occurs. The first scenario group (A1 and A2) concerns the impact of morphological alteration of the estuary on the oxygen budget, while the scenario B is assuming a strong reduction of the organic load entering the estuary, e.g. load of algal biomass and related organic degradation products. The impact of the different scenarios on the oxygen content will be compared to the modelled oxygen content of the recent state 2006. On the basis of this comparison the impact of morphology vs. organic carbon load on the oxygen budget can be estimated.

Recent state - Year 2006

For the year 2006, the seasonal cycle of the water quality parameters (i.e. oxygen, nutrients and phytoplankton) is simulated with the model QSim by using measured input data at the model boundaries (Tab. 2, Fig 2). The results are validated by comparison with measurements. In addition, the modelled results of the year 2006 are used as a reference for the evaluation of the scenario results.

Scenario A1

The existing model topography is altered by introducing a shallow river stretch of 25 km length as a side channel of the Elbe Estuary, stretching from km 618 to 643, with a mean water depth of 3.5 m.

Scenario A2

The existing model topography of one harbour basin (located at river-km 624) is altered by lowering the mean water depth from 12 m to 3.5 m and increasing the length of the basin from km 0 to 2.2 km.

Scenario B

This scenario is dealing with the change of algal biomass and related organic carbon load from the river into the estuary. The boundary conditions for algal biomass (chl_a) are strongly reduced to concentration below 1 µg chl_a/l. The strong reduction is needed, because of the

high productive conditions in the Elbe river, which in summer lead to a 3-4 fold increase of algal biomass from the upper boundary (km 0 at Schmilka) to the weir of Geesthacht.

For modelling the oxygen budget of the Elbe estuary it is important to use the best available and the most consistent input data of the river concerning discharge and load. Therefore the German part of the river Elbe from km 0 (Schmilka) to the weir of Geesthacht (km 586) is part of the model approach too. Tab.1 gives the conversion of the official German kilometres of the whole Elbe (river + estuary) to the kilometres for Elbe estuary used in the TIDE-Project.

Table 1: Conversion of the official German Elbe-km with location to TIDE-km

Elbe-km	Location	TIDE-km
River		
0	Schmilka	-
318	Magdeburg	-
470	Cumlosen	-
474	Schnackenburg	-
536	Neu-Darchau	-
Estuary		
586	Geesthacht	0
609	Bunthaus	25
620	St. Pauli	34
624	Altona	38
629	Seemannshöft	43
632,5	Köhlbrand	46.5
636	Blankenese	50
655	Lühesand	69
727	Cuxhaven	141

2. QSim – the water quality model of the Federal Institute of Hydrology (BfG)

The water quality model QSim is a tool to simulate and predict the dynamics of nutrients and plankton in rivers. It describes in a mathematical way the complex chemical and biological processes in running waters. An important feature of QSim is the close linkage of hydraulic with ecological modules. In these central components of the model, the most important biological processes of the oxygen and nutrient budget as well as the development of phyto- and zooplankton and the processes at the river bottom are calculated (Schöl et al. 1999) (Figure 1). The model is suited to simulate processes in simple channels as well as in complex river networks and water bodies with variable flow directions like estuaries. Furthermore, engineered river stretches with groynes (wing dams), and their influence on budgets of nutrients and oxygen, can be modelled (Kirchesch et al. 2006, Schöl et al. 2006). As major results, annual cycles of oxygen and nutrient concentration as well as biological variables (e. g. algal biomass) can be calculated for the river continuum.

Model description

QSim is a deterministic model, meaning that the processes relevant for the water quality of a river are described functionally by differential and algebraic equations without any stochastic effect. Identification and parameterisation of the mathematical functions are based on published scientific knowledge or on own experimental results, if this is not sufficient, empirical equations are used. The variables are considered to be homogeneously distributed across the river's cross section (one-dimensional model). The model has a modular structure, i. e. for each process exists a separate subroutine (Figure 1, Table 2).

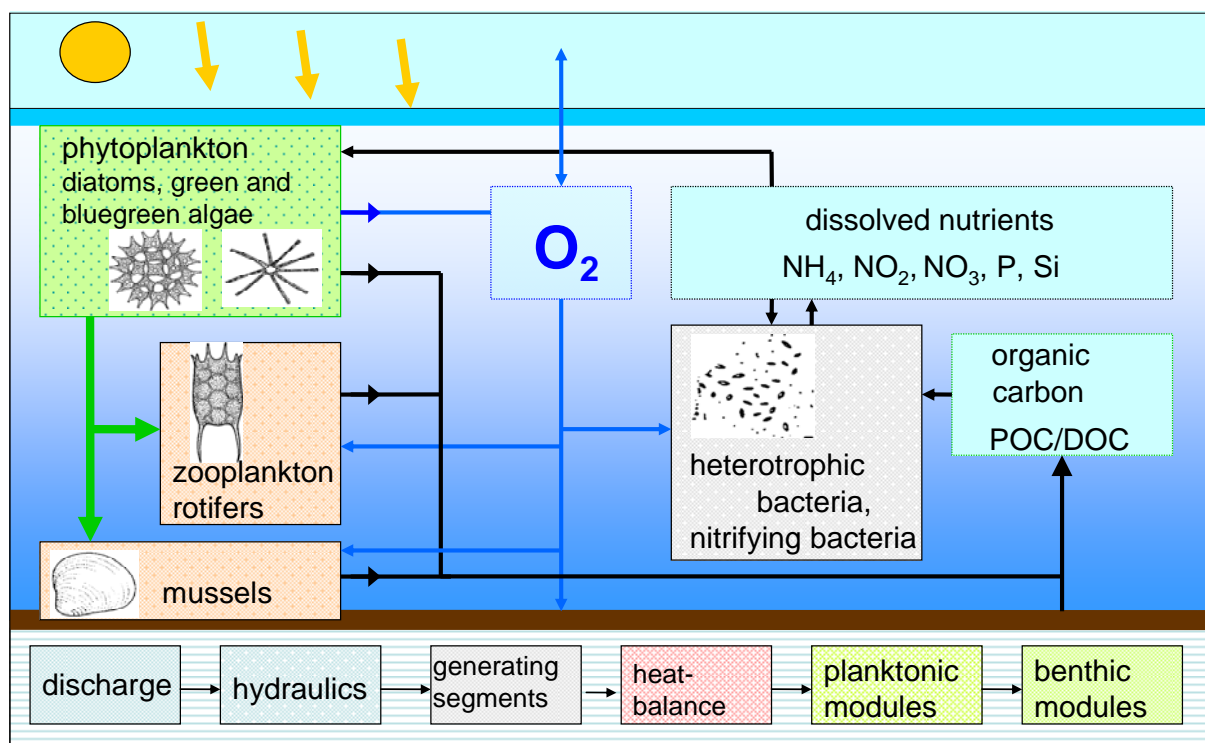


Figure 1: Modules and functionality of QSim

The discharge at the upper boundary (the starting point of the model section) and of the main tributaries as well as meteorological conditions (global radiation, air temperature, cloudiness,

wind velocity) drive the ecological modules of the model. The discharge can be calculated either in a stationary (no change of discharge during the model run) or a dynamic way (changing discharge during the model run). All variables that depend on solar radiation (e.g. algal growth) are modelled in a dynamic way by using a specific value for radiation for each calculation step (which is usually one hour). The model requires input data of water quality parameters that are usually determined during routine monitoring programmes.

Table 2: Processes and input variables of QSim

Processes	Input variables
Simulation of discharge	Morphological and hydrological: Cross sections, discharge
Sedimentation	Meteorological: Global radiation, air temperature, cloud cover, humidity, wind velocity
Heat budget	Physical and chemical: water temperature, oxygen, chemical oxygen demand, nitrate, ammonium, ortho-phosphate, silicate, pH, alkalinity, seston
Light climate	
Calcium-Carbon dioxide budget	
Oxygen and nutrient budgets	
Bacterial growth	Biological: Biological oxygen demand (carbon-derived and nitrification-derived), biomass of planktonic algae (chlorophyll a) and proportion of diatoms, green algae and cyanobacteria, zooplankton (abundance of flagellates and rotifers), benthic algae, macrophytes, benthic filter feeders (density of <i>Dreissena polymorpha</i>)
Nitrification	
Algal growth	
Macrophyte growth	
Zooplankton growth	
Growth of benthic filter feeders	

