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Darss-Zingst Bodden Chain and Vistula Lagoon in a context of numerical modelling application

1 Introduction

Numerical modelling is an essential method of coastal waters investigation and is a tool to solve applied problems. Every model means certain physical assumptions and definite time/space discretisations; hence, decision on model selection should be made before the real study.

The paper presents discussion on scopes of application of physical models of different dimensionality and an adequate physical platform for different tasks like hydraulic and water quality modelling, or operational oceanographic modelling.

The Darss-Zingst Bodden Chain (DZBC) and the Vistula Lagoon (VL) have been subjected to various applications of numerical models. Calculation of annual water exchange between sub-basins was an example for a zero-dimensional approach to analyse water dynamics in the DZBC *(*CORRENS 1978*)*. Plane two-dimensional modelling approach was also implemented in the DZBC (VIETINGHOFF et al. 1975, STÜCKARD et al. 1995, SCHÖNFELDT 1997) and in the VL (CHUBARENKO & CHUBARENKO 2003, KWIATKOWSKI et al. 1997, CHUBARENKO & TCHEPIKOVA 2000*)*. General analysis of water level variations (including extreme storm situations), water exchange processes through the lagoon inlets, role of navigable channels and passes between sub-basins, structure of currents fields, influence of dams, harbour constructions and dredging in the lagoons areas have been discussed in the related literature.

2 Comparative description of study areas

Both coastal water bodies are located at the southern coast of the Baltic Sea (Fig. 1), and are influenced by marine water and river discharge. Therefore they could be referred to as estuarine non-tidal lagoons or non-tidal plane estuaries (KJERFVE 1994), and the Darss-Zingst Bodden Chain may be placed among choked lagoons otherwise the Vistula lagoon could be considered as intermediate between chocked and restricted lagoon.

The basic geomorphic and hydrological characteristics for both lagoons are as follows: The volume of water body equals ca. 0.4 (DZBC) and 2.3 (VL) km^3. Average area of the lagoon surface is ca. 197 (DZBC) and 838 (VL) km^2. Average and maximum lagoon depths are ca. 2 and 4 m (DZBC), and 2.7 and 5.2 m (VL). Length of inner shore line equals 120 (DZBC) and 270 (VL) km. The lagoons have an elongated shape, are separated from the sea by sandy barrier spits covered by forest. The lengths of lagoons along the longitudinal axis are 55 (DZBC) and 91 (VL) km. Both lagoons have one inlet. Its characteristic length and width are ca. 10 km and 400 m (DZBC) and 2 km and 400 m (VL), while the minimal vertical cross-sections equals ca. 900 m^2 (DZBC) and 4200 m^2 (VL). Darss-Zingst Bodden Chain is subdivided into several sub-basins (Bodden), which are connected with each other by narrow passes. Range of the area for narrowing transversal lagoon transects equals 250-1300 m^2 (DZBC) and 4500 ÷ 19500 m^2 (VL).

