

Fundamentals on Ecological Modelling in Coastal Waters Including an Example from the River Elbe

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Summary

Modelling dissolved oxygen in water encompasses a range of requirements and process descriptions. Among a good representation of hydraulic, including advection/dispersion, the processes in the ecological part of the model are crucial for a reliable model.

A MIKE 21 (DHI 2013) flexible mesh model was used to simulate the hydrodynamic conditions in the River Elbe around Hamburg. The model is based on the numerical solution of twodimensional incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature and density equations and is solved by a turbulent closure scheme. The spatial discretisation is performed using a cell-centred finite volume method. In the horizontal plane an unstructured mesh is used.

This hydrodynamic model was coupled to the ecological module (ECO Lab) to form the basis for the water quality model. ECO Lab (DHI 2013) is a numerical lab for ecological modelling. It is an open and generic tool for customising aquatic ecosystem models to describe water quality. The module is mostly used for modelling water quality as part of an environmental impact assessment.

In the present case a eutrophication model was used to describe the concentrations of phytoplankton, chlorophyll-a, zooplankton, organic matter (detritus), inorganic nutrients and oxygen in the river Elbe in Hamburg. Rooted vegetation and macroalgae were not implemented as their influence in this part of the Elbe is negligible. The eutrophication module is integrated within the advection-dispersion module which describes the physical transport processes at each node in the model domain.

The model was used to describe the oxygen conditions in the Port of Hamburg, especially the change of dissolved oxygen in the Reiherstieg, a lateral channel which is usually closed with a sluice at the southern end to prevent suspended solids to deposit in the port. Due to plans for a new sluice gate the Hamburg Port Authority tested if a temporary opening of the gate could improve the oxygen conditions in the port. The model showed that resuspension and mineralization of organic material play an important role in this system. The balance between opening the gates to flush oxygen rich water into the port and preventing the introduction of organic material is crucial for better oxygen balance in the Reiherstieg.

Keywords

oxygen, nutrients, water quality, Elbe, model, MIKE21, ECO Lab

Zusammenfassung

Die mathematische Modellierung von Sauerstoff im Gewässer umfasst zahlreiche Prozesse. Neben einer präzisen Berechnung der Hydraulik, sowie der Advektion/Dispersion, sind die formulierten Prozesse im Wasserqualitätsmodell eine wichtige Voraussetzung für ein verlässliches Modell.

Ein MIKE 21 (DHI, 2013) flexible Mesh Modell wurde in der vorliegenden Untersuchung verwendet, um die hydraulischen Bedingung im Hafen von Hamburg und der angrenzenden Tideelbe zu berechnen. Das Modell basiert Reynolds-gemittelten Navier-Stokes Gleichungen unter Berücksichtigung der Annahmen von Boussinesq und unter Annahme einer hydrostatischen Druckverteilung. Impuls- und Massenerhaltung auch für die Inhaltsstoffe wie z. B. Salz und Temperatur sind in dem zugrunde liegenden Ansatz erfasst. Die räumliche Diskretisierung erfolgt über einen Element-zentrierten Finite Volumen Ansatz. Horizontal wird ein unstrukturiertes Mesh verwendet.

Das hydrodynamische Modell wurde an einen ökologischen Gleichungslöser (ECO Lab) als Basis für das Wasserqualitätsmodell gekoppelt. ECO Lab (DHI, 2013) ist eine numerischen Gleichungslöser zur Programmierung von ökologischen Modellen.

In der vorliegenden Untersuchung wurde ein Eutrophierungsmodell in ECO Lab verwendet, um die Konzentrationen von Phytoplankton, Chlorophyll-a, Zooplankton, Detritus, anorganischen Nährstoffen und Sauerstoff in der Elbe bei Hamburg zu berechnen. Makroalgen wurden im Modell nicht berücksichtigt, da ihr Einfluss in diesem Teil der Elbe vernachlässigbar ist. Das Eutrophierungsmodell ist in das Advektions/Dispersionsmodul integriert, welches den physikalischen Transport im Modell rechnet.