3. Model Application Elbe (river + estuary)

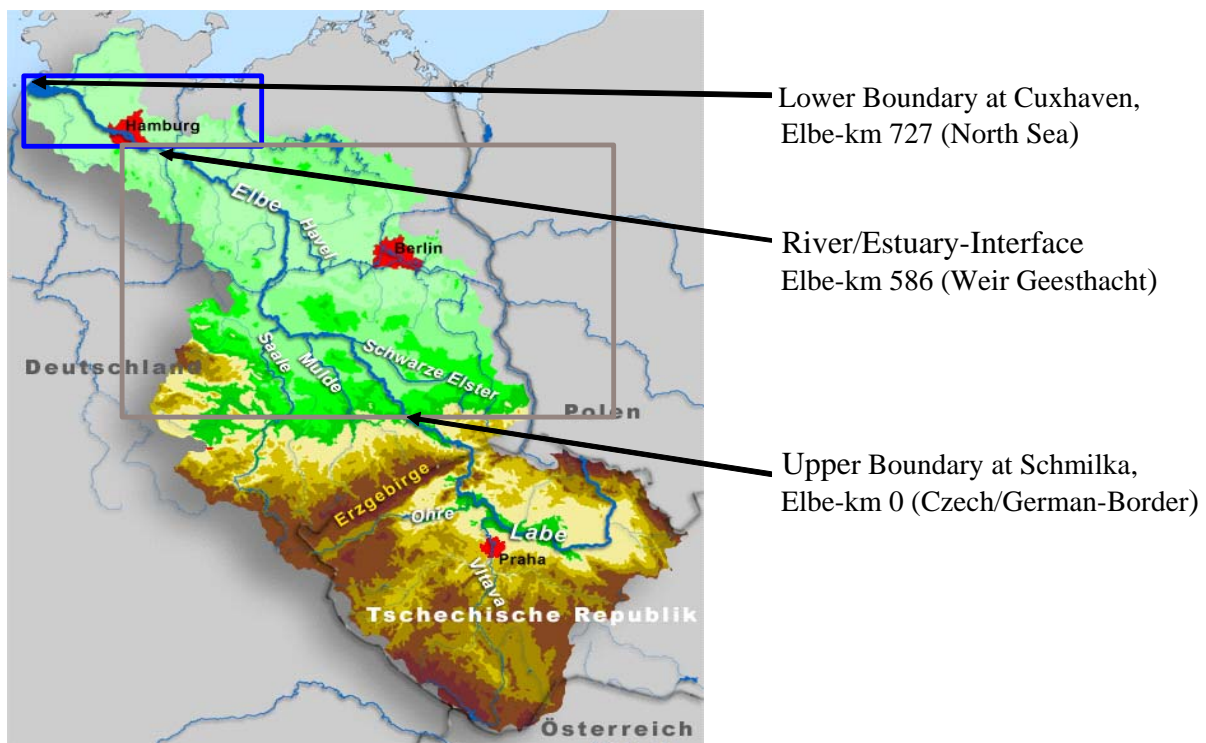


Fig. 2: Catchment of the Elbe and model area

The model is driven by input data at the upper (Elbe-km 0, Czech/German border) and lower boundaries (Elbe-km 727, Cuxhaven) and lateral inputs by the 4 main tributaries (Schwarze Elster, Mulde, Saale and Havel) of the River Elbe.

Cross-sectional profiles every 500 m (data of the German Waterways and Shipping Administration) were used to reproduce the morphological structure of the riverbed. All tributaries contributing, at their mouth, a mean flow of at least 0.4% of the mean flow of the Elbe river were integrated into the model. Thus, all in all 95% of the flow from tributaries has been taken into account. Wastewater treatment plants discharging into the German river section were considered when exceeding a population equivalent of 8,000 in the upper river section and 30,000 in the lower river section, covering 90% of the total wastewater discharge in this section. A total of 21 tributaries, one industrial discharger and 2 wastewater treatment plants were implemented in the model. Data on global radiation, air temperature, humidity, cloudiness and wind speed from four meteorological stations (Dresden, Magdeburg, Wittenberge-Seehausen and Hamburg-Sasel) along the river were used as climatic input parameters. Each station was assigned to a river section reaching half way to the next station.

4. Set up of Scenarios

For each scenario a whole seasonal cycle of all modelled parameters is calculated.

Scenarios A1 and A2: Shallow Side Channel (SSC) and Shallow Harbour Basin (SHB)

To simulate the impact of different bathymetries on the oxygen budget a hypothetical side channel and an altered harbour basin is introduced in the model topography. This side channel connects to the Northern Elbe branch within the port area and enters the estuary again at Elbe km 632.5 shortly upstream of the Mühlenberger Loch. The width of the channel is assumed to be comparable to that of the Northern Elbe.

In the model, the shallow harbour basin is inserted in the port area closely to the Köhlbrand which connects to the Southern Elbe (Elbe km 624).

Main factors determining the function of shallow water zones (SWZ) are: The mean depth (here 3.5 m for the channel and the harbour basin) and the volume of the SWZ and the connectivity to the main channel (see Fig. 3).

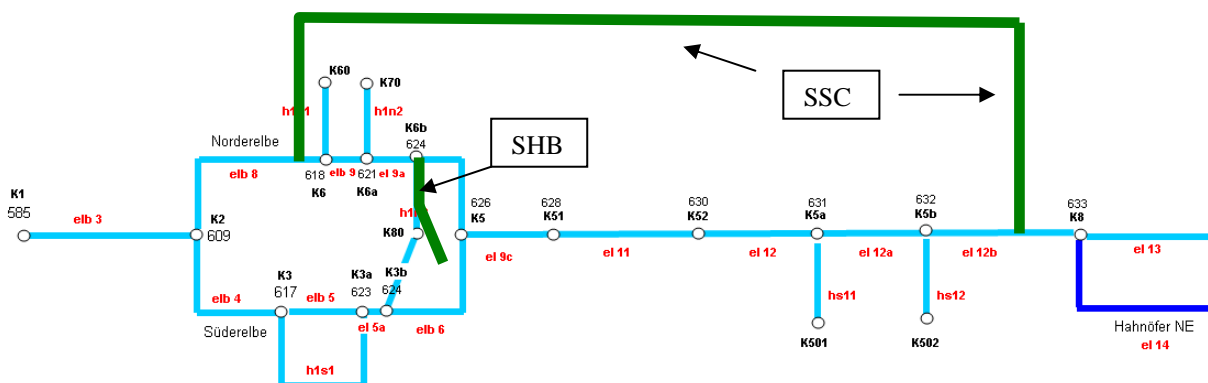


Fig. 3: Diagram of the model topography with implemented shallow water zones, scenario A1 - shallow side channel (SSC) along the longitudinal axis of the Elbe, scenario A2 - shallow harbour basin (SHB).

The development of the state variables oxygen, chlorophyll a, zooplankton are modeled inside the SWZ 's. In relation to the exchange rate (= connectivity) the impact on the oxygen content in the main channel is modelled too.

Scenario B – reduced algal biomass (no_Chla)

In this scenario, the morphological characteristics remain unchanged. The impact of the load of algae from the river on the oxygen budget of the estuary is investigated by a strong reduction of the chlorophyll a (chla) input values at each boundary of the model area. This means that the chla values are set to 0.1 µg/l at the upper boundary (km 0, Schmilka) and the lateral boundaries, the four major tributaries (Schwarze Elster, Mulde, Saale, Havel). Nevertheless there will be a growth of phytoplankton during its downstream transport in the river and especially in the estuary. The increase of algal biomass depends on the residence time, which is about one week for the river and might reach up to several weeks in the estuary.

5. Recent State – Year 2006

For the validation of the model measured chlorophyll a data of 2006 are used. During the summer period algal biomass functions as a main parameter to describe the trophic state of the Elbe. The results of the modelling show an increase of chlorophyll along the river from Elbe km 0 to km 586, where the tidal weir is located. In the estuary, approximately in the port area, the algal biomass declines (Fig 4).

