A 3D MATHEMATICAL MODEL OF VISTULA LAGOON HYDRODYNAMICS - GENERAL ASSUMPTIONS AND RESULTS OF PRELIMINARY CALCULATIONS

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ABSTRACT
The paper presents general assumptions and preliminary results of calculations with use of the 3D hydrodynamic model (Delft3D Flow), applied to determine salinity and flow fields in the Vistula Lagoon. The model uses a curvilinear orthogonal grid with variable dimensions of grid cells starting from 200 m up to 1 300 m. In the vertical direction 11 layers are used in the ó-co-ordinate approach. Water exchange through the Baltiysk Strait, with salt transport from Gulf of Gdansk, is described as open boundary condition in the Strait.
Preliminary calculations of the velocity and salinity fields were performed. There were ten open boundaries defined with two different conditions- water level variations in Baltiysk Strait and flows in case of rivers discharging to the Lagoon. Wind action was another important forcing factor to run the model. The model was calibrated against salinity data available for year 1998. The results of calculations proved that even in such shallow water reservoir differences in vertical velocities distribution of wind driven currents and in vertical distribution of salinity should be expected.

KEYWORDS: Vistula Lagoon, hydrodynamics, 3D hydrodynamic model, currents, salinity

INTRODUCTION

The Vistula Lagoon (838 km^2) is located in the southeastern part of the Baltic Sea (Fig. 1).

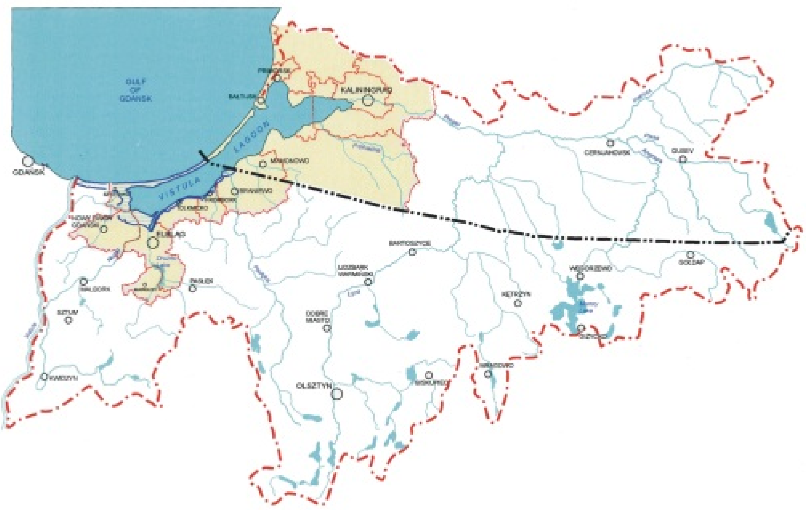

Fig. 1. Vistula Lagoon and its drainage basin

Its length is of 90,7 km, average width - 8,9 km and average depth - 2,7 m. It is connected with the Gulf of Gdansk through narrow channel - the Baltiysk Strait (width of 440 m, over 2 km long, mean depth of 8.8 m) where intensive water exchange takes place influencing water dynamics and quality in the Lagoon (Fig. 2). Saline water inflows occur here frequently. The total volume of marine water inflowing to the Lagoon during 24 hours is estimated as 23 million cubic meters, which makes about 1% of the total water body of the Lagoon (Chubarenko B.V. & Chubarenko I.P., 1998). Water balance of the Lagoon is presented in Table 1.

Table 1. Water balance of Vistula Lagoon (1951-1965, [km^3], [%]), (Silicz, 1975)

	Ingoing (km^3)	%
Water from the rivers	3.62	17.1
Marine inflow	17.00	80.2
Atm.precipitation	0.50	2.4
Ground water	0.07	0.3
Total	21.19	100.0
	Outgoing (km^3)	%
Flowing to the sea	20.48	96.9
Evaporation	0.65	3.1
Total	21.13	100.0

Baltiysk Strait continues up to the harbor of Kaliningrad as a fairway (navigation channel) crossing the Lagoon. The channel is twice deeper than the largest natural depth in the Lagoon. Despite its relative narrowness, it plays an important role as a way of salt transport from the Gulf to the Lagoon. The Lagoon is also supplied with inland waters mainly by rivers (Fig. 2).