Das Modell wurde zur Berechnung der Sauerstoffkonzentration im Hafen von Hamburg verwendet. Speziell die Veränderungen der Sauerstoffkonzentration im Reiberstieg, einem Kanal im Süden Hamburgs, der normalerweise zur Süderelbe hin durch eine Schleuse verschlossen ist, sollte im Modell erfasst werden. Die geschlossene Schleuse soll vor allem den Eintrag und die Sedimentation von Schwebstoffen in das Hafengebiet verhindern. Im Rahmen der Planungen für eine neue Schleuse am Reiberstieg sollte mithilfe des Modells untersucht werden, ob durch eine zeitweilige Öffnung der Schleuse die Sauerstoffkonzentration im Reiberstieg verbessert werden kann. Die Untersuchung zeigt, dass die Resuspension und anschließende sauerstoffzehrende Mineralisation von organischem Material eine wichtige Rolle spielt. Eine optimale Steuerung der Schleuse muss ein Kompromiss sein, zwischen möglichst langer Öffnung der Schleusentore, um viel sauerstoffreiches Wasser in den Hafen zu spülen, und einer möglichst geringen Resuspension von organischem Material, da diese immer eine Sauerstoffzehrung durch Mineralisation nach sich zieht.

Schlagwörter

Sauerstoff, Nährstoff, Wasserqualität, Elbe, Modell, MIKE 21, ECO Lab

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1 Introduction

Although modelling hydrodynamics is well-established since years, ecological modelling rather plays a minor role. As ecological models are usually very complex, a major problem so far was computational time. But with decreasing prices for powerful computers ecological modelling more and more evolves into a tool for investigating anthropogenic impacts in coastal waters.

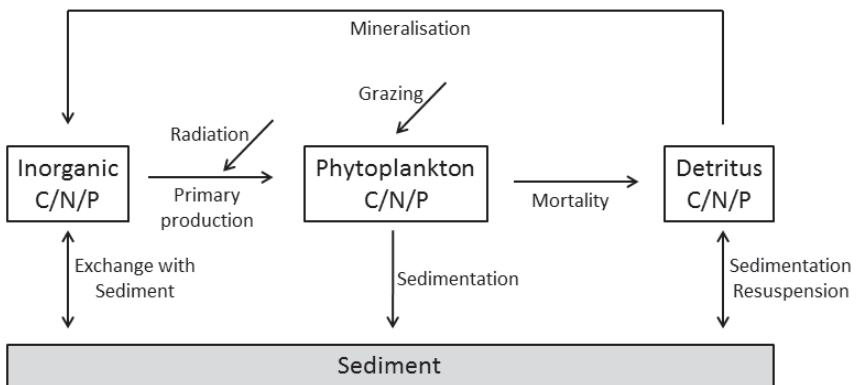


Figure 1: Typical conceptual ecological model.

The complexity of such models derives from tight interlocking biological and chemical processes, which highly depend on each other. The concentration of oxygen for example depends on temperature and the concentration of phytoplankton, whereas the phytoplankton concentration itself depends on light and the availability of nutrients. This in turn means, that an oxygen-model requires to model temperature and all nutrient cycles (especially for carbon, nitrogen and phosphorous) as well. A typical conceptual model which neglects the influence of benthic vegetation is shown in Fig. 1.

All phytoplankton is built up in primary production from inorganic matter under the influence of light. This primary production is the only oxygen producing process in water. All dead matter (detritus) in turn is mineralised under oxygen consumption to inorganic

matter. Both organic pools (phytoplankton and detritus) are subject to settling. Usually only the detritus fraction can resuspend again, as it is often assumed, that settled phytoplankton dies off.

As light is the superior driver in primary production, all factors that have an influence on light penetration, e.g. turbidity, directly impact the dissolved oxygen. Another important factor is that turbidity often enhances the biological oxygen demand (BOD), because organic compounds mineralise after resuspension, which consumes dissolved oxygen.

Here we present a study that deals with the problem of resuspended matter that caused strong oxygen depletions in the Port of Hamburg.

The so called “Reiherstieg” in the southern part of the Port of Hamburg is a port basin which is closed at its southern end by a sluice (Fig. 2). To prevent suspended solids from entering the Reiherstieg the sluice is usually closed, which causes long retention times and low oxygen concentrations. As this sluice is planned to be renewed, it was debated if an intermittent opening of the sluice gates could lower the retention time and improve the oxygen conditions within the port. Obviously any opening would lower the retention time, but it remained unclear, if sediments could resuspend due to increased current velocities and cause an increase of BOD in the Reiherstieg.