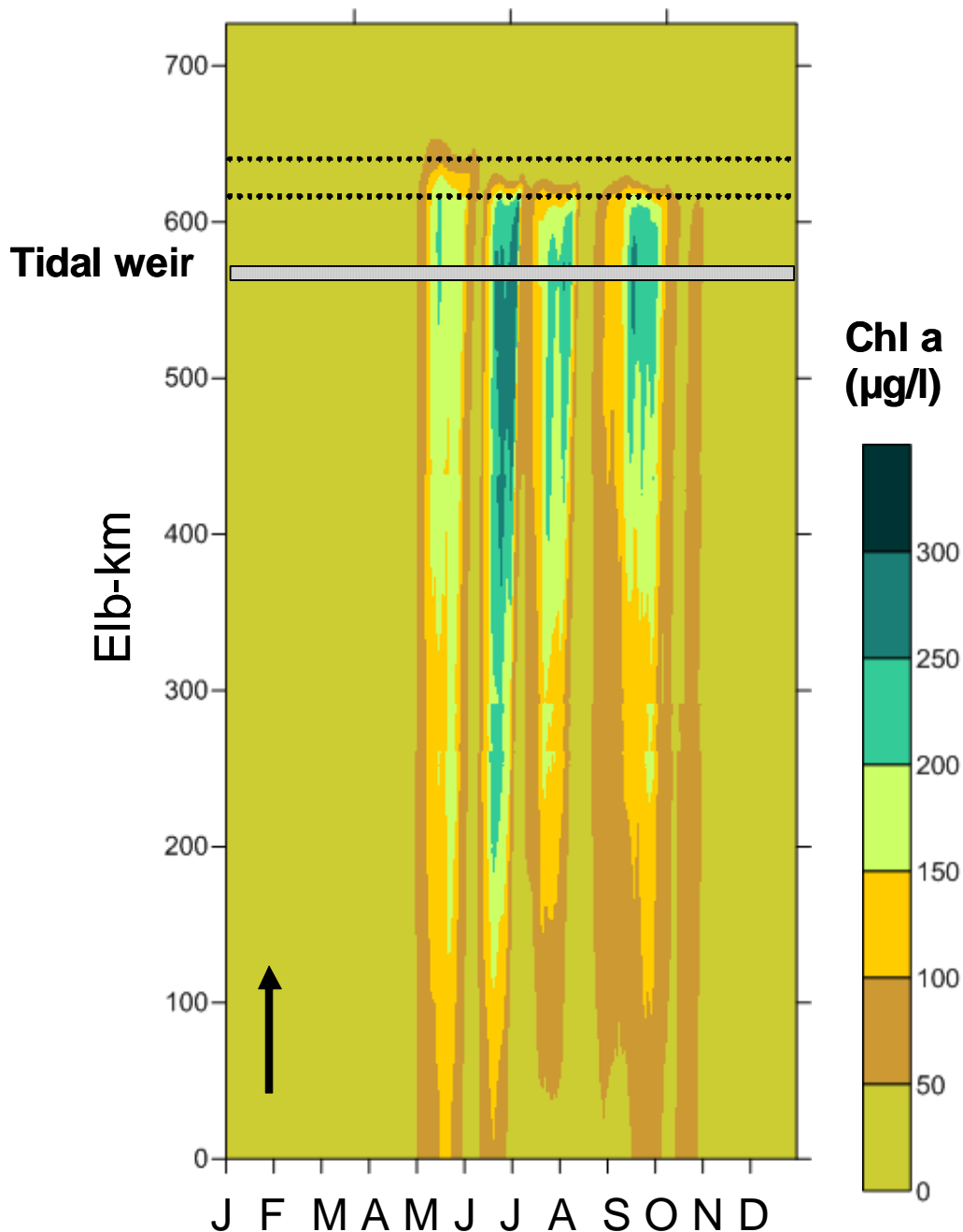


Fig 4: Modelled chlorophyll content of the Elbe River and Estuary in 2006. Dotted lines mark measuring sites for model validation, see Fig. 5.

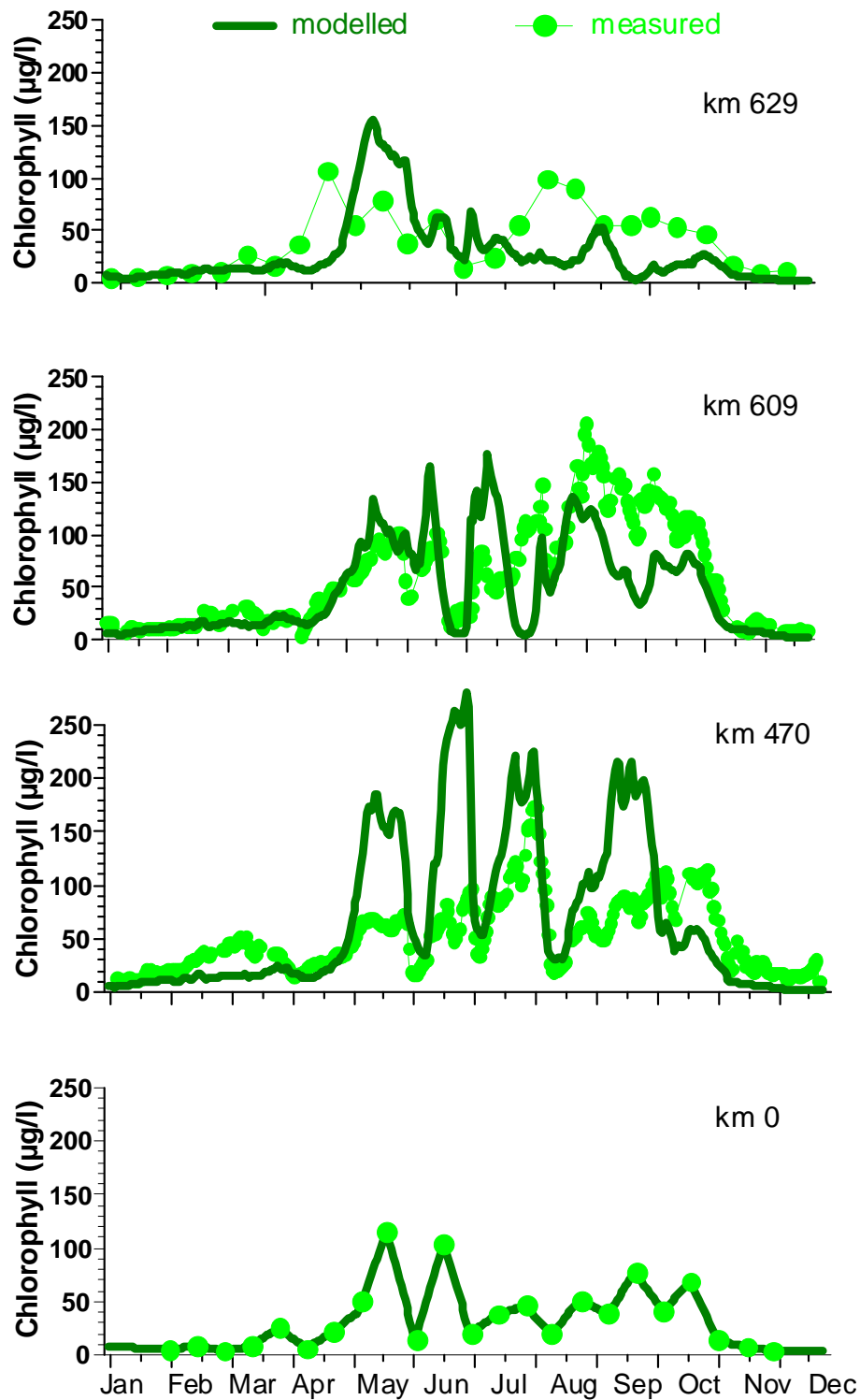


Fig. 5: Validation of modelled chlorophyll values by measurements at two sites in the river (km 0, start and km 470) and two sites in the estuary (km 609 and km 629). Chl_a values at km 470 and 609 are measured by fluorescence-method and scaled by a factor of 2.

The measured and the modelled data for chlorophyll show some deviation concerning the seasonal cycle. At km 470 (Cumlosen) the model calculates four chl_a peaks, while only two distinct peaks in late summer and autumn could be observed. The measuring site at km 470 is located at the right bank of the Elbe river. It is influenced by the tributary Havel, which merge into the Elbe at km 438 and mostly have a lower chlorophyll content compared to the Elbe. In the estuary at km 609 the spring, the late summer and the autumn peak is matched quite well by the model results, while the mid summer peak in July is overestimated. In the center of the port Hamburg at km 629 the modelled chlorophyll concentrations in spring and summer are a little bit higher than the measured data, while in late summer and in autumn the modelled chlorophyll fell below the observed data.

Despite the deviations concerning the seasonal course of the modelled and observed chlorophyll concentrations, the general trend of increasing chlorophyll concentrations along the river and drastically decreasing concentrations in the freshwater part of the estuary is well matched by the model results.

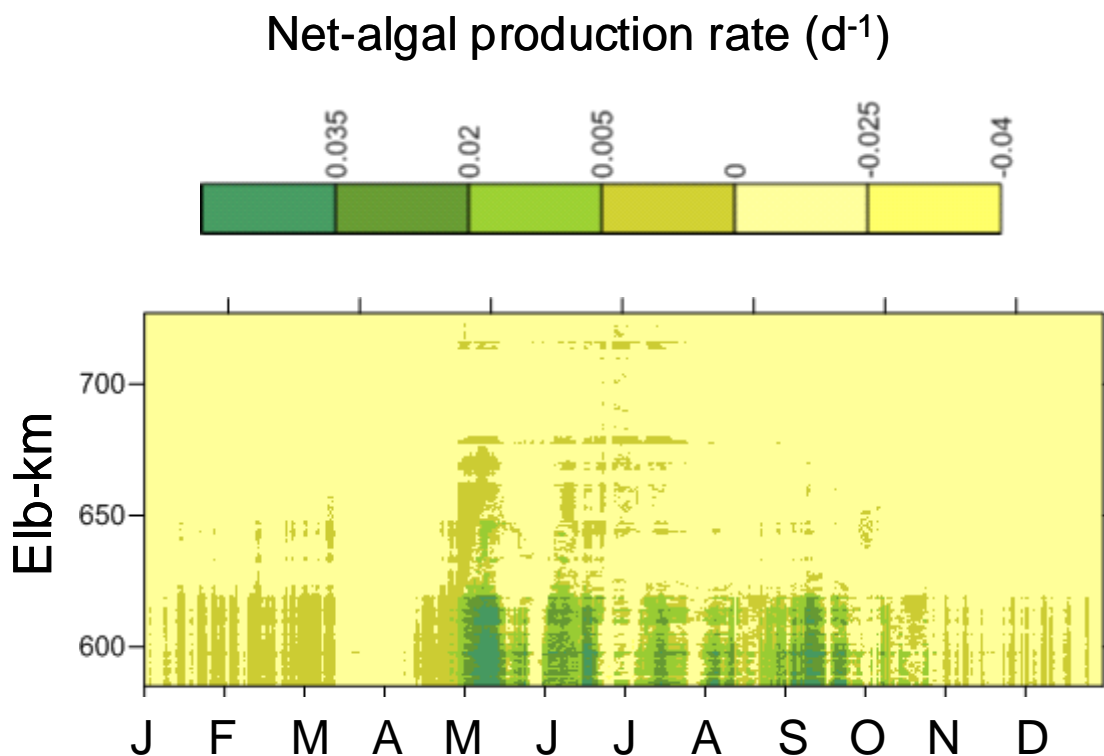


Fig. 6: Modelled net production rate of phytoplankton in the Elbe Estuary in 2006.

