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Hydrological forecasting in the Oder Estuary using a three-dimensional hydrodynamic model

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Abstract

A three-dimensional operational hydrodynamic model, developed at the Institute of Oceanography, University of Gdańsk was used to forecast hydrological conditions in the Oder Estuary. The model was based on the coastal ocean circulation model known as the Princeton Ocean Model (POM). Because of wind-driven water backup in the Oder mouth, a simplified operational model of river discharge, based on water budget in a stream channel, was developed. Linking these two models into a single system made it possible to forecast water levels, currents, water temperature, and salinity in the estuary. A good fit between the observed and computed data allowed to consider the model as a reliable environmental tool. Obtaining a hydrological forecast via a quick website access gives potential users an opportunity to predict the day-by-day course of processes that may affect different areas of human life and activities, e.g., navigation, port operations, flood protection of coastal areas; the predictions may also be used in studies of coastal processes in the estuary.

Introduction

The Oder River forms one of major estuaries in the southern Baltic Sea (Fig. 1). In its downstream reach, the Oder opens into the Szczecin Lagoon, a coastal water body of about 680 km^2 surface area and 3.8 m in mean depth. Water circulation in the estuary is greatly affected by the navigational channel, 10–11 m deep and 250 m wide, which intersects the lagoon. The Oder discharge is buffered in the Szczecin Lagoon before it drains into the Baltic coastal zone through three straits: the Świna, the Dziwna and the Peenestrom. The Świna serves as the most important conduit of the water exchange between the Lagoon and the Bay, as three quarters of the total exchange take place there. Usually, the exchange proceeds as pulse-like inflows and outflows. During flooding events, however, the outflow from the Lagoon into the Pomeranian Bay can change from pulse-like to a continuous flow (Majewski, 1980; Buchholz, 1990, 1991; Jasińska, 1991; Mohrholz et al., 1998).

The Pomeranian Bay, with a mean depth of about 13 m, is bordered to the south by the Polish and German coasts and to the north by the 20 m depth contour. The dynamic regime of the southern part of the Bay is governed mainly by a wind-driven Ekman current and a compensating one in the deep layer. When westerly winds prevail, the coastal current transports the Lagoon waters eastwards in a narrow band. During periods of prolonged prevalence of easterly winds, advection associated with the Ekman offshore transport separates the Szczecin Lagoon waters from the Pomeranian coast, replacing it by the upwelled Bay water. Entering the Pomeranian Bay, the freshly discharged lagoon water is transported along the coast of the Usedom Island (Majewski, 1974; Lass et al., 2001).

Figure 1. The modelled regions: the Baltic Sea and the Oder Estuary with localizations of stations. Legend: 1, the West Oder River; 2, the East Oder River; 3, the Dąbie Lake; 4, the Szczecin Lagoon; 5, the Świna Strait; 6, the Dziwna Strait; 7, the Peenestrom Strait.

The influence of the Oder River in the Pomeranian Bay changes in its range over a year and is periodically noticeable throughout the water mass. The strongest impact of fresh water is observed in the straits and at the coasts, with some eastward-trending asymmetry resulting from the predomination of westerly winds. The water inflows from the North Sea occasionally affect the bottom layer of the Bay's water column. Then, on account of the deep fairways, high salinity is recorded in the straits. However, should any stratification develop in the shallow Pomeranian Bay, exposed to enhanced dynamics, it can be easily broken up as a result of strong wind (Majewski, 1974; Matthäus & Franck, 1992; Lass et al., 2001).

Over the recent years, the hydrodynamic regime of the Baltic Sea has been a target of many numerical studies, starting from the 1970s research on wind-driven circulation (Kowalik, 1972; Kowalik & Staśkiewicz, 1976; Jankowski & Kowalik, 1980). Subsequently, other numerical models describing the physical state of the Baltic Sea in response to atmospheric and hydrological forcing have been developed by, i.a., Stigebrandt (1983, 1987), Omstedt (1990), Lehmann (1995), Lehmann & Hinrichsen (2000), and Jankowski (2002a). Fennel & Sturm (1992), Fennel & Seifert (1995), Kowalewski (1998), and Jankowski (2000, 2002b) studied, with the help of numerical models, dynamics of specific phenomena observed in nature, e.g., upwellings. The research of latter two authors was based on the Princeton Ocean Model (POM).