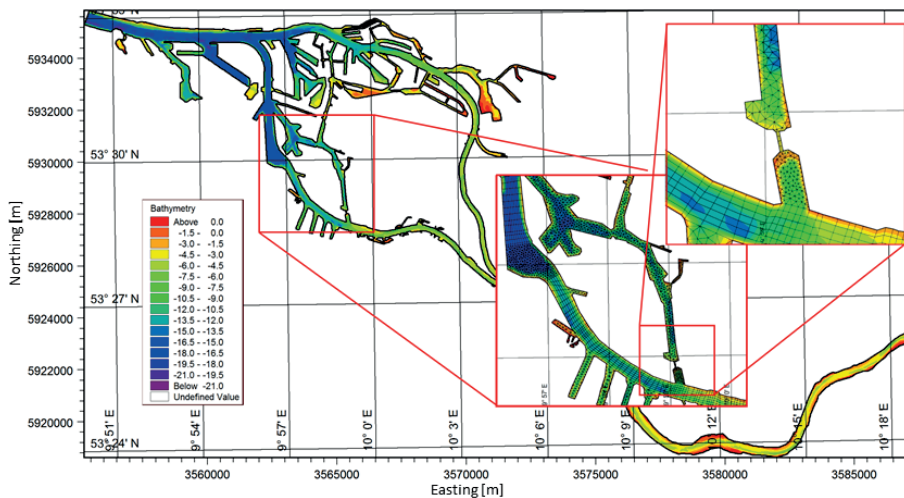


Figure 2: The “Reiherstieg” in the Port of Hamburg.

2 Methods

2.1 Hydrodynamic Model

A MIKE 21 (DHI 2013) flexible mesh model was used to simulate the hydrodynamic conditions in the River Elbe around Hamburg. The model is based on the numerical solution of twodimensional incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature and density equations and is solved by a

turbulent closure scheme. The spatial discretisation is performed using a cell-centred finite volume method. In the horizontal plane an unstructured mesh is used.

The model domain (Fig. 3) extends in the tidal part of the River Elbe from the weir in Geesthacht (upstream) to Blankenese (downstream).

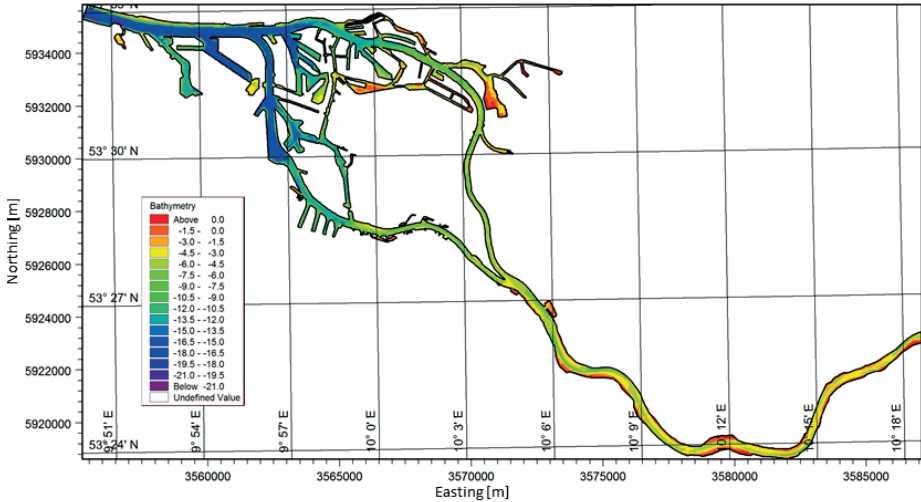


Figure 3: Model domain of the M21FM model.

2.2 Ecological Model

Into the 2D hydrodynamic model we embedded an ecological model, in order to simulate the simultaneous processes of transport, dispersion and biological/chemical processes. The ecological model is based on the DHI ECO Lab template “Eutrophication 1” (DHI 2013), which describes the following 11 state variables, which are subject to advection and dispersion:

- Phytoplankton Carbon (gC/m³)
- Phytoplankton Nitrogen (gN/m³)
- Phytoplankton phosphorous (gP/m³)
- Chlorophyll-a (g/m³)
- Zooplankton carbon (gC/m³)
- Detritus carbon (gC/m³)
- Detritus nitrogen (gN/m³)
- Detritus phosphorus (gP/m³)
- Inorganic nitrogen (gN/m³)
- Inorganic phosphorous (gP/m³)
- Dissolved oxygen (g/m³)

Benthic vegetation was considered to be negligible in this tidal part of the River Elbe and the Port of Hamburg.

A particular focus was set to the resuspension of sediments close to the sluice due to higher currents speeds when the gates are opened. Therefore sediment samples have been

taken at the sluice to measure the grain size distribution. Based on these measurements a correlation between current speed and resuspended sediment for different grain size classes was established (Fig. 4).