The modelling results show that only in the upper, shallow freshwater section of the Elbe estuary up to km 610 (which is quite shallow compared to the port area), a positive net-production rate of the phytoplankton of approximately 0.04 day⁻¹ could be reached for some periods during the summer. In most parts of the estuary and during longest times of the season, the net production rate is lower than zero, due to strong light limitation of algal growth, meaning the algal growth rate is negative and their biomass is declining. During that time, the respiration of the phytoplankton is higher than its oxygen production.

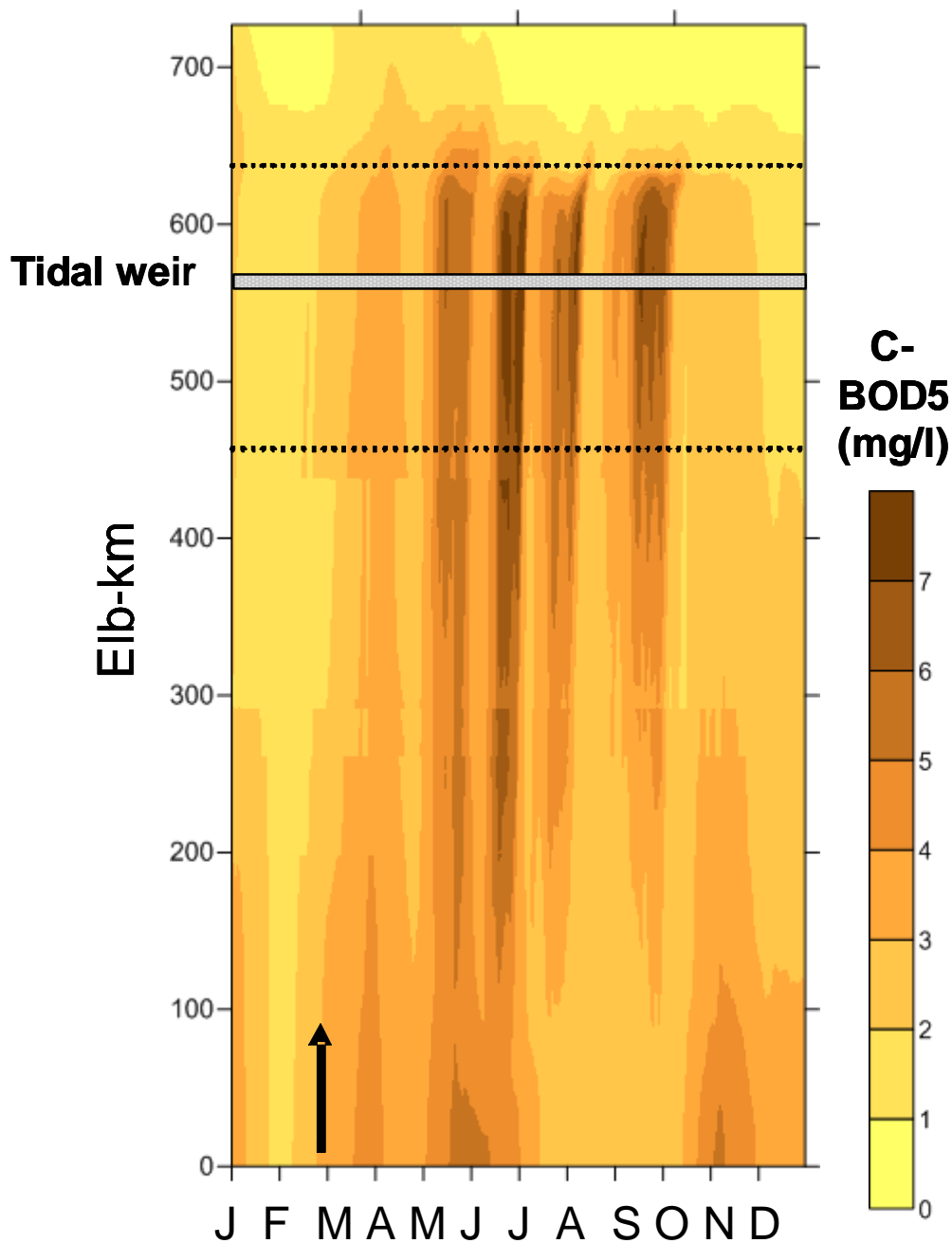


Fig 7: Modelled carbon related C-BOD₅ content of the Elbe River and Estuary in 2006. Dotted lines mark measuring sites for model validation, see Fig. 8.

Fig. 7 shows the modelled C-BOD 5 values as a proxy for the substrate concentration of the heterotrophic bacteria and the related oxygen consumption process. In summer the C-BOD 5-values increase during the downstream transport. The model results show, that the degradable organic carbon derives from the phytoplankton biomass, mainly by respiration, die off or grazing. Consequently, the organic carbon reaching the estuary is produced autochthonously in the river.

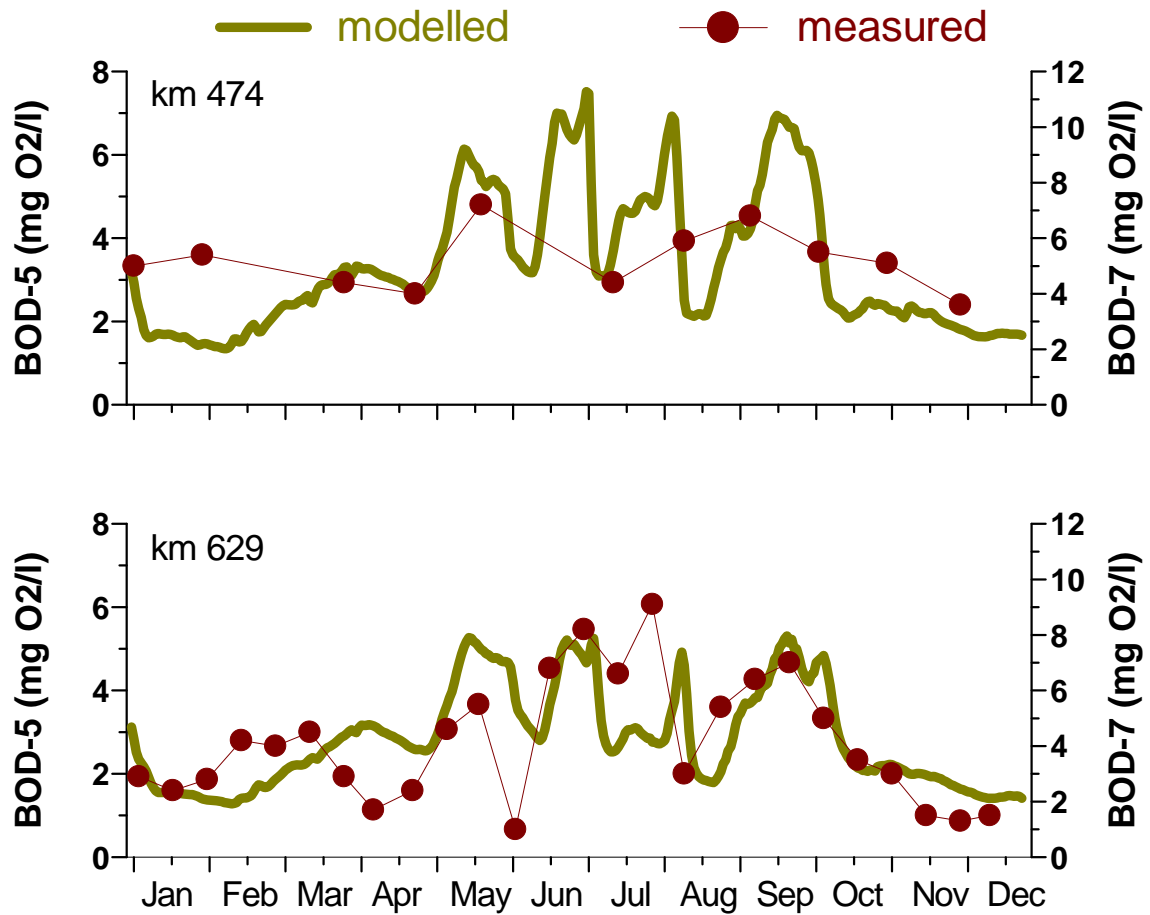


Fig. 8: Comparison of modelled BOD5 and measured BOD7 at two sites: Elbe River (km 474), upper graph and Elbe Estuary (km 629), lower graph.

A high load of degradable organic carbon is reaching the estuary from the river. This high organic carbon content fuels the heterotrophic processes in the upper part of the estuary and thus the related heterotrophic oxygen consumption.