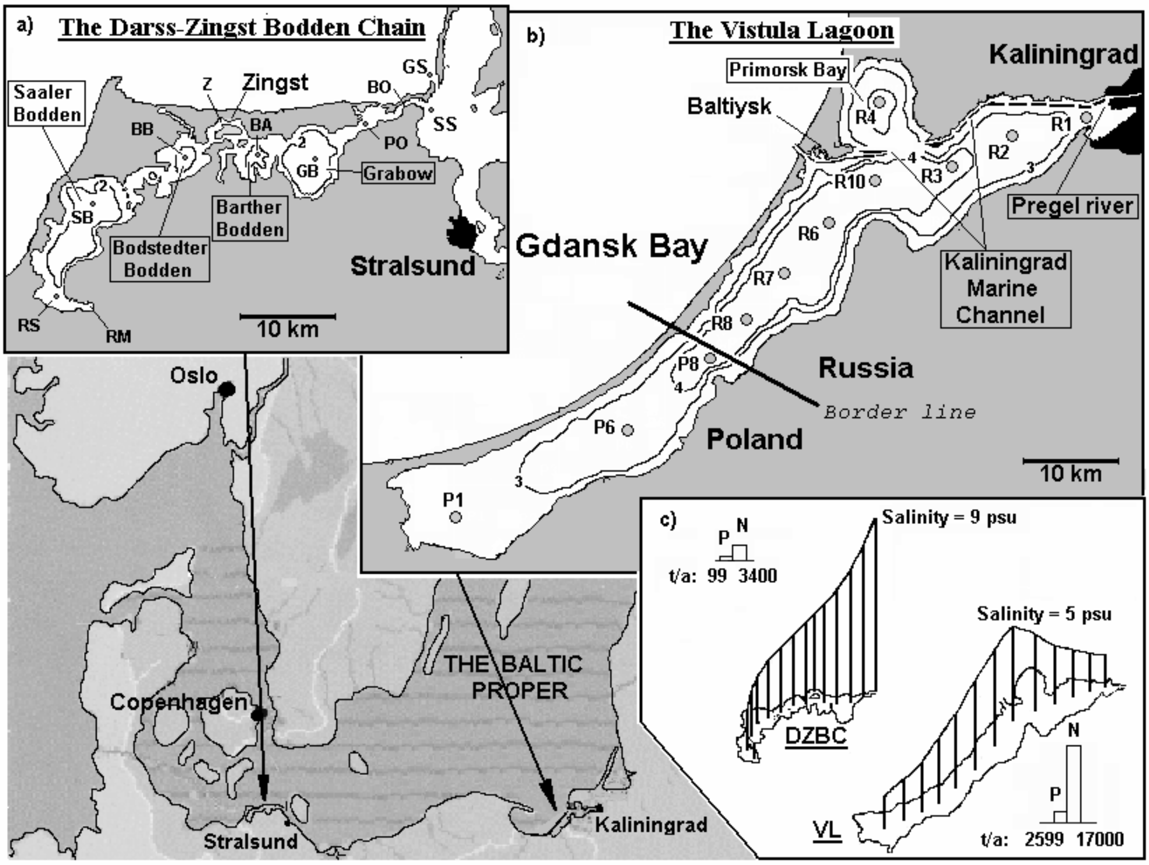

Fig. 1 Locations of Darss-Zingst Bodden Chain (a) and the Vistula Lagoon (b) in the Baltic Sea. The net of monitoring stations for both lagoons, lines of constant depth as well as the names for some places in their areas, are indicated. The average distribution of salinity along the lagoons and general average nutrient load are presented in the incut (c).

Darss-Zingst Bodden Chain has a wide rush areas spreading up to 1.2-1.5 m depth in opposite to the Vistula Lagoon, where rush coverage is much less. The portion of area covered with rooted vegetation ranges between 5-30% (DZBC) and 0.3-0.5 % (VL) for different sub-basins in the lagoons. Muddy sediments cover most parts of the lagoons bottom, marine originated sandy sediments are found in the area adjacent to inlet only.

Both lagoons have navigable channels. The channel in the DZBC has a depth of 2.5-3.5 m and a width of 30-50 m, and it mostly follows the central axis of lagoon being 1-2 meters deeper than surrounding area. In VL, the navigable channel passes along the northern shore, from lagoon inlet to the mouth of the Pregel river. It has a depth of 9-10.5 m, width of 50-80 m at the bottom and of 80-150 m at the depth of 1.0-1.5 m. The channel is passing through relatively narrow (width of 200-1000 m) littoral area (depth of 0.5-1.5 m) and is separated from the main lagoon body by a set of artificial dams.

Even the absolute values of average nutrient load (Fig. 1c) are bigger for the VL, the real press to lagoon ecosystems could be estimated through comparison of ratios between appropriate load and lagoon volume. And, according this, the VL is under higher effective phosphorus load. Effective nitrogen load is nearly the same for both lagoons.

Water inflow from the Baltic and freshwater river runoff are the main components of water budget for DZBC and the VL. These terms comprise together 96.2 % and 97.3 % of water budget, and namely equals to 2.76 and 0.29 $km^3\ a^{-1}$, 17 and 3.68 $km^3\ a^{-1}$ respectively for DZBC and VL. For both lagoons the evaporation exceeds the precipitation in 1.3-1.4 times. While the role of groundwater infiltration is approximately the same for both lagoons (0.6 % and 0.3 % of water budget), infiltration through the sandy spit (the barrier separating the lagoon from the sea) is unknown for both systems.

Though VL has a catchment area (23870 km^2) which is in 15 times higher then DZBC, its freshwater gain is only in 12.7 times higher. The more wet climate is a reason for this specific watershed freshwater capacity, which equals to the ration of fresh water gain to watershed surface, and is 20% higher for the DZBC (18 cm year). The absolute annual influx from the Baltic Sea to the VL is 6.2 times higher then to DZBC, what is the result of synergetic action of main driving forces: the time variations of the Baltic Sea water level, local wind and river runoff, and inlet hydraulic resistance.