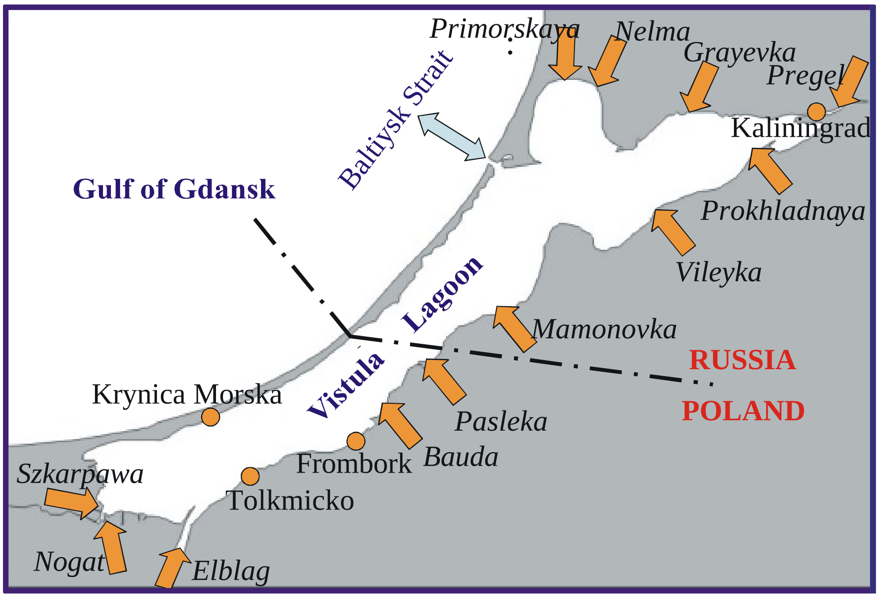

Fig. 2 Water discharges to the Vistula Lagoon

Average salinity in the Lagoon varies from 7 psu in the area of the Baltiysk Strait to 1.8 psu in the bottom layers in the area of Elblag River (Bochenski, Talaga, Olech, 1999).
Recent research indicates an existence of the vertical variability of water currents in the Vistula Lagoon despite its relatively small depths. In Baltiysk Strait area also the presence of

variable salinity distribution over the depth has been measured, as a result of water exchange with the Gulf of Gdansk (Chubarenko B.V. & Chubarenko I.P., 1998). This suggests a 3D nature of hydrodynamic processes in the Lagoon. Therefore in order to simulate properly current's velocities and salinity distributions it is necessary to use a 3D model of the Lagoon hydrodynamics. This case is studied within an EU 5 FP project MANTRA-East – "Integrated Strategies for the Management of Transboundary Waters on the Eastern European fringe – the pilot study of Lake Peipsi and its drainage basin", which has been extended by additional study area - the Vistula Lagoon.

METHODS

In the past various numerical models were applied to investigate flow fields and mass transport in the Vistula Lagoon. However, these were 2D models that didn't include vertical variability of investigated parameters.

First 2D models were used for operational purposes in order to predict floods that occur in the Zulawy region during winter storm season. They were useful tools for water level forecasts in the Lagoon (Catewicz, Jankowski, 1983, Szymkiewicz, 1992). Later, starting from 1994, followed 2D models based on MIKE21 modeling system. The system comprised few different modules: hydrodynamics, water quality and eutrophication that were used for modeling of hydrobiological and hydrochemical processes (Oldakowski, Kwiatkowski, 1995, Chubarenko B.V. & Chubarenko I.P., 1997, Kwiatkowski, Rasmussen, Ezhova, Chubarenko B.V., 1997, Chubarenko I.P., Tchepikova, 2001).

At present the 3D hydrodynamic model has been applied to simulate Vistula Lagoon hydrodynamics. The model bases on the Delft3D modeling system (WL | Delft Hydraulics, 2001). The FLOW module of Delft3D is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid in a water reservoir. It takes into account also inflows from rivers and other point sources. The model uses as an input real physical parameters of the water: its salinity, temperature, and diluted or suspended conservative constituents, and gives as output their 3D distribution in the reservoir.

In MANTRA-East project the 3D model has been applied to calculate water current velocities and salinity distributions, depending mainly on wind velocities and direction, discharges from rivers and water exchange with the Baltic Sea. The results from Delft3D Flow model are a base for calculations of hydrochemical and hydrobiological processes in the Lagoon with use of Delft3D WAQ - water quality model.