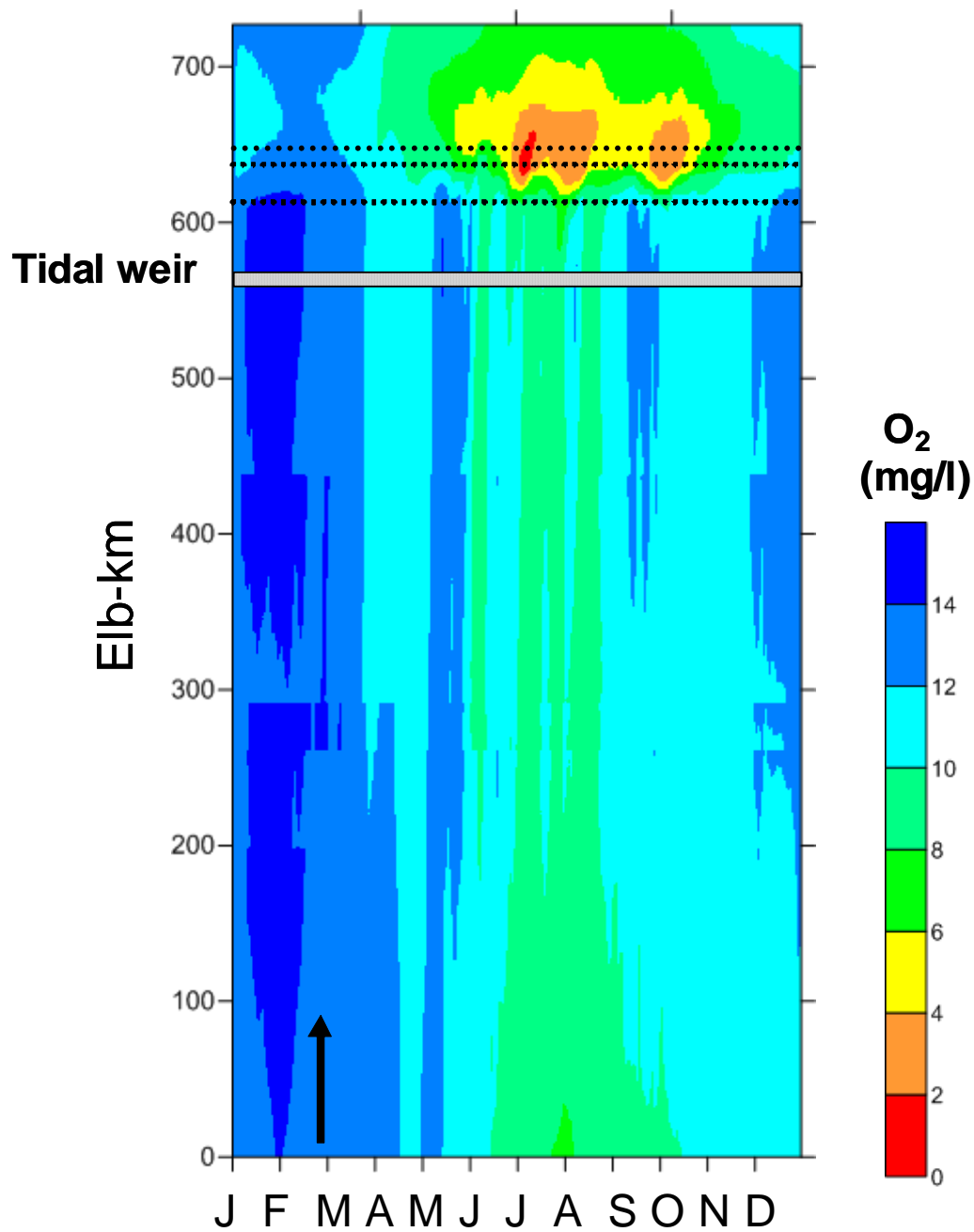


Fig. 9: Modelled oxygen content of the Elbe River and Estuary in 2006. Dotted lines mark measuring sites for model validation, see Fig. 10.

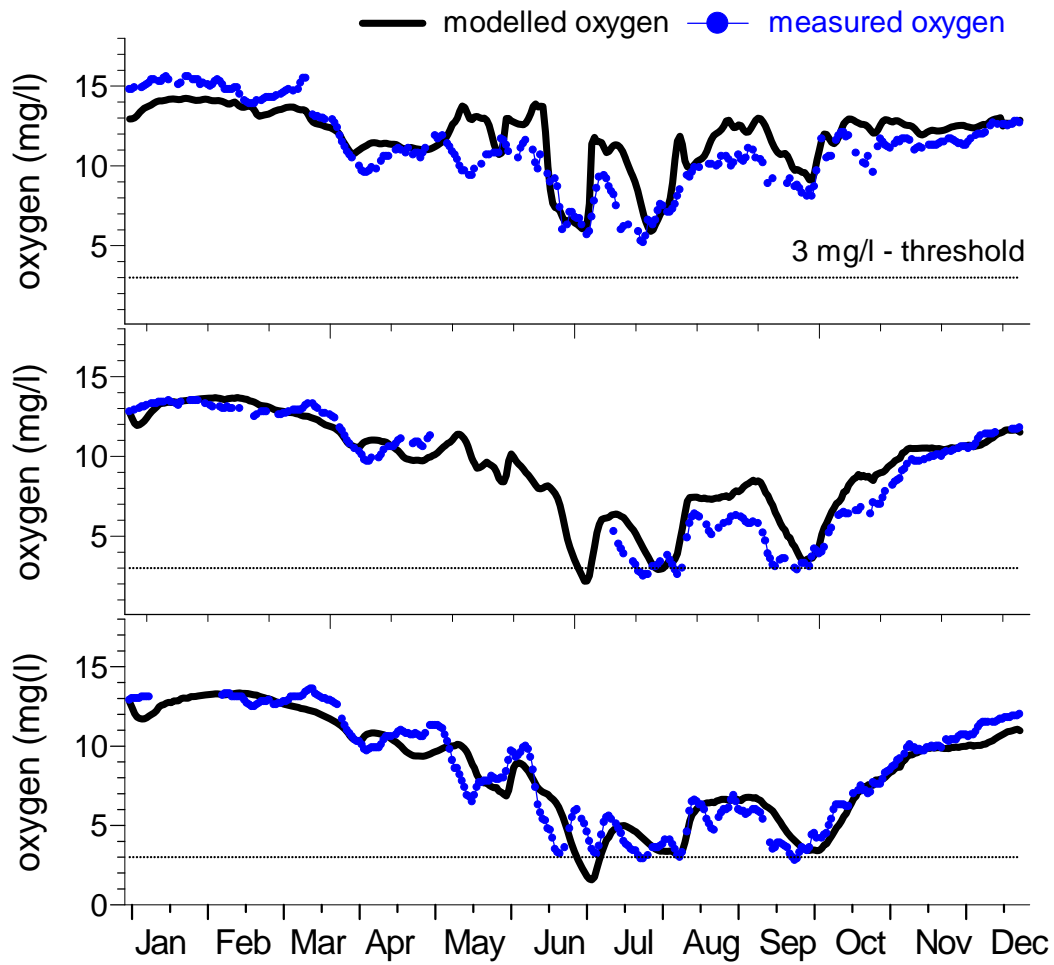


Fig. 10: Validation of modelled oxygen content by measurements at three sites in the estuary (km 609, km 629 and km 636) for 2006. Threshold value of 3 mg O₂/l marks the critical concentration for fish in the Elbe Estuary.

6. Scenario A1 and A2 - simulation with changes in bathymetry

Scenario A1 – Shallow Side Channel (SSC)

The SSC has a mean water depth of 3.5m and a length of 25 km. It is connecting the northern main channel of the Elbe estuary from km 617.5 (near the upper entrance to the harbour) to km 632.5 (just below the outlet of the harbour (see Fig. 3)). The 'real' main northern branch of the Elbe has the same length as the simulated channel, but it has a mean depth of about 10.7 m. During the ebb phase, the modelled side channel is filled from upstream by about 10 % of the total discharge of the existing northern branch of the Elbe. Both channels show a comparable tidal range of about 3.5 m. The modelled side channel is always filled with water (high water level: 5.2 m, low water level: 1.7 m)

Due to the decrease in mean water depth and the related lower mixing depth, the SSC functions, compared to the main channel, as an oxygen producing system throughout the season concerning the phytoplankton, while in the main channel only occasionally a net oxygen production is calculated (Fig. 13).

These favourable conditions for phytoplankton growth lead to an increase of algal biomass (chl_a) and oxygen in the SSC in comparison to the main channel (Fig. 11 and 12).

A part of the additional algal biomass in the SSC is grazed by the higher zooplankton densities in the SSC, which is an effect of the better food supply of the zooplankton (data not shown).

Beside the biological processes, the lowering of the mean water depth enhances the reaeration rate of the water column via the water surface. During times of oxygen under saturation this process increases the oxygen content in the SSC.

Scenario A2 – Shallow Harbour Basin (SHB)

The harbour basin at Elbe-km 624 (see Fig. 3) has a length of 2.2 km and a mean water depth of 3.5 m. The strong reduction in water depth causes a stronger exchange of water masses between the harbour basin and the main channel, leading to an equalisation of concentrations between both compartments (Fig. 14).

In addition to the processes described above, enhanced algal growth due to a better light supply and the consequences concerning the oxygen content are causes for the increase of algae and oxygen in the SHB (Fig. 11 and 12).