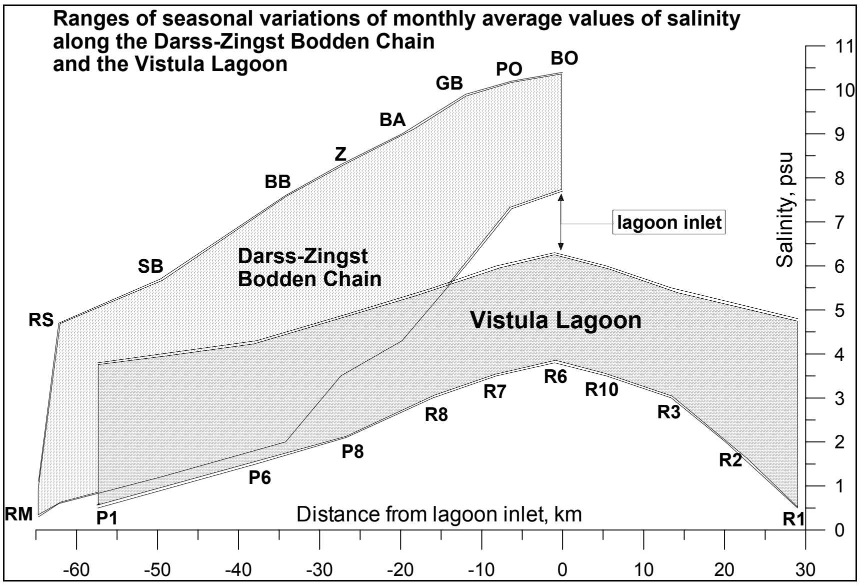

Fig. 2 Average ranges of salinity variations along the central axis of the Darss-Zingst Bodden Chain and the Vistula Lagoon. Positions of stations are identical to those in Fig.1.

DZBC has a permanent salinity gradient from its inlet towards the western end of the lagoon (Fig. 2). While the salinity at the lagoon entrance is more stable, the yearly average salinity inside the lagoon, especially at its central part, varies significantly from year to year. The salinity distribution in VL is characterized by spatial salinity decrease from the lagoon inlet eastward to the river Pregel mouth, and southward. The maximum average range of annual salinity variations is observed at the Pregel river mouth (0.5-5.0 psu), the minimum is measured near the lagoon inlet (3.5-6.5 psu).

3 Model selection versus research goal

3.1 Zero-dimensional approach (0D)

Water inflow and outflow are mostly controlled by water level variations at the inlets of both lagoons. By this reason, a zero-dimensional (in space) or box model is applicable to estimate the temporal dynamics of water exchange between the lagoons and open sea with a time scale of weeks, months or years. If VL could be described as one box, the DZBC has to be approximated as a cascade of linearly connected boxes corresponding to different sub-basins. In such a model the lagoon or sub-basins are considered as well mixed i.e. are homogenous along the lagoon volume in horizontal and vertical directions. While salinity and temperature are the state variables, precipitation (i), evaporation (ii), river (iii) and underground (iv) runoffs and, of main importance, level variations (v) at the inlet are to be treated like forcing factors, as well as temperatures of air, river and marine waters and solar heating. Evaporation has to be included in model simulation by its parameterisation through difference between water and air temperature. Including the chemical and biological cycles in such a model gives rise to simulate the seasonal dynamics of multitude parameters of water quality. To avoid an overestimation of lagoon salinity because of accounting in the model for any level raise at the inlet the high frequent level variations have to be filtered. And it is the vary point of model calibration versus salinity annual variations: level rise of which amplitude actually brings marine salt water intrusion into the lagoon.

3.2 One-dimensional approach (1D)

Both lagoons are elongated and the main rivers enter in their remote ends. Due to intensive wind influence DZBC and VL are well vertically mixed. Vertical stratification in salinity is localised in limited areas (near inlet and river mouths). Therefore, the one-dimensional model with the spatial lengthwise extension could reasonably simulate the spatial variations of salinity, temperature or any other parameter in the lagoon. It is expected that the deep navigable channel in VL (separated from proper lagoon by set of islands) will be described as additional brunch in the one-dimensional computation grid. If for the BZBC the open marine boundary will be at the one end of 1D-grid, for the VL it will be in the middle of it. Model has to be driven by river discharges, marine level variations at the open boundary and by wind.