Numerical modelling has become an essential tool in coastal management and environmental protection of the Oder Estuary. In the 1980s, hydrodynamic regime of the Lower Oder River flows was described in detail by Ewertowski (1988). Further studies focused on, i.a., the influence of wind field on the calculated water levels (Ewertowski, 1996, 1998). The hydrodynamic regime of the Szczecin Lagoon–Pomeranian Bay area have been mostly described by 3-D models. The first 3-D hydrodynamic model was developed at the Polish Academy of Sciences' Institute of Hydro-Engeneering (IBW PAN) and at the Hamburg University (Jasińska & Robakiewicz, 1988; Jasińska, 1991; Pfeiffer et al., 1993; Robakiewicz, 1993). Then, a 3-D model known as ESTURO, was worked out at IBW PAN as well (Jasińska & Robakiewicz, 1999). Mohrholz & Lass (1998) developed a simple barotropic box model of the Oder Estuary to study water exchange between the Szczecin Lagoon and the Pomeranian Bay. Another model, the Warnemünder Ostee Model (WOM) based on the GFDL ocean circulation model proved successful in this respect as well (Lass et al., 2001). HIROMB, a 3-D operational numerical model was developed at the Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Hamburg and subsequently extended in cooperation with the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping (Funkquist, 2001). In addition, the Maritime

Institute in Gdańsk extended the model onto the Polish zone of the Baltic (Kałas et al., 2001). Hydrodynamic forecasts produced by that model, based on analysis of meteorological conditions and the 48-hour forecast, cover the whole Baltic Sea and its individual parts.

A reliable forecast of water level, currents as well as water physical variables is essential for the emergency centres and services responsible for coastal flood protection, especially for the protection of polders and zones adjoining river mouths. Therefore, our study focused on application of a 3-D operational hydrodynamic model of the Baltic Sea, developed in 1995–1997 at the Institute of Oceanography, University of Gdańsk, to forecast hydrological conditions in the Oder Estuary.

Model description

The hydrodynamic model

To forecast hydrological conditions in the Oder Estuary, a 3-D operational hydrodynamic model of the Baltic Sea, developed at the Institute of Oceanography, University of Gdańsk was used. Theoretical and numerical solutions of the numerical model were based on the coastal ocean circulation model known as the Princeton Ocean Model (POM), described in detail by Blumberg & Mellor (1987) and Mellor (1996). Adaptation of the model to the Baltic Sea required few changes in the numerical calculation algorithm, described in detail by Kowalewski (1997). The open boundary was located between the Kattegat and the Skagerrak to parameterise water exchange between the North and the Baltic Seas. A radiation boundary condition was applied to average vertical flows. If the instantaneous free surface elevation is higher than the pre-set value, the water outflow from the Baltic occurs and is proportional to the difference between those values. When the sea level in Kattegat is lower, the inflow of waters from Skagerrak takes place. A monthly averaged vertical distribution of salinity was applied to the open boundary, which means that the waters flowing from the North to the Baltic Sea show a climatic vertical distribution of salinity. However, the salinity distribution in the water flowing out from the Baltic Sea is identical as that found at the grid points nearest to the open boundary. It was assumed next that the horizontal temperature gradient in the normal direction of the border equals zero. It means that both the water flowing out and that flowing into the calculation area have identical temperatures. The use of different border conditions for water temperature and salinity can occasionally cause vertical hydrostatic instability adjacent to the open boundary. However, the vertical temperature profile simulated in the model will adjust to the salinity profile to restore the stable density distribution.

To obtain an adequate resolution and reliable data, two grids with different spatial steps were applied: on involved 5 nautical mile (NM)-long steps for the Baltic Sea and 0.5 NM-long ones for the other region that comprises the Pomeranian Bay and the Szczecin Lagoon up to Police at the Oder mouth (Fig. 1). Calculations run parallel for the two areas, information being exchanged on the common boundary on each common time step. All the model variables calculated on the border of one area serve as a boundary condition for the other area. The connection is realised by an algorithm which ensures mass and energy conservation.

The data inputs necessary for the hydrodynamic model of the Baltic Sea are derived from the operational weather model, the solar radiation model, and the model of the Oder discharge (Fig. 2). Meteorological data (wind field, air temperature, atmospheric pressure, and vapour pressure) are supplied by the mesoscale operational weather model known as UMPL (Unified Model for Poland Area), developed by the Interdisciplinary Centre of Mathematical and Computational

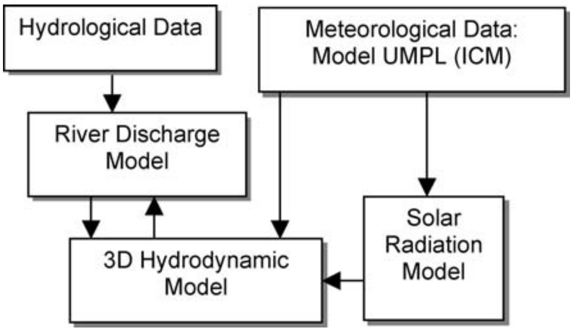

Figure 2. The model scheme.