Oxygen content – Simulation results

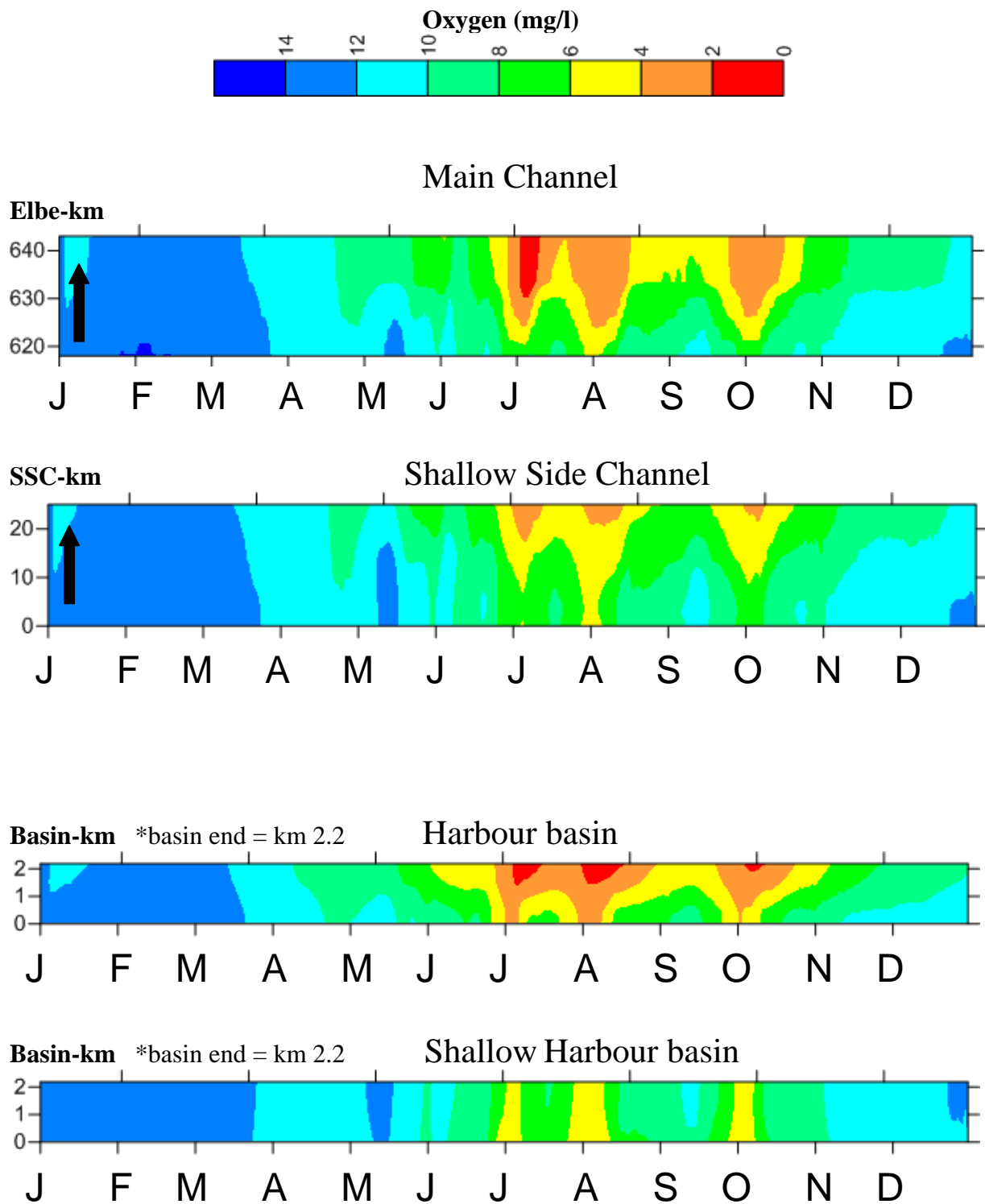


Fig. 11: Comparison of the oxygen content of scenario A1 (Main channel and SSC) and scenario A2 (Harbour basin and SHB)

Chlorophyll – simulation results

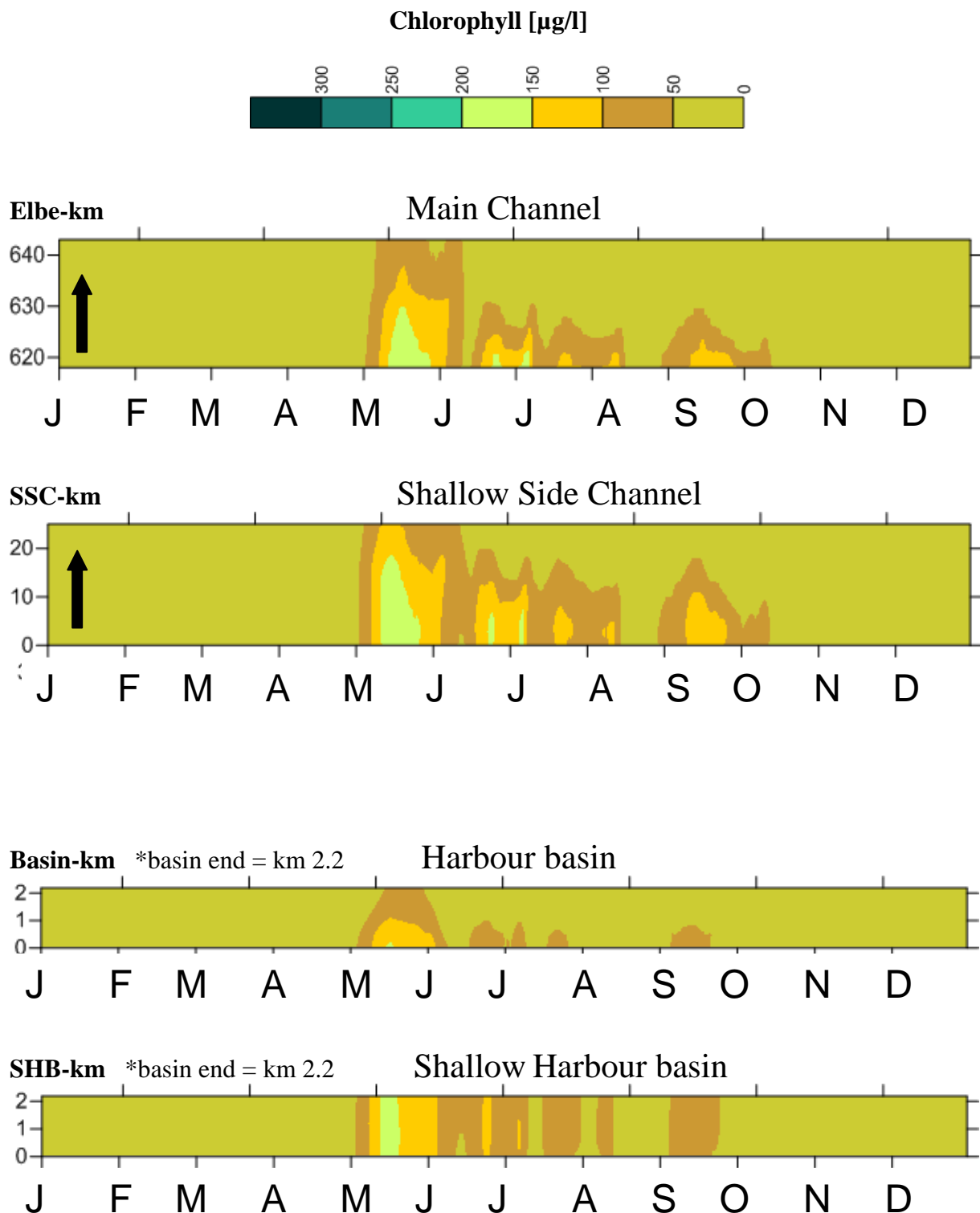


Fig. 12: Comparison of the chlorophyll a content of scenario A1 (Main channel and SSC) and scenario A2 (Harbour basin and SHB).