The model is based on the non-stationary equations of motion and continuity as well as equations of state and salinity diffusion. The equations are solved numerically using orthogonal curvilinear system of horizontal coordinates that give good fitting of the computational grid to the shape of modeled area. Model uses a horizontal grid consisting of 912 cells (Fig. 3).

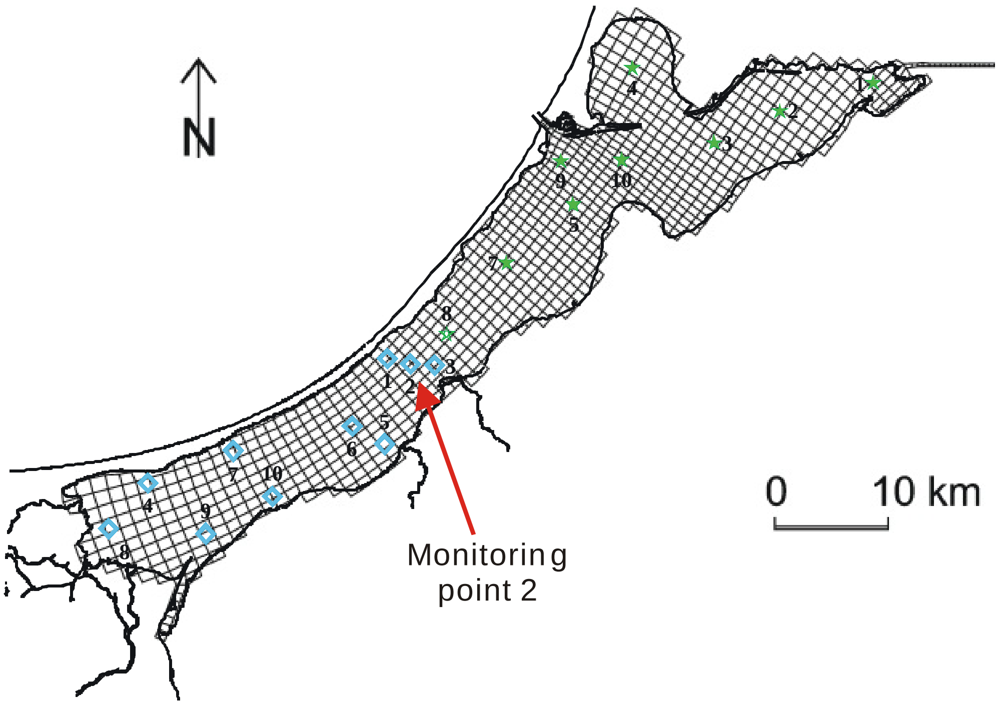

Fig 3. Computational horizontal grid of the Vistula Lagoon hydrodynamic model and monitoring points.

The cell dimensions vary from 200 to 1300 m. The smaller cells are applied close to the Baltiysk Strait, where large velocity gradients are expected. Vertical Sigma-coordinates system assumes the same number of proportional vertical layers in each horizontal cell. Vertical grid of the model consists of 11 layers of different thickness, from 4 to 15% of actual depth. The computational time step is equal to 1 minute.
The following forcing factors controlling the water currents and salinity distribution are taken into account: wind action, river run-off, sea level and salinity variations at the seaward boundary.
Boundary conditions on ten open boundaries are defined as follows:

- in the Baltiysk Strait measured every 6 hours water levels and actual salinity monitored once a day;
- in nine rivers (out of 12 – Fig. 2) monthly averaged discharges of fresh water.

There are relatively large differences between discharges in particular rivers. The greatest river is Pregel and it supplies the Lagoon with about half of the total amount of inflowing fresh inland water. Among other smaller rivers, Pasleka River only has multi-seasonal average discharge exceeding 10% of total supply of fresh water.
The wind stress is calculated from actual wind data measured in Baltiysk, Russia, with the time step of 6 hours during the whole year 1998. At the bottom the Manning friction formula is applied, with coefficient value equal to 0,02. The friction is rather large here because of small depths and reed with other water vegetables in the Lagoon. The Delft3D is equipped with several turbulence models. In this case the *k*-e turbulence model is applied. There are two reasons for that choice: one is the presence of density stratification in the Lagoon, and the second is the rate of discharge in the Baltiysk Strait region.