Modelling, University of Warsaw (Herman-Iżycki et al., 2002). The surface wind stress vector on the sea surface, used in the model, is calculated with the standard formula employing the drag coefficient C_D of 0.002. The solar energy input is calculated for each time step on the basis of astronomical data (the solar zenith angle) and meteorological conditions (cloudiness, atmospheric pressure, air humidity) (Krężel, 1997). Other components of the heat budget at the sea surface are derived from meteorological data and simulated sea surface temperature (Jędrasik, 1997). The climatic monthly mean values of run-off of 153 rivers discharging into the Baltic Sea are supplied by the Baltic Environmental Database (BED, http://data.ecology.su.se/models/bed.htm). The initial conditions for hydrodynamic fields are adopted based on the climate temperature and salinity distributions of the Baltic Sea. The 3-D distributions of water temperature and salinity were prepared using the Data Assimilation System (Sokolov et al., 1997) based on the BED data for 1970–1994.

The Oder discharge model

Modelling the hydrological conditions of the Oder estuary or the whole Pomeranian Bay requires assessment of the Oder discharge at the boundary condition. The ESTURO 3-D model covers the area up to Police in the Lower Oder (Jasińska & Robakiewicz, 1999). However, the discharge at the Police gauge station is not easy to assess as the water level changes in that section are strongly influenced by water level changes in the Szczecin Lagoon and Pomeranian Bay as well as by the wind. When the sea level in the Bay is higher than that in the Lagoon, the Bay's brackish water enters the Lagoon and raises the water level throughout the estuary. As a result of a very low gradient of the Lower Oder River channels, the wind-driven water back-up, forming in the Oder mouth, reaches as high upriver as to Gozdowice, as shown by Buchholz (1990, 1991). The effect is particularly pronounced during autumn and winter storm surges under very strong winds from the northern sector. Hence the Gozdowice gauge station provides the last opportunity to calculate the water level-based discharge from the function $Q = f(h)$. As the wind-driven water back-up in the Oder mouth occurs only occasionally, some studies (e.g., Mohrholz & Lass, 1998) neglect the effect and use the river discharge measured at Widuchowa (105 km upstream of the Oder mouth).

In our study, a simplified operational model of the Oder discharge was developed. The model is based on the water budget in a stream channel between two profiles A_1 and A_2 for which current water level data are available (Fig. 3). In time Δt, the changes of water level Δh_1 and Δh_2 in profiles A_1 and A_2 cause the change of water volume included in the section:

$$\Delta V = P_m \cdot \Delta h_m$$

where: P_m is the average free water surface area; Δh_m is the mean water level difference at a section between A_1 and A_2.. Assuming the lack of precipitation and evaporation as well as no additional inflows and outflows between the profiles, the resultant water volume difference will be due to the difference of discharges Q_1 and Q_2 at individual profiles:

$$\Delta V = Q_1 - Q_2$$

The discharge Q_2 can be calculated from the water budget then, if Q_1 is known:

$$Q_2 = Q_1 - P_m \cdot \Delta h_m$$

Assuming no significant change in the width of the river between A_1 and A_2 and when the river section is sufficiently short, the shape of the water area can be approximated using the linear function:

$$\Delta h_m = \frac{\Delta h_1 + \Delta h_2}{2}$$

The free water surface area is a function of water level in the river $P_m = f(h_m)$ and depends on the shape of the channel. In the simplest case, under the assumption that the river banks are

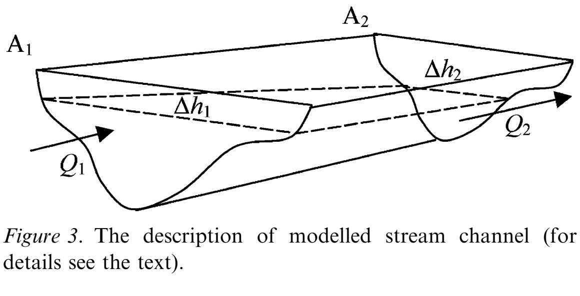

Figure 3. The description of modelled stream channel (for details see the text).

vertical, the water surface area remains unchanged as the water level changes (constant P_m). Then, the discharge in profile A_2 can be expressed as follows:

$$Q_2 = Q_1 - P_m \cdot \frac{\Delta h_1 + \Delta h_2}{2}$$

If the river banks are assumed to have linear inclination (α), the water surface area is a linear function of the water level:

$$P(h) = \alpha(h - h_0) + P_0$$

where: $h_{0,}$ the mean water level; $P_{0,}$ the free water surface responding to h_0; α, a coefficient describing the change in the water surface area resulting from the change of water level, i.e., $\alpha = \frac{\partial P}{\partial h}$. The mean area of the free water surface in time step i–1 and i can be approximated as follows:

$$P_m = \frac{P(h_m^{i-1}) + P(h_m^i)}{2} = \frac{\alpha}{2}(h_m^{i-1} + h_m^i) - P_0$$

where:

$$h_m^i = \frac{h_1^i + h_2^i}{2}$$

In that case, when the mean water level is assumed, the discharge Q_2 can be calculated from:

$$\begin{aligned} Q_2 &= Q_1 - P_m \cdot \Delta h_m \\ &= Q_1 - \left(\frac{\alpha}{2}(h_m^{i-1} + h_m^i) - P_0\right) \cdot \Delta h_m \end{aligned}$$