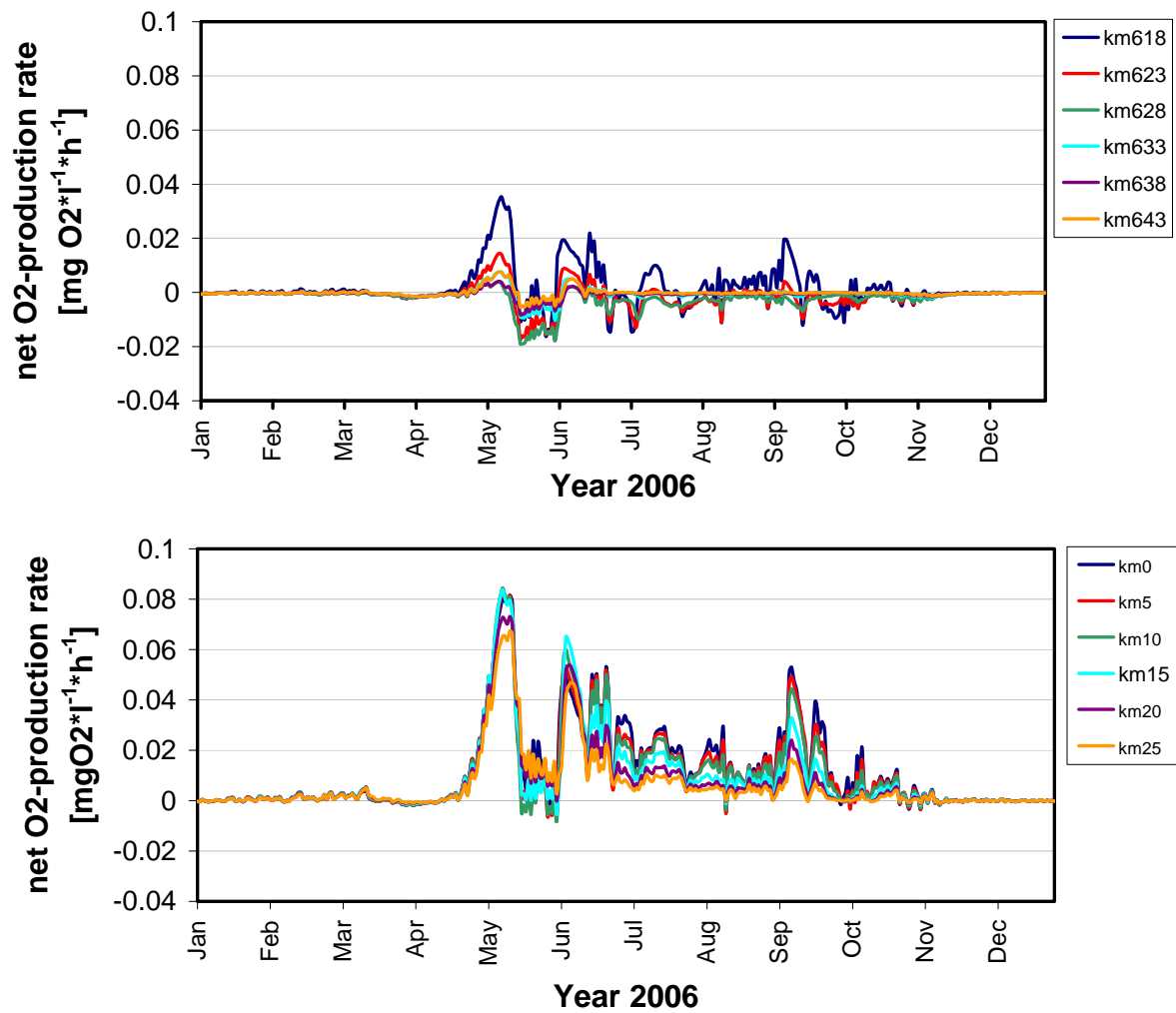


Fig. 13: Net oxygen production rate along the main channel between km 618 and km 643 (above) and the SSC between km 0 and km 25 (below) for year 2006.

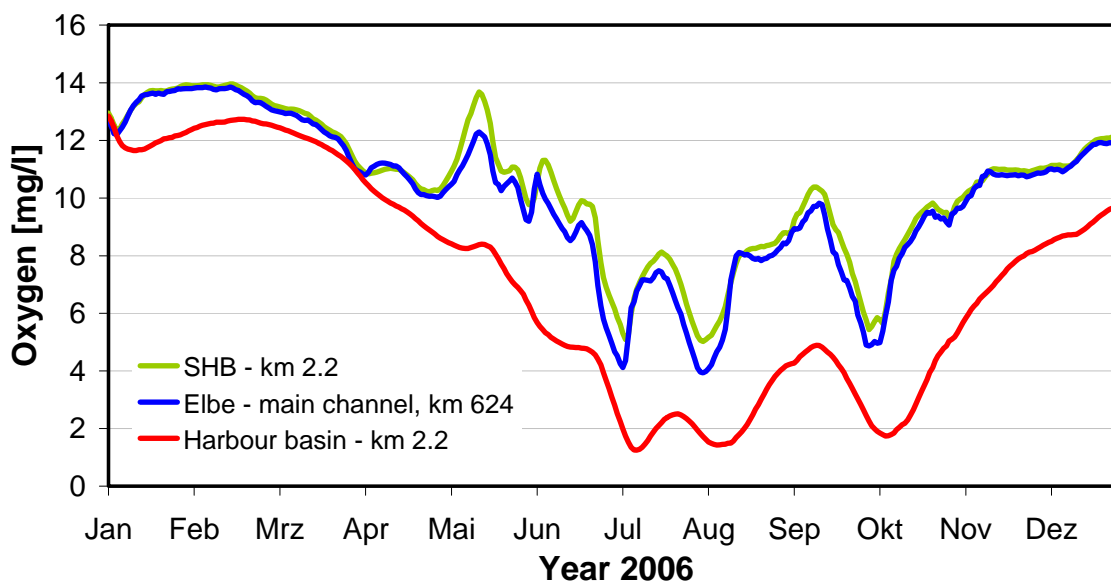


Fig. 14: Oxygen content at the end of the Harbour basin (km 2.2) and the shallow Harbour basin (SHB, km 2.2) and in the main channel at Elbe-km 624.

7. Scenario B - Simulation without input of algal biomass from upstream

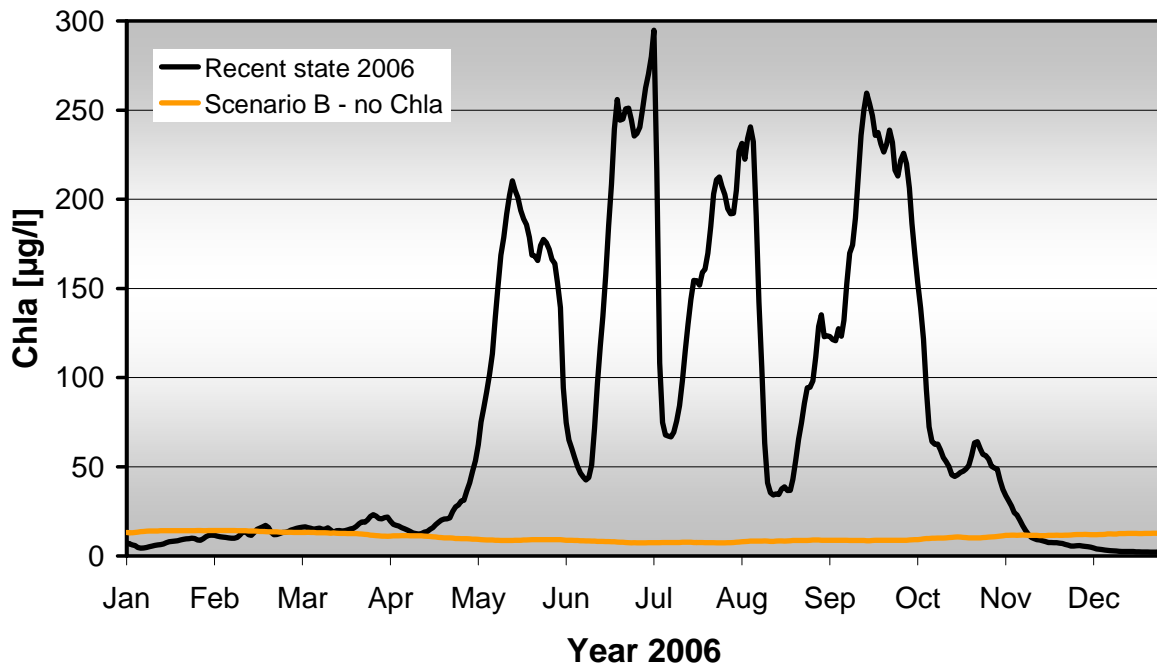


Fig. 15: Chlorophyll at Elbe-km 585, the tidal weir of Geesthacht for the recent state 2006 and the Scenario B (= no Chla)

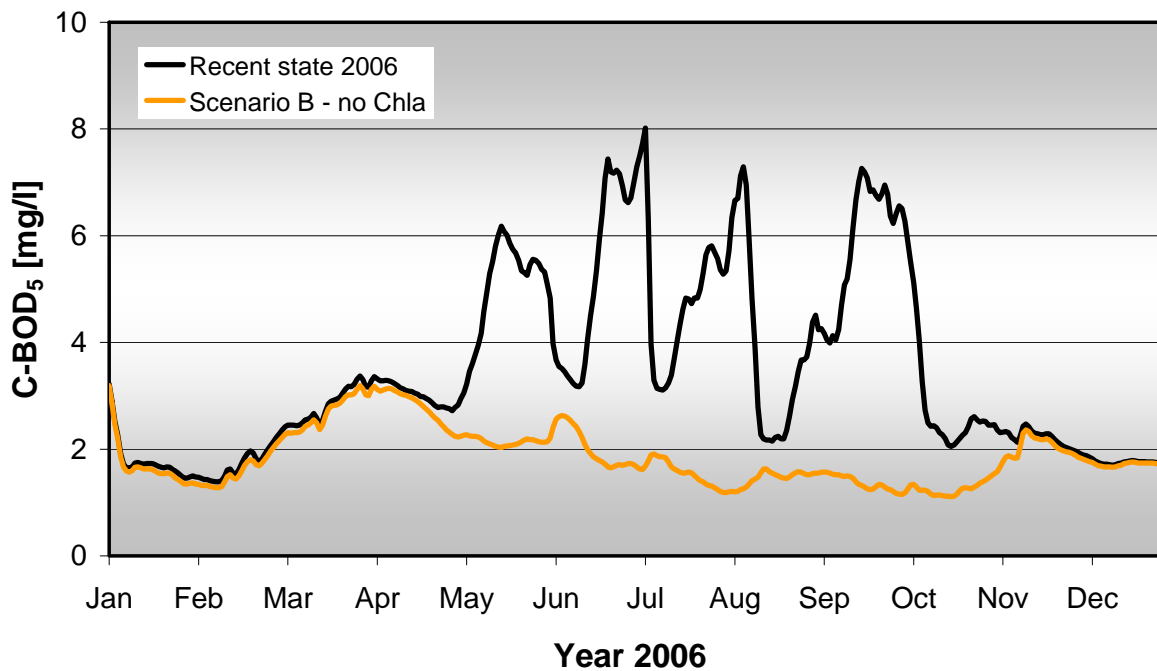


Fig. 16: C-BOD5 at Elbe-km 585, the tidal weir of Geesthacht for recent state 2006 and the Scenario B (= no Chla)

In Scenario B with nearly no algal biomass input ($= 0.1 \mu\text{g chl}a/l$) at the upper boundary and the lateral boundaries (= tributaries) of the model, only low chlorophyll a concentrations are produced in the Elbe river. As a consequence, chlorophyll concentrations entering the estuary at the tidal weir (km 585) are always lower than $15 \mu\text{g chl}a/l$ (Fig. 15). In Scenario B, also the C-BOD5 input from the river into the estuary is diminished drastically to values below $3 \text{ mg O}_2/l$ in spring and autumn and lower than 2 mg/l during the summer season (Fig. 16). Scenario B shows a clear decrease of algal biomass and related organic carbon load from the river into the estuary in comparison to the model run “recent state 2006”. Due to this load reduction, the oxygen concentration stays at a comparably high level ($> 4.5 \text{ mg/l}$) along the Elbe Estuary and throughout the season (Fig. 17 and 18). The still existing oxygen consumption is due to the heterotrophic carbon respiration and especially to the sediment oxygen consumption.