RESULTS AND DISCUSSION

The model was calibrated against water levels and salinity. The calibration point for water levels was Nowa Pasleka (close to Pasleka River discharge, Fig. 2). The agreement of calculated and measured water levels was very good here. Calculated water levels for the whole year 1998 correspond very well to the measured values, with several small differences only, in cases of fast changes (Fig. 4).

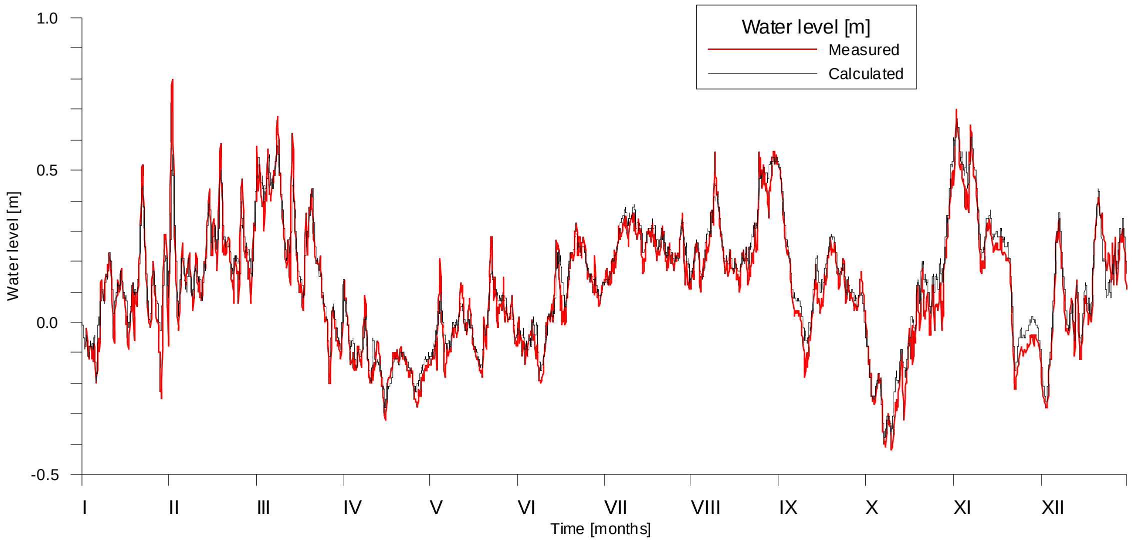

Fig 4. Measured and calculated water levels in Nowa Pasleka in 1998.

However, the main calibration parameter was the salinity of the Lagoon water. In case of insufficient flow velocity monitoring data it is practiced to use salinity for hydrodynamics calibration. One of the calibration points (monitoring point No 2) was set at the Polish/Russian border in the center of the Lagoon (Fig. 3). The model simulated the salinity distribution in this point rather correctly (Fig. 5).