The calculated discharge Q_2 can be used as the boundary condition for the next section of the river. The above procedure is applied first for the section between Gozdowice and Widuchowa. The upper boundary condition is defined based on the water level and river discharge (as calculated from the water level data with the function $Q = f(h)$) at Gozdowice. In that case, the discharge at Widuchowa is obtained. Next, the discharge in Szczecin is computed in the same way. Finally, the discharge at Police is computed and used as the boundary condition for the hydrodynamic model of the Szczecin Lagoon. Discharge calculations are performed automatically by using water level data from the Gozdowice, Widuchowa, and Szczecin gauge stations available at the IMWM website (http://www.imgw.pl/wl/internet/hydro/biuletyn.jsp).

The current water levels and their changes at individual stations in time Δt make it possible to calculate the current river discharge. To arrive at short-term forecasts, it is necessary to predict changes in water level at individual stations. The forecast for Police is derived from the hydrodynamic model, the predicted water levels resulting mainly from weather forecasts. Water level forecasts for other stations are calculated from multiple regression equations. They allow to assess both 24- and 48-hour change of water level at a station, based on current water levels at the nearest stations.

The 24-hour water level forecasts in the Oder Estuary result from solving the following equations:

$$\begin{aligned} H_{\text{Gozd}} &= 7.3134 + 0.0667 H_{\text{Slub(-24h)}} \\ &\quad + 0.9318 H_{\text{Gozd(-24h)}} \\ H_{\text{Wid}} &= 37.5113 + 0.082 H_{\text{Gozd(-24h)}} \\ &\quad + 0.8593 H_{\text{Wid(-24h)}} \\ &\quad - 0.6501 H_{\text{Szcz(-24h)}} \\ &\quad + 0.6802 H_{\text{Pol(-24h)}} \\ H_{\text{Szcz}} &= 62.1667 + 0.032 H_{\text{Gozd(-24h)}} \\ &\quad + 0.0486 H_{\text{Wid(-24h)}} \\ &\quad - 0.3099 H_{\text{Szcz(-24h)}} \\ &\quad + 1.127 H_{\text{Pol(-24h)}} \end{aligned}$$

The 48-hour water level forecasts in the Oder Estuary assume the form of:

$$\begin{aligned} H_{\text{Gozd}} &= 15.596 + 0.1155 H_{\text{Slub(-48h)}} \\ &\quad + 0.8734 H_{\text{Gozd(-48h)}} \\ H_{\text{Wid}} &= 92.0463 + 0.1439 H_{\text{Gozd(-48h)}} \\ &\quad + 0.7084 H_{\text{Wid(-48h)}} \\ &\quad - 0.5002 H_{\text{Szcz(-48h)}} \\ &\quad + 0.5439 H_{\text{Pol(-48h)}} \\ H_{\text{Szcz}} &= 128.3677 + 0.073 H_{\text{Wid(-48h)}} \\ &\quad + 0.672 H_{\text{Szcz(-48h)}} \end{aligned}$$

where: H_{Slub}, H_{Gozd}, H_{Wid}, H_{Pol}, H_{Szcz} are the mean water levels at the Oder gauge stations of Słubice, Gozdowice, Widuchowa, Police and Szczecin, respectively. The water level forecasts have time lags of 24 and 48 h. The correlation coefficients computed for the relationships between water levels observed at individual gauge stations and produced by multiple regression equations were highly statistically significant (Fig. 4).

Model results and discussion

The model was tested using observed and calculated data sets for water level, currents, water temperature, and salinity in the Oder Estuary,

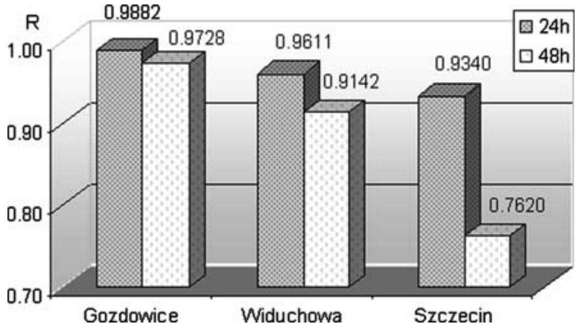

Figure 4. Correlation coefficients (*R*) for 24- and 48-hour water level forecasts in the Oder Estuary (multiple regression equations explained in detail in the text).

including the Szczecin Lagoon and the southern part of the Pomeranian Bay. The observed data series for 2002 were taken from the websites of IMWM in Poland and BSH in Germany. In addition, data on meteorological and hydrological conditions along the Szczecin-Świnoujście Fairway were obtained from Szczecin-Świnoujście Harbour Master's Office as well as from IMWM.