Additionally the biological oxygen demand (BOD) of the sediment samples was measured. The empiric correlations for resuspension and the BOD were then implemented into the ecological model. By this approach we ensured that the biological/chemical oxygen consumption caused by the mineralisation of resuspended sediments at the sluice gate is implemented appropriately in the model.

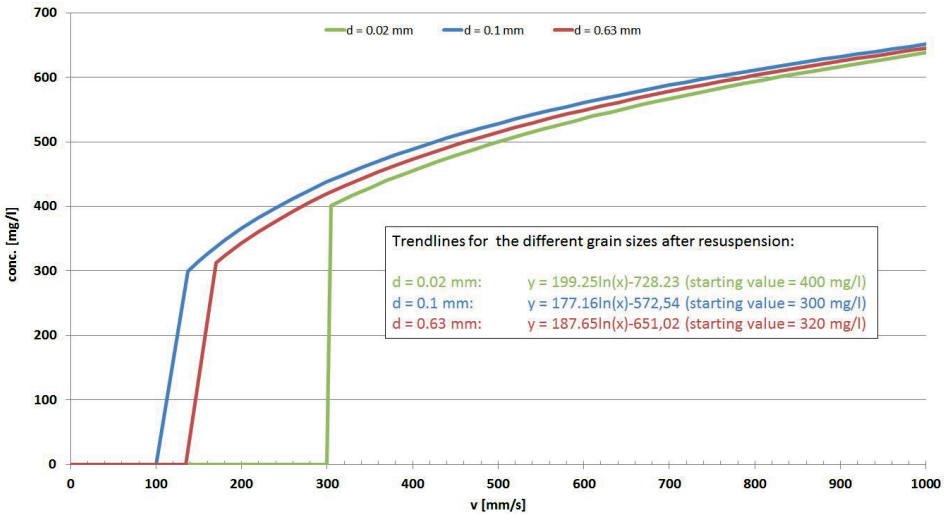


Figure 4: Correlation between current speed and resuspended sediment for different grain size classes.

3 Results

3.1 Hydrodynamic Model

The hydrodynamic model was calibrated against the water level at the gauging stations in St. Pauli (Fig. 5) and Bunthaus (Fig. 6). At tidal low water the model tends to overestimate the measured values, especially at Bunthaus, but in general there is a good accordance between measured and simulated water levels.

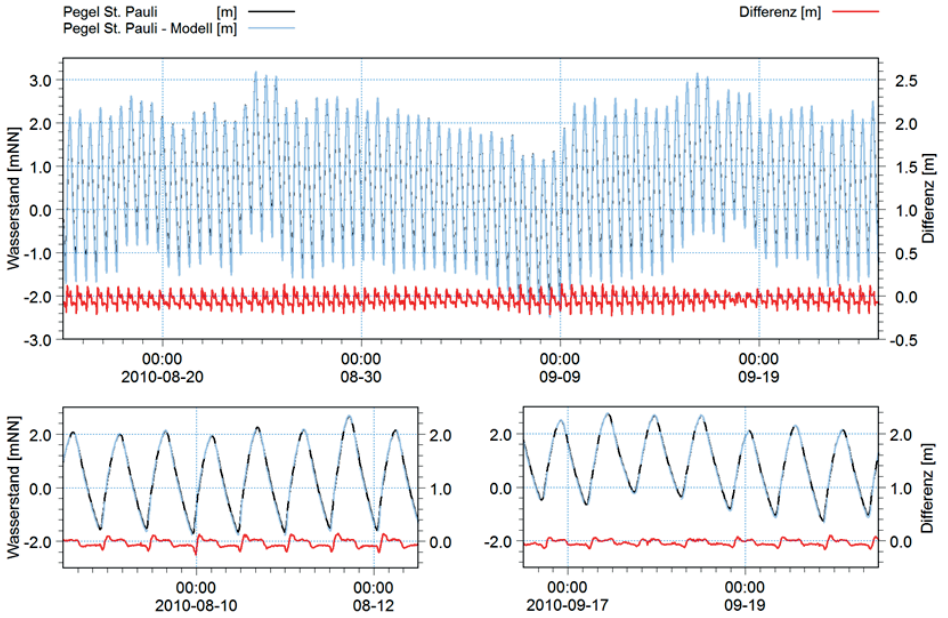


Figure 5: Measured (black line) and simulated (blue line) water levels at the gauging station St. Pauli. The red line denotes the difference between measured and simulated values.