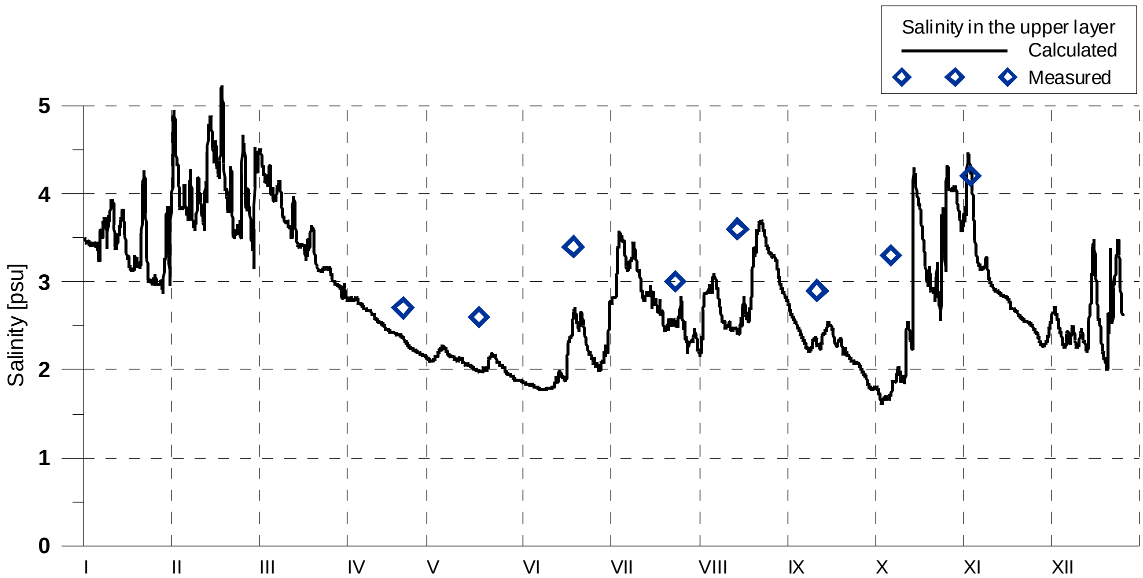

Fig 5. Measured and calculated salinity distributions in the monitoring point No 2, in 1998.

The best fitting of the model simulation to the measured parameters was achieved using horizontal eddy viscosity $E = 0.1\ m^2/s$, and horizontal eddy diffusivity $D_h = 1\ m^2/s$. Calculated spatial salinity distribution agreed with the measured during the greater part of the year 1998. In the last months of the year small differences between measured and calculated values were observed, of about 0,5 – 1,0 psu, in south–western end of the Lagoon. However, these are preliminary results only and better agreement of calculated and measured parameters is expected after further calibration of the model.

Two different cases of flow field distributions are presented in Fig. 6: one after large inflow of saline water from Gulf of Gdansk, and the second - after relatively large outflow of the Lagoon water to the Gulf.

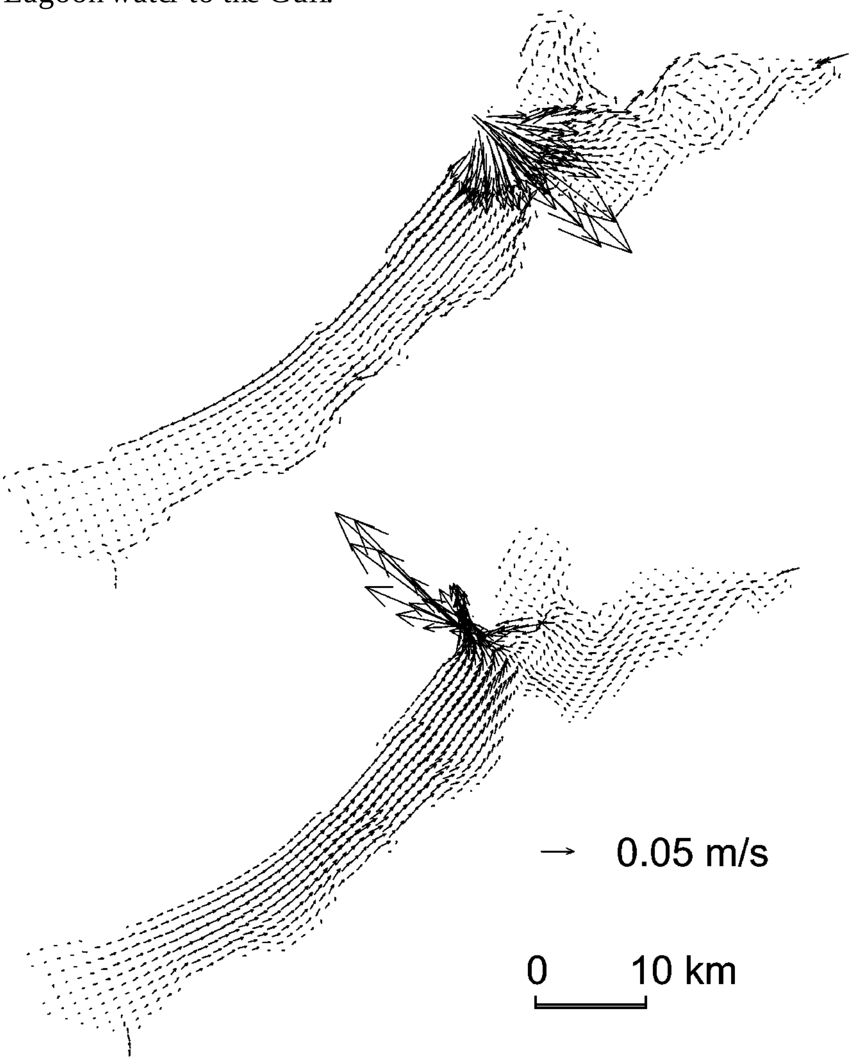

Fig 6. Calculated velocity distribution in the upper layer during inflow in March 1998 of saline waters from Gulf of Gdansk (upper) and outflow from the Lagoon in September 1998 (lower).