First standard statistical parameters were calculated for the observed and numerically simulated series of water level, water temperature and salinity as well as currents. Next, regression analysis and Student's *t*-tests for paired averages and *F*-test for two variances were run to test the fit between empirical and predicted data series at the significance level of $\alpha = 0.05$ (Table 1).

With respect to the water level series, the best fit between the observed and predicted data was achieved for the Świnoujście gauge station. The modelled average value was higher only about 0.26 cm than for observed one. The largest difference between the observed and predicted averages was that at Koserow, the model average being lower than the observed one by 3.56 cm. Among the minimum values, the greatest underestimation produced by the model (6.1 cm) was at Koserow. At Świnoujście, the model overestimated the maximum water level by 17.0 cm. At all the locations, the coefficient of variation ranged from 0.041 to 0.044; however, both the standard deviations and the coefficients of variation were higher for the observed than for the modelled data. At all the stations, correlation coefficients between the observed and predicted values (0.939–0.955) were highly significant. The highest correlation coefficient (0.955) was that at the Trzebież gauge station (Fig. 5a).

The model produced a very good fit between the observed and predicted water temperatures. The modelled mean values were lower than the observed data by as little as 0.02–0.43 °C. The largest underestimation of the maxima, found in the Oder Bank (3 m depth) in the Pomeranian Bay, amounted to 1.64 °C. As for the water level, standard deviations and coefficients of variation of the observed data were higher, albeit non-significantly so, than those of the predicted data set. The highest

Table 1. The results of *t*-test for two averages and *F*-test for two variances

Feature	Station	*N*	AVG_O	AVG_M	*t*	STD_O	STD_M	*F*
Water level	Świnoujście	2189	505.10	505.36	−0.3958	22.367	21.224	1.1106
	Trzebież	2185	510.72	511.58	−1.3188	22.196	21.032	1.1137
	Koserow	6389	506.71	503.17	9.2962	22.221	20.777	1.1439
Water temperature	Świnoujście	366	10.40	10.51	−0.1760	7.255	9.755	1.8079
	Trzebież	366	11.32	11.46	−0.2070	7.796	10.048	1.6611
	Ueckemuende	1819	14.31	13.88	1.7714	7.494	7.377	1.0320
	Oder Bank (Depth 3m)	1920	11.06	11.04	0.0686	6.733	6.131	1.2060
	Oder Bank (Depth 12m)	1799	11.78	11.67	0.5452	6.085	5.763	1.1146
Salinity	Oder Bank (Depth 3m)	1909	6.630	7.490	−56.755	0.5185	0.411	1.5895
	Oder Bank (Depth 12m)	1783	7.071	7.797	−91.430	0.2156	0.257	1.4206
Currents	Świnoujście	2185	0.161	0.138	2.9782	0.305	0.204	2.2292

N – The number of data; AVG_O – the average value for observed series of data; AVG_M – the average value for modelled series of data; *t* – the value of *t*-test; STD_O – the standard deviation for observed series of data; STD_M – the standard deviation for modelled series of data; *F* – the value of *F*-test. The assumed significance level α equalled 0.05.

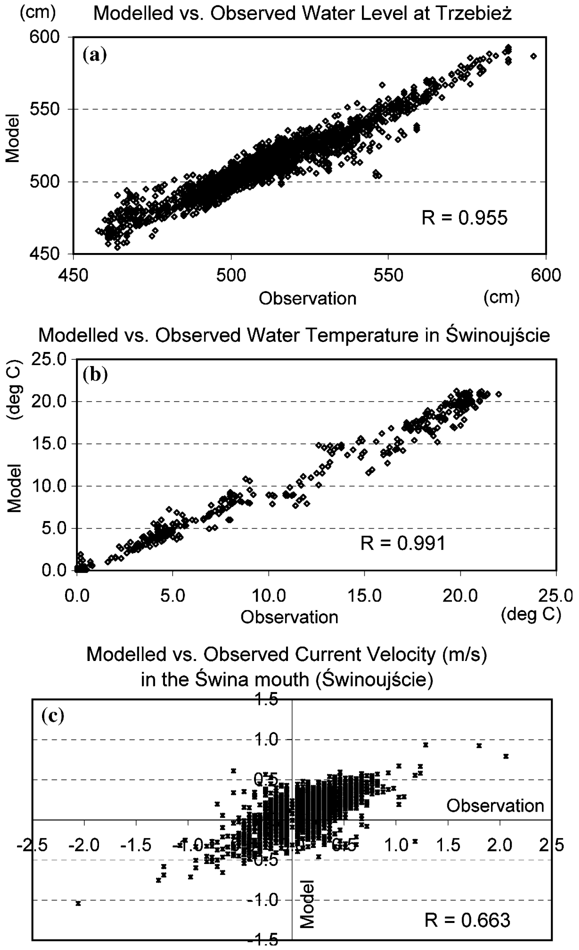

Figure 5. Modelled vs. observed water level at Trzebież (a), water temperature at Świnoujście (b) and current velocity in the Świna mouth (c). *R* is the correlation coefficient.

variability was typical of the coastal stations. However, the correlation coefficients for all the stations exceeded 0.99, i.e., they were highly significant (Fig. 5b).