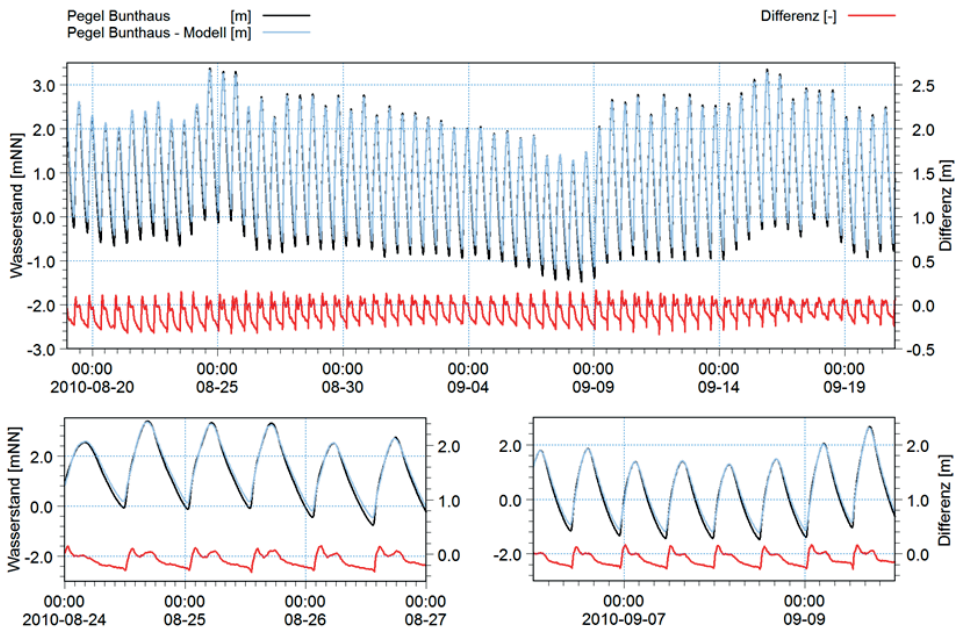


Figure 6: Measured (black line) and simulated (blue line) water levels at the gauging station Bunthaus. The red line denotes the difference between measured and simulated values.

3.2 Ecological Model

The oxygen concentrations were calibrated against measurements at two monitoring stations. One oxygen sensor was deployed south of the Reiherstieg-sluiice; the second sensor was deployed in the Reiherstieg north of the sluice (Fig. 7).

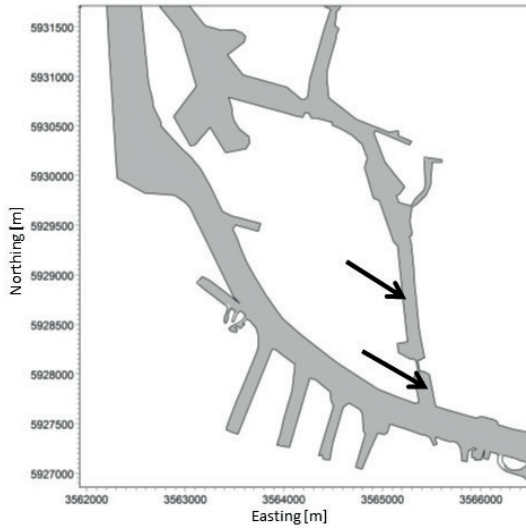


Figure 7: Positions of the two oxygen probes.