3.3 Two-dimensional approach (2D)

Two-dimensional modelling already proved its applicability through real practice, e.g. giving very precise solution for water level variations in cases of extreme stormy events (SCHÖNFELDT 1997). The lag between the maximum water levels in individual "Bodden" were also successfully revealed for DZBC. To get more reliable results for the entrance of DZBC boarded by low flooded land the simulation area was extended to east from inlet, and boundary conditions in terms of level variations were applied not at the lagoon inlet but far from it in adjacent marine area (SCHÖNFELDT 1997). A 2D model for VL was completely prepared for practical use in problems of (i) variations of the water level and fluxes (basic hydrodynamics), (ii) transport of 'passive' tracers like salinity (basic hydrology), and (iii) transport and chemical transformation of nutrients (water quality and eutrophication). It allowed to analyse different scenarios of nutrient loading in the VL catchment (KWIATKOWSKI et. al. 1997), scenarios of dredging or artificially establishing new entrance in the lagoon (CHUBARENKO & TCHEPIKOVA 2000). The success in using 2D models for practical problems is ensured by a principal peculiarity of sufficient resolution of average fluxes between parts of elongated basin under two dimensional shallow water approach.

3.4 Three-dimensional approach (3D).

Three-dimensional modelling is required to study the real physical processes happening in both lagoons. The actual current in VL is three-dimensional as proved by direct measurements of currents both in the lagoon deep and on the surface in 1994-1995 (CHUBARENKO & CHUBARENKO 2003). The depth average currents obtained by 2D model does not confirm field observations. In both lagoons there are areas where dynamic processes have to be simulated under 3D approaches only. For example, the penetration of marine water intrusion into the VL when marine water comes into the lagoon area and plunges down along the bottom to the lagoon after flow over the sandy near-entrance bar. Such a process is not a rare event. The ordinary 'pumping' of salt water in considering non-tidal estuarine lagoons is happening through such deep penetration of salt intrusions. The sharp changes of bottom topography are always a reason of three-dimensionality in currents. Thus, the local upwelling-downwelling zones are permanently existing along the steep depth gradients in the DZBC.

First results from a 3D model for VL indicate by using a curvilinear orthogonal grid with cells of 200-1300 m and 11 levels in vertical direction that even in such shallow water reservoir differences in vertical velocity and salinity distribution exist. The correct account of vertical stratification at the open boundary (at the lagoon inlet) is a crucial point for proper simulation of currents and salinity variations in the lagoon.

When a reverse current in the deeper basins of VL during lengthwise local wind is studied the use of a 3D model is recommended (CHUBARENKO & CHUBARENKO 2003). The current structure can only be simulated using a 3D hydrodynamic model or if the conditions for benthic or pelagic aquaculture are studied. Finally, the simulation tasks involving short-term forecasts or following the accidental oil-spills (some oil fractions spread over the surface, some oil fractions sink) definitely require a 3D approach for the hydrodynamic and transport problems because of possible different directions in advective transports existed at different depths. These must be simulated precisely in order to, for example, predict the fate of the oil spill and optimise timely recovery operations.

4 Conclusions

A 2D modelling approach is efficient and provides reasonable information for such flat coastal estuarine lagoons as DZBC and VL. Two principal types of problems can be solved with an accuracy sufficient for practical management purposes, namely, the simulation of water level variations with a time scale of hours, and water quality variations with a time scale of months. In addition, 2D models are a good platform for water management purposes to analyse different scenarios of economic activity in the lagoon watershed area.

A 3D modelling approach accounting for Coriolis force are prerequisites required for successful simulation of real currents in such a shallow estuarine lagoons, especially in case of operational following of oil-spills or other incidents. The main obstacle for wide application of 3D model is still the huge amount of data required.

Even though the real currents structure in the lagoons should be simulated only by 3D-models, some simplification is possible. For instance, the fluxes between sub-basins are the important variables required for ecological modules, so, the spatial dimensions can be reduced from 3D to 2D considering only general ecological application of modelling. Finally, tasks involving the study of water exchange between sub-basins of the lagoons should be solved in 3D for precise short-term simulations and in 2D for simulations involving seasonal variations. For tasks involving lagoon water quality, 2D hydrodynamic and advection-dispersion models are usually sufficient to resolve the seasonal variation of simulated parameters, and, in this case, it should be calibrated using some conservative tracer time series such as seasonal salinity changes. A 2D time-dependent hydrodynamic approach is also sufficient to simulate wind surges or current structure variations in a lagoon. The water exchange between a lagoon and adjacent marine coastal waters is also well simulated using a horizontally 2D approach.

The comparison of characteristic features of two Baltic non-tidal estuarine lagoons, DZBC and VL, showed, that even though there is a considerable similarity in their general hydrologic behaviour, the lagoons possess very individual features influenced due to their hydraulic and mixing. Especial effect is caused by existence of deep navigable channels.

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