A poorer fit was obtained between the observed and predicted salinities on the Oder Bank. Nevertheless, the correlation coefficients proved statistically significant (0.566–0.727). The average calculated salinities were higher than the observed values by about 0.8 PSU. Extreme values were overestimated as well. A lower variability and a better correlation between the data series was achieved for the depth of 12 m (0.727).

The high variability of hydrodynamic conditions in the Świna mouth resulted in a weaker correlation between the observed and predicted current speeds. However, the correlation coefficient obtained (0.663) was significant (Fig. 5c). The current speeds differed by an average of 0.023 m/s^{-1}. The highest underestimation of the maximum and minimum current speeds amounted to about 1.12 m/s^{-1}.

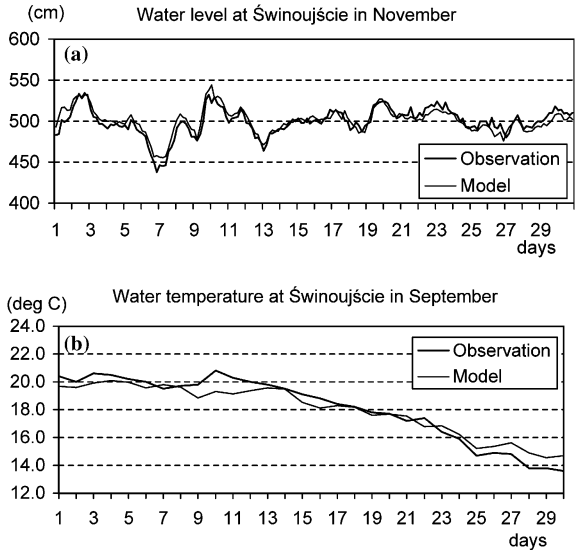

Figure 6. Comparison between modelled (thin solid line) and observed (thick solid line) data of water level in November 2002 (a) and water temperature in September 2002 (b) as measured at Świnoujście.

Figure 6 shows a comparison between predicted and computed time series of water level and temperature. It is evident that the model adequately approximated temporal variations of the two parameters.

The Baltic Sea model has generated time series of water levels, currents, water temperature, and salinity for various regions of the southern Baltic Sea, covering the period of 1999 till present. Results of the model runs are placed daily on the University of Gdańsk website (http://model.ocean.univ.gda.pl). As the model developed in this study is an adequate representation of hydrological conditions, those prevailing in the Oder Estuary can be operationally simulated as well (Fig. 7).

Conclusions

Linking the Oder discharge model with the 3-D operational hydrodynamic model of the Baltic Sea