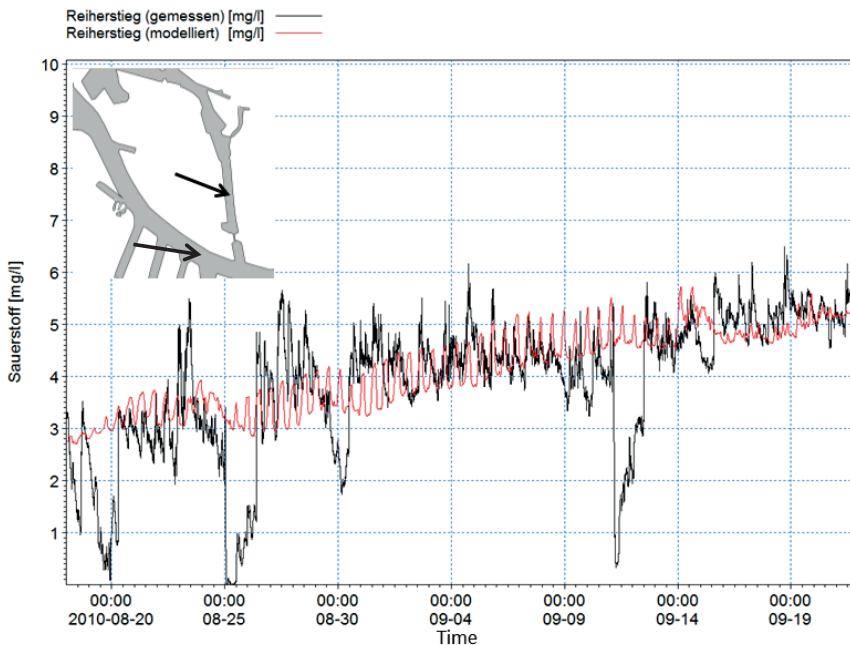


Figure 8: Measured (black) and simulated (red) oxygen concentrations in the Reiherstieg.

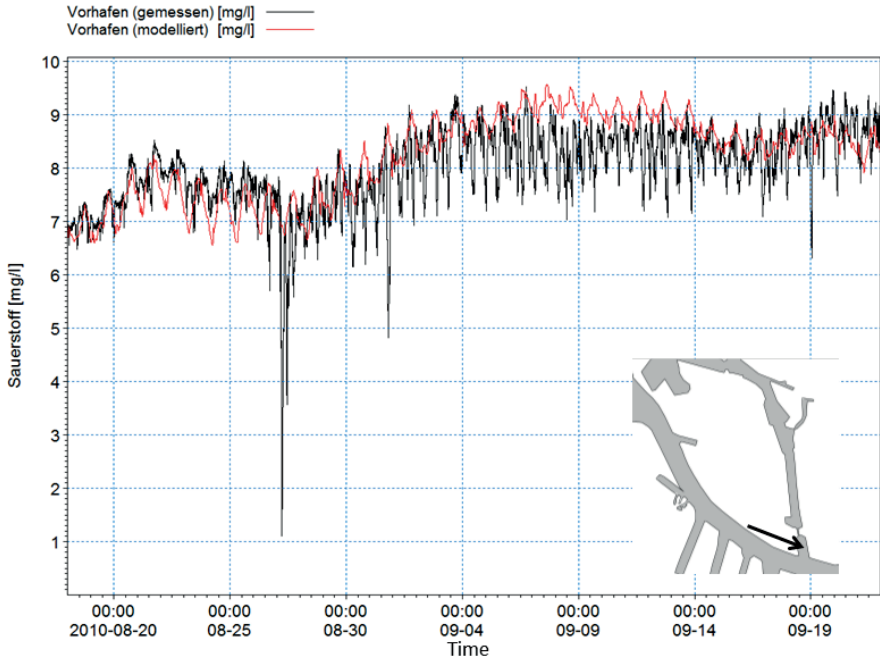


Figure 9: Measured (black) and simulated (red) oxygen concentrations south of the Reiherstieg-sludge.

The oxygen measurements showed strong fluctuations which did not coincide with a diurnal or tidal cycle (Fig. 8 and Fig. 9). It is likely that the strong decreases in the Reiherstieg could be caused by ship movements, where large amounts of sediments are resuspended. Another explanation could be local industrial discharges or introduced organic waste after rain events. However due to lacking data these possible explanations cannot be confirmed. Consequently these events cannot be reproduced by the present model. Apart from these unexplained events the model reproduces the general trends and diurnal and tidal cycles.

After calibration a scenario with intermittent open sluice gates was run. The model was set up in such way that the gates opened one hour after high tide, and closed one hour before low tide. The intention of this controlled strategy was, to pump as much water from the southern branch of the Elbe into the Reiherstieg. During flood period the gates were kept close to prevent water from downstream to enter the Reiherstieg. The downstream water usually has a lower dissolved oxygen concentration than the upstream water, therefore it was intended to pump as much water from upstream into the Reiherstieg, and prevent water from downstream to enter the Reiherstieg.

Fig. 10 shows the general development of dissolved oxygen, BOD and resuspended sediment over several tides. The time series depicts the situation directly at the sluice gates in the Reiherstieg. For dissolved oxygen a clear positive effect can be seen when the gates are opened. Large amounts of water with a high dissolved oxygen concentration enter the Reiherstieg, which immediately raises the dissolved oxygen concentration at the sluice gates.

