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BALTICA Volume 18 Number 2 December 2005 : 56-67

Comparison of Darss-Zingst Bodden Chain and Vistula Lagoon (Baltic Sea) in a view of hydrodynamic numerical modelling

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Chubarenko, B., Chubarenko, I., Baudler, H., 2005. Comparison of Darss-Zingst Bodden Chain and Vistula Lagoon (