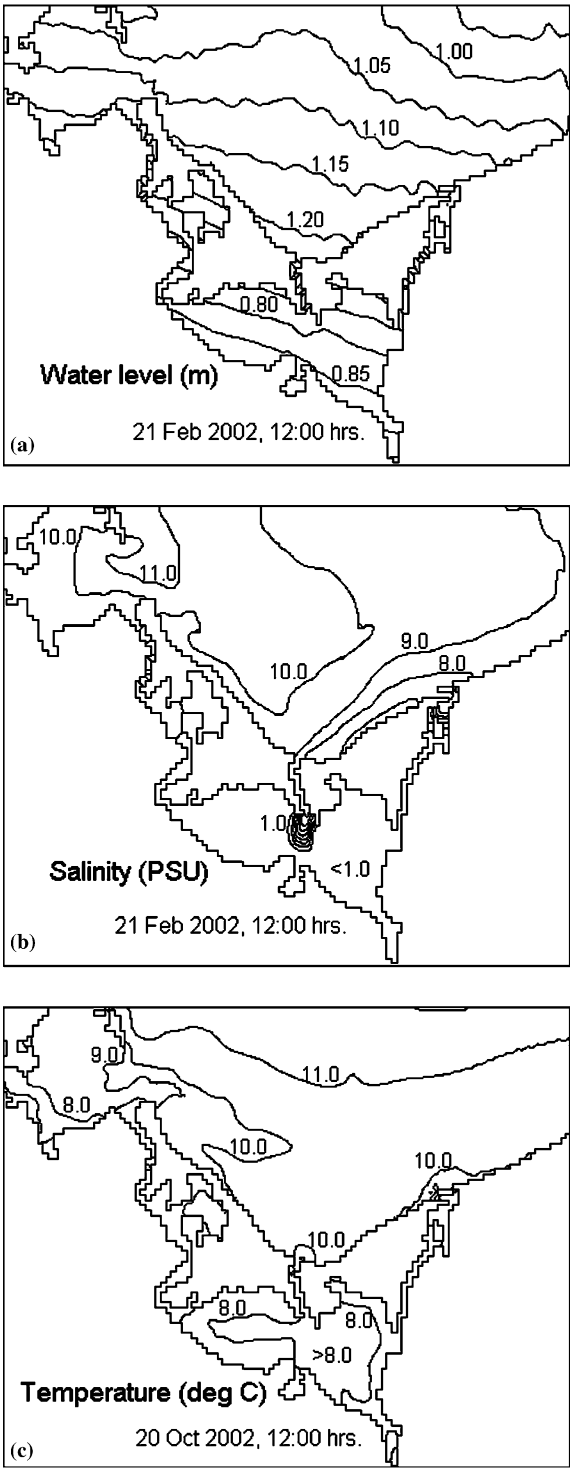

Figure 7. Simulation results with the 3-D operational numerical model of the Oder Estuary: water level (a) and salinity (b) on 21 February as well as water temperature (c) on 20 October 2002.

into a single system made it possible to operationally simulate hydrological conditions (water levels, currents, water temperature, and salinity) in the Oder Estuary. The best fit between the observed and modelled data were achieved for the water level and temperature in the coastal Pomeranian Bay as well as in the Szczecin Lagoon. The predicted current speed and salinity produced a poorer fit, but the differences with the observed data were not significant.

The adequate approximation of hydrological variability in the Estuary by the model makes it a reliable tool for studying coastal processes (e.g., storm surges, mixing of fresh and saline waters in the coastal zone of the Pomeranian Bay) in the area. To arrive at a better fit between the observed and computed data, the model will be subject to further refinement.

A quick website access to daily hydrological forecast (http://model.ocean.univ.gda.pl) provides potential users with an opportunity of predicting the extent of processes that may affect different coastal areas. Therefore, the model can be useful in improving the safety of navigation and harbour operations, in flood control, environmental protection of coastal areas, and in tourism-related activities.

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References

Buchholz, W. (ed.), 1990. Materiały do monografii Dolnej Odry. Warunki hydrologiczno-hydrodynamiczne [Materials for Monograph of the Lower Oder River. Hydrological and hydrodynamical conditions]. No. 22, Wyd. IBW PAN, Gdańsk [in Polish].

Buchholz, W. (ed.), 1991. Monografia Dolnej Odry. Hydrologia i Hydrodynamika [Monograph of the Lower Oder River. Hydrology and Hydrodynamics]. No. 25, Wyd. IBW PAN, Gdańsk [in Polish].

Blumberg, A. F. & G. L. Mellor, 1987. A description of a three-dimensional coastal ocean circulation model. In Heaps, N. S. (ed.), Three-Dimensional Coastal Ocean Models. American Geophysical Union: 1–16.

Ewertowski, R., 1988. Mathematical model of the Odra Estuary. A.I.P.C.N.-P.I.A.N.C. Bulletin, Bruxelles 60: 95–114.

Ewertowski, R., 1996. Influence of wind field on calculated water levels and flows in the Odra River system. Hydrotechnical Transactions 60: 21–35.

Ewertowski, R., 1998. Unsteady flow in Odra River outlet generated during the passage of strong cyclones. In Holz, K. P., W. Bechteler, S. S. Y. Wang, & M. Kawahara (eds) Advances in Hydro-Science and -Engineering. Proceedings of Abstracts and Papers of 3rd International Conference Hydro-Science and -Engineering. Cottbus/Berlin 1998 III. Univ. Mississippi, CDROM, ICHE-98.

Fennel, W. & M. Sturm, 1992. Dynamics of the western Baltic. Journal of Marine Systems 3: 183–205.

Fennel, W. & T. Seifert, 1995. Kelvin wave controlled upwelling in the western Baltic. Journal of Marine Systems 6: 286–300.

Funkquist, L., 2001. HIROMB, an operational eddy-resolving model for the Baltic Sea. Bulletin of Maritime Institute, Gdańsk 29(2): 7–16.

Herman-Iżycki, L., B. Jakubiak, K. Nowiński & B. Niezgódka, 2002. UMPL – numerical weather prediction system for operational applications, In Research works based on the ICM's UMPL numerical weather prediction system results. Wyd. ICM, Warszawa pp 14–27.

Jankowski, A., 2000. Wind-induced variability of hydrological parameters in the coastal zone of the southern Baltic Sea – numerical study. Oceanological Studies 29(3): 5–34.

Jankowski, A., 2002a. Application of a σ-coordinate baroclinic model to the Baltic Sea. Oceanologia 44(1): 59–80.

Jankowski, A., 2002b. Variability of coastal water hydrodynamics in the Southern Baltic hindcast modelling of an upwelling event along the Polish coast. Oceanologia 44(4): 395–418.

Jankowski, A. & Z. Kowalik, 1980. Diagnostic model of wind- and density-driven currents the Baltic Sea. Oceanologica Acta 3(3): 301–308.