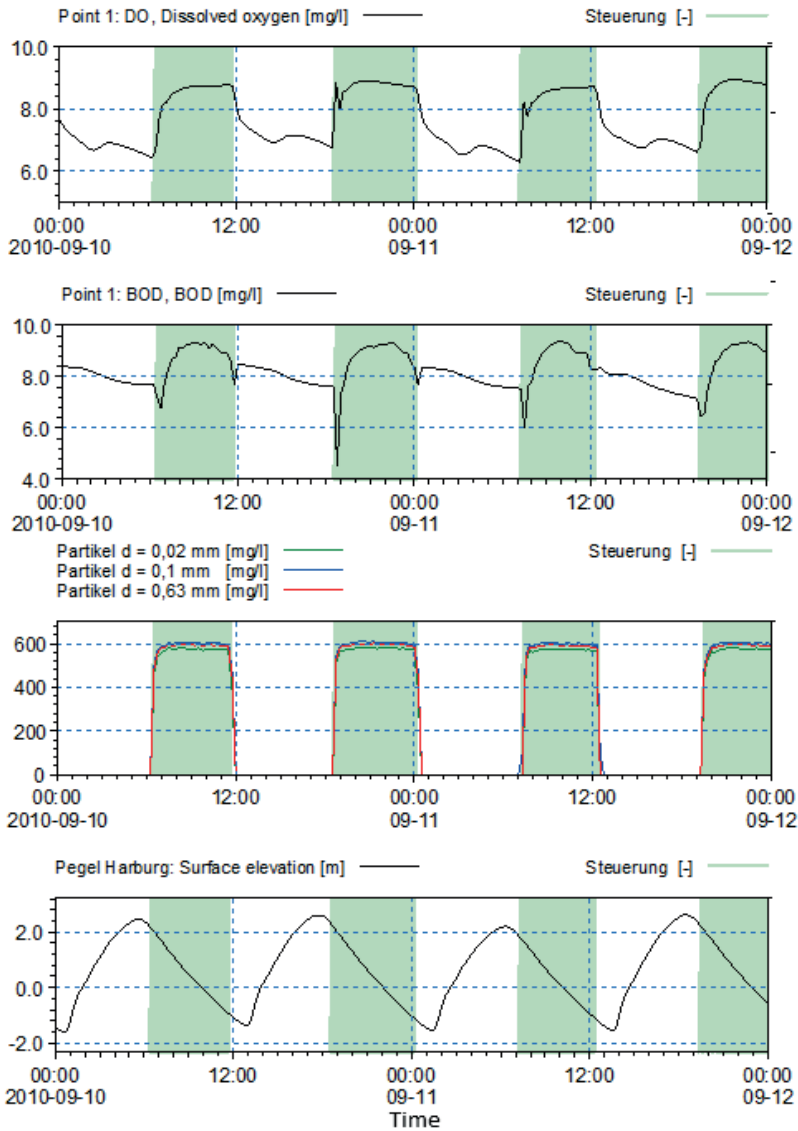


Figure 10: Characteristics of dissolved oxygen, BOD and resuspended sediments at the sluice gate during different tide periods. The lowest panel shows the water level. Periods when the sluice gates are opened are highlighted in green.

Synced with the entry of water and oxygen into the Reiherstieg, large amounts of sediments resuspend due to higher current speeds at the gate (Fig. 10). In consequence, the BOD rises as well.

In between, when the gates are closed, the BOD declines, because the organic compounds start to mineralise. This process is also reflected in the dropping concentration of dissolved oxygen, as the mineralisation is an oxygen consuming process.

Fig. 11 and Fig. 12 show the spatial effect of the intermittent opening for dissolved oxygen at high tide and low tide on 30.08.2010. At the initial state (Fig. 11) the lowest dissolved oxygen concentration in the Reiherstieg is around 1.5 mg/l. Depending on the tide the lowest concentration oscillates between the “Äußerer Schmidtkanal” and the “Mittlerer Reiherstieg”. The intermittent opening (Fig. 12) does not change the spatial pattern, but causes much lower dissolved oxygen concentrations around 0.5 mg/l caused by the oxygen consuming BOD. Only on the first few hundred metres north of the gate the positive effect of oxygen rich Elbe water is visible.