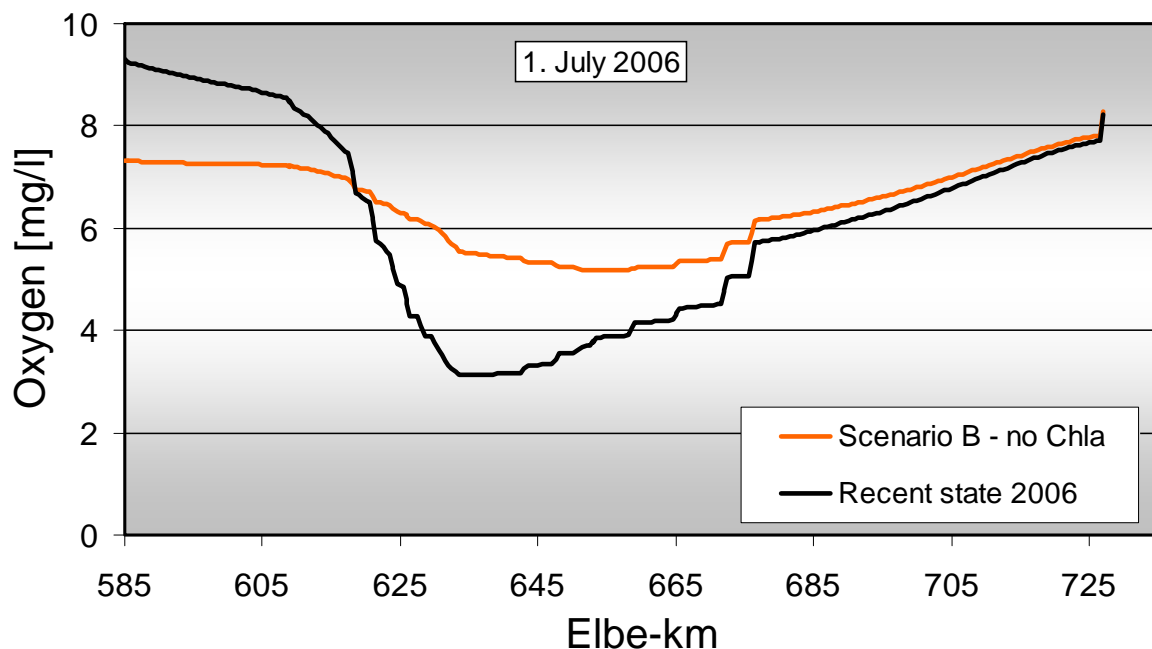


Fig. 17: Comparison of the oxygen content along the Elbe-Estuary on 1st July 2006 for the recent state 2006 (black line) and for Scenario B (orange line).

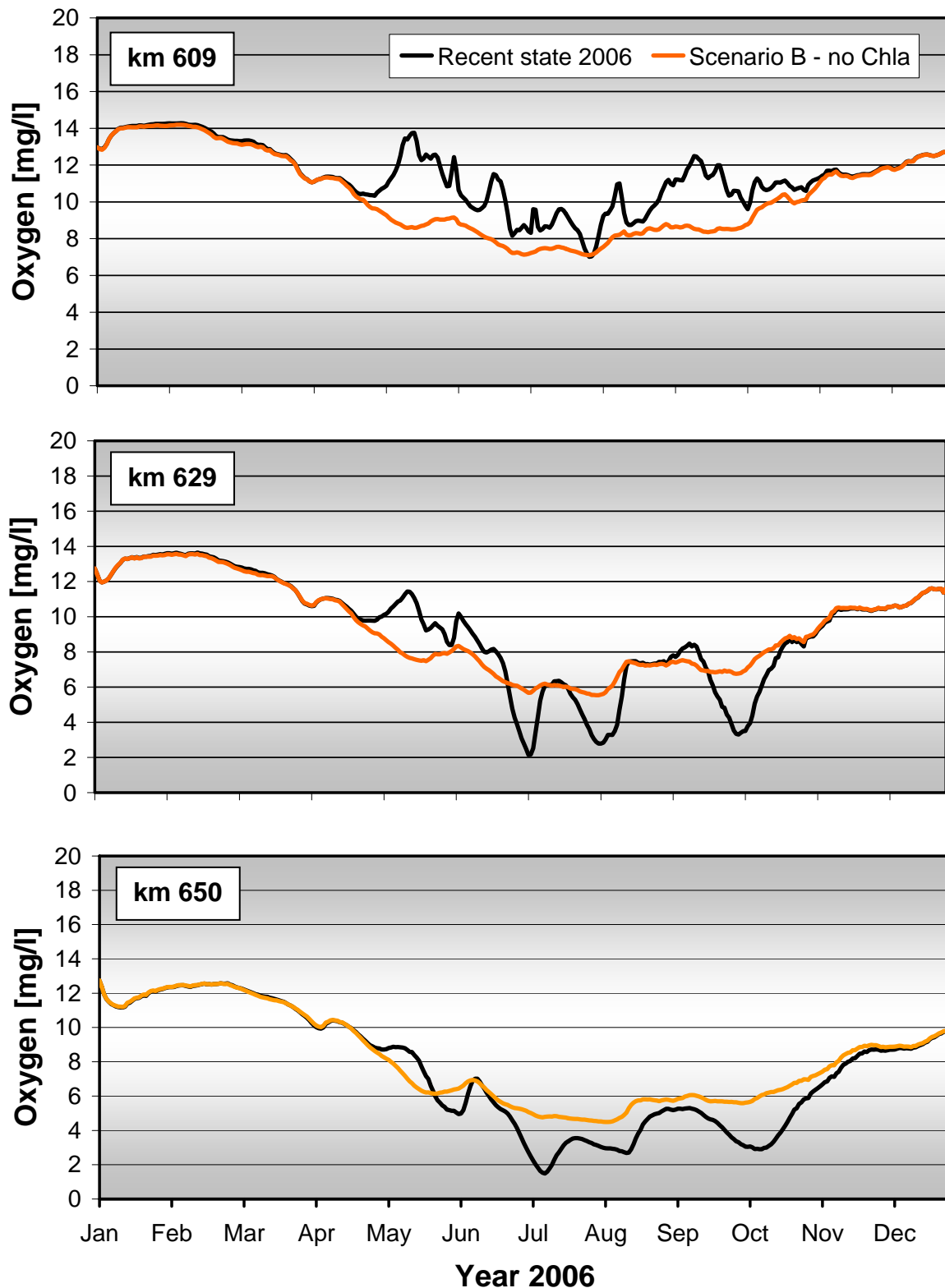


Fig. 18: Comparison of the oxygen content in the Elbe-Estuary at km 609, 629 and 650 calculated for the recent state 2006 (black line) and for Scenario B (orange line).

8. Conclusions

By comparing the model results for the recent state 2006 and scenarios A and B it is obvious, that the overwhelming load of algal biomass and related organic carbon drive the oxygen budget of the Elbe estuary.

Introducing shallow water zones (scenario A1 and A2) characterized by low water depth of 3.5 m will have a positive impact on the oxygen content. In the shallow water zones the primary production is stimulated due to a better light supply and a better re-aeration of oxygen via the water surface. The loss process due to an enhanced grazing by zooplankton is lowering the positive growth balance of the phytoplankton only a little bit.

The positive effect of the lowered water depth is restricted to the altered compartments (shallow water zones, scenario A1 and A2) themselves, while the effect on the oxygen level in the whole Elbe Estuary is minor.

The strong impact of the algal and organic carbon load on the oxygen budget becomes clearly visible by the scenario B. In this case, due to an almost total reduction of algae input at the boundaries of the model system, a drastic reduction of the load of algal biomass and related organic carbon entering the estuary can be achieved, leading to comparably high oxygen contents in the whole estuary throughout the season.

In the GLOWA-Elbe project, the development of phytoplankton and nutrient concentrations under conditions of global change was modeled with QSim along a 700 km stretch of the river (Quiel et al. 2011). Under reduced river flow, combined with increasing temperature and global radiation, phytoplankton biomass increased and phytoplankton maxima shifted in upstream direction, followed by higher system respiration rates in the adjacent downstream sections. In contrast, higher flow shifted the phytoplankton maximum toward the downstream sections. It is probable that in the upstream sections of rivers, oxygen concentrations are enhanced due to intensified phytoplankton growth, while in downstream sections oxygen deficiencies will become more severe.

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QSim-Homepage

http://www.bafg.de/DE/08_Ref/U2/01_mikrobiologie/QSIM/qsim_node.html