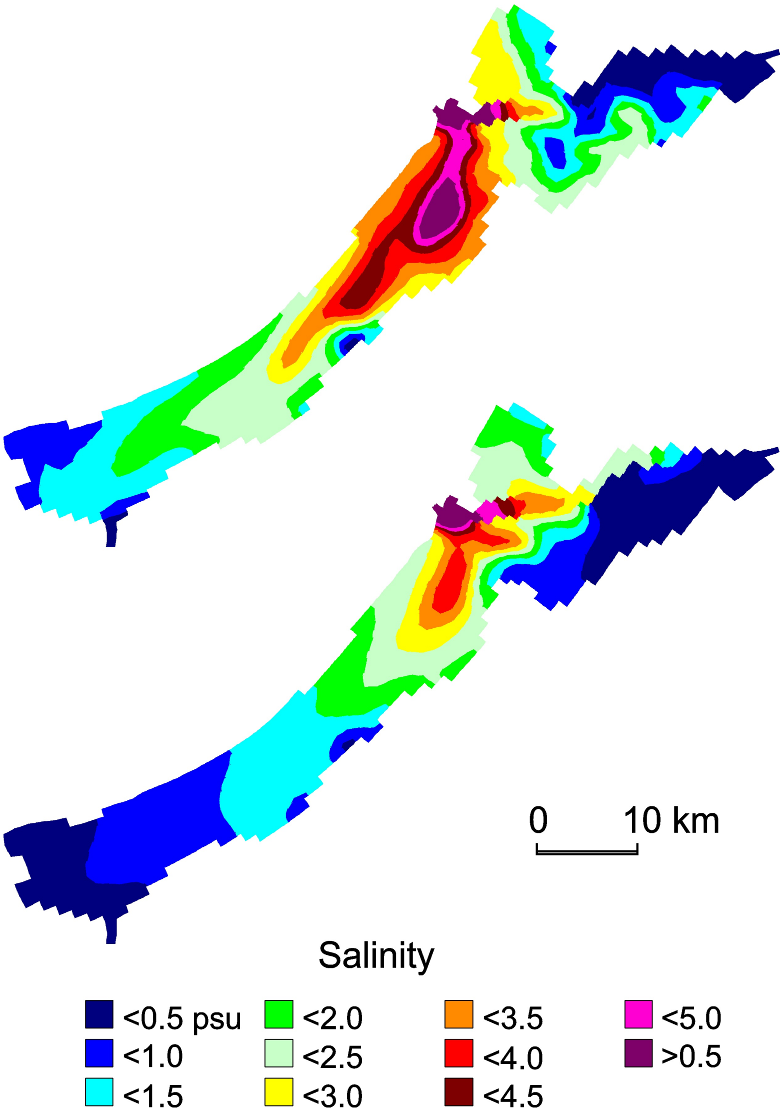

Fig 7. Calculated salinity distribution in the upper layer during inflow in March 1998 of saline waters from Gulf of Gdansk (upper) and outflow from the Lagoon in September 1998 (lower).

Results of calculations indicate that salinity along longitudinal axis of the Lagoon is greater than close to borders, as it is shown in the upper picture of the Fig. 7. That is a result of greater horizontal velocities in deeper parts of Lagoon where saline water inflowing from Gulf of Gdansk penetrates the Lagoon faster. The 3D character of the hydrodynamics was observed in part of velocity calculation results. Over the depth some differences in velocities' direction occurred. However, the calculated salinity was almost the same in the vertical direction and that was in agreement with the most of the measured data. More significant vertical differences are expected at the entrance to the Strait, where greater salinity gradient was observed and calculated.

CONCLUSIONS

The Delft3D model properly reproduces water level and salinity variations in the Vistula Lagoon during the greater part of the year. Those factors where a base for the calibration of the model as an indication of proper simulation of flow fields in the Lagoon. In order to model water quality processes correctly it is necessary to produce a reliable 3D velocity pattern. Better results can be achieved by better description of conditions at open boundaries. The most important are the conditions in the Baltiysk Strait, where more frequent observations of water levels and salinity are necessary. This would improve the description of salinity balance in the Lagoon.

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