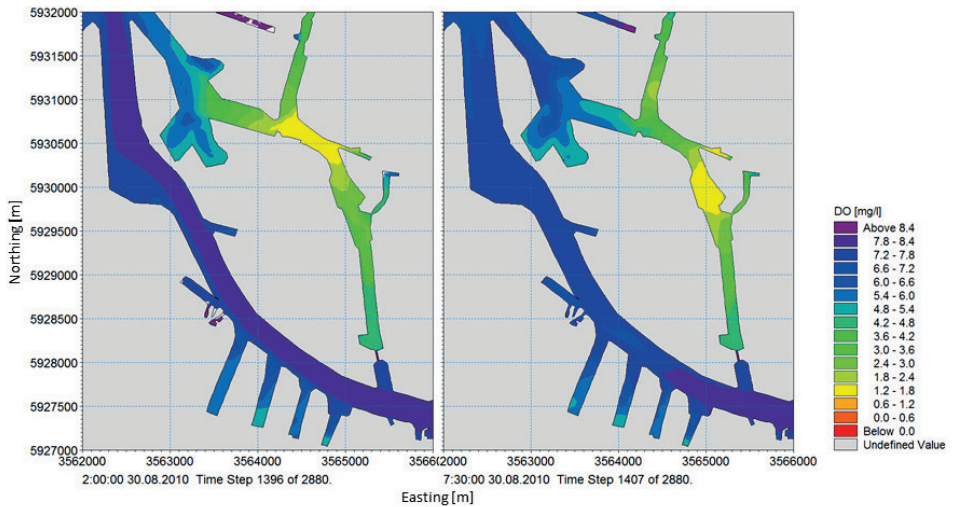


Figure 11: Dissolved oxygen concentration in the Reiherstieg in the scenario with permanently closed sluice gates. The left panel shows conditions at low tide, the right panel shows high tide.

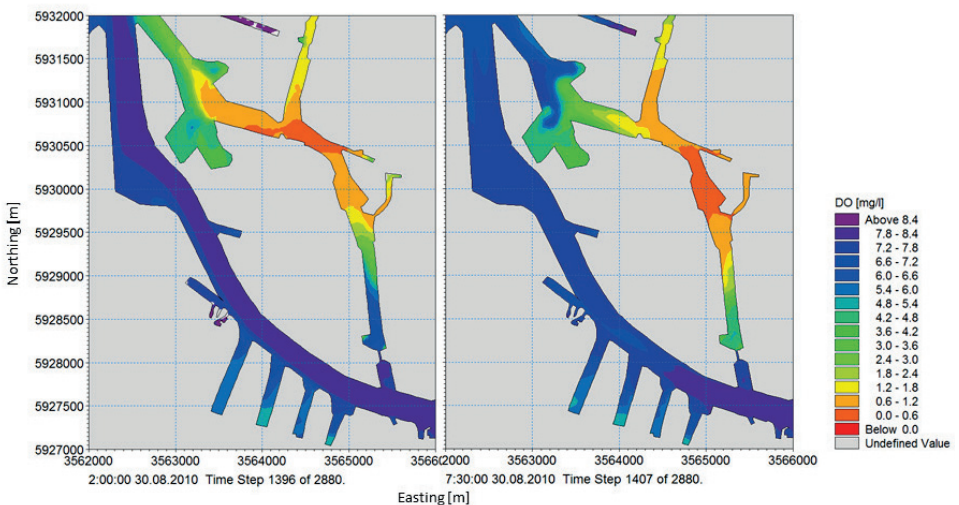


Figure 12: Dissolved oxygen concentration in the Reiherstieg in the scenario with intermittently opened sluice gates. The left panel shows conditions at low tide, the right panel shows high tide.

4 Discussion

The present study shows the influence of mineralising resuspended sediment. The aspired improvement for dissolved oxygen by intermittent opening of the sluice gates shows unexpectedly worth oxygen conditions in wide areas of the Reiherstieg. The positive effect of oxygen rich Elbe water vanishes after a few hundred metres in the Reiherstieg. North of this little zone the dissolved oxygen decreases to lower values than to the scenario with permanently closed gates. This decrease can be attributed to the strong oxygen consumption of mineralising material (BOD), which derives mainly from resuspended sediments due to high current speeds around the sluice gates. The material is transported northwards into the Reiherstieg and starts to mineralise, which causes strong oxygen consumptions in the centre of the Reiherstieg. Although large amounts of oxygen rich water enters the Reiherstieg, this positive effect is completely counteracted by the BOD in most areas of the Reiherstieg.

The present results show that a sustainable positive effect for the oxygen concentration in the Reiherstieg is a compromise between getting as much as possible oxygen rich Elbe water, but keeping the BOD as low as possible. Therefore the current has to be kept low to prevent sediments to resuspend.

5 References

- DHI: MIKE 21 & MIKE 3 Flow Model FM, Hydrodynamic and Transport Module, Scientific Documentation, 2013.
DHI: ECO Lab, Short scientific description, 2013.