Jasińska, E., 1991. Dynamika słonych wód w estuariach polskich rzek [Dynamics of saline waters in estuaries of Polish rivers]. Wyd. IBW PAN, Gdańsk [in Polish].

Jasińska, E. & W. Robakiewicz, 1988. Hydrodynamic conditions and salinity of the Świna Strait and the Szczecin Bay. A.I.P.C.N.- P.I.A.N.C. Bulletin, Brussels 60: 77–94.

Jasińska, E. & W. Robakiewicz, 1999. Three dimensional numerical model of the Odra estuary ESTURO. Proceedings of Problems of Environmental Engineering in the Odra River Mouth. Technical University, Szczecin pp 141–153.

Jędrasik, J., 1997. A model of matter exchange and flow of energy in the Gulf of Gdańsk ecosystem – overview. Oceanological Studies 26(4): 3–20.

Kałas, M., A. Staśkiewicz & K. Szefler, 2001. Water level forecast for the Pomeranian Bay from the HIROMB Model. Oceanological Studies 30(3–4): 39–57.

Kowalewski, M., 1997. A three-dimensional hydrodynamic model of the Gulf of Gdańsk. Oceanological Studies 26(4): 77–98.

Kowalewski, M., 1998. Upwellingi przybrzeżne w płytkim morzu stratyfikowanym na przykładzie Bałtyku [Coastal upwellings in stratified shallow sea based on the Baltic Sea as an example]. Ph.D. Thesis, University of Gdańsk, Gdynia [in Polish].

Kowalik, Z., 1972. Wind-driven circulation in a shallow stratified sea. Deutsche Hydrographische Zeitschrift 25(6): 265–278.

Kowalik, Z. & A. Staśkiewicz, 1976. Diagnostic model of the circulation in the Baltic Sea. Deutsche Hydrographische Zeitschrift 29(6): 239–250.

Krężel, A., 1997. A model of solar energy input to the sea surface. Oceanological Studies 26(4): 21–34.

Lass, H. U., V. Mohrholz & T. Seifert, 2001. On the dynamics of the Pomeranian Bight. Continental Shelf Research 21: 1237–1261.

Lehmann, A., 1995. A three-dimensional baroclinic eddy-resolving model of the Baltic Sea. Tellus 47A: 1013–1031.

Lehmann, A. & H. H. Hinrichsen, 2000. On the thermohaline variability of the Baltic Sea. Journal of Marine Systems 25: 333–357.

Matthäus, W. & H. Franck, 1992. Characteristics of major Baltic inflows – A statistical analysis. Continental Shelf Research 12: 1375–1400.

Majewski, A., 1974. Charakterystyka hydrologiczna Zatoki Pomorskiej [Hydrological characteristics of the Pomeranian Bay]. Wyd. Komunikacji i Łączności, Warszawa.

Majewski, A., 1980. Zalew Szczeciński [The Szczecin Lagoon]. Wyd. Komunikacji i Łączności, Warszawa.

Mellor, G. L., 1996. User's guide for a three-dimensional, primitive equation, numerical ocean model. Program in Atmospheric and Oceanic Sciences, Princeton University.

Mohrholz, V. & H. U. Lass, 1998. Transports between Oderhaff and Pomeranian Bight – A simple Barotropic Box Model. Deutsche Hydrographische Zeitschrift 50(4): 371–383.

Mohrholz, V., M. Pastuszak, S. Sitek, K. Nagel & H. U. Lass, 1998. The Exceptional Oder flood in summer 1997 – Riverine mass and nutrient transport into the Pomeranian Bight – A simple Barotropic Box Model. Deutsche Hydrographische Zeitschrift 50(2/3): 129–143.

Omstedt, A., 1990. Modelling the Baltic Sea as thirteen sub-basins with vertical resolution. Tellus 42A: 286–301.

Pfeiffer, K. D., I. Nöhren, E. Jasińska & K. Duwe, 1993. Dynamic Features and Variability in the Szczecin Bay. Proceedings of 5th German-Polish Seminar on Coastal and Estuary Dynamics, 26–30 October 1993, Geesthacht: 179–210.

Robakiewicz, W. (ed), 1993. Warunki hydrodynamiczne Zalewu Szczecińskiego i cieśnin łączących Zalew z Zatoką Pomorską [Hydrodynamic conditions of the Szczecin Lagoon and straits connecting the Lagoon with the Pomeranian Bay] Wyd. IBW PAN Gdańsk.

Sokolov, A., O. Andrejev, F. Wulff & M. Rodriguez Medina, 1997. The Data Assimilation System for Data Analysis in the Baltic Sea. Systems Ecology Contributions, 3, Stockholm University.

Stigebrandt, A., 1983. A model for the exchange of water and salt between the Baltic and the Skagerrak. Journal of Physical Oceanography 13(2): 411–427.

Stigebrandt, A., 1987. A model of the vertical circulation of the Baltic deep water. Journal of Physical Oceanography 17(2): 1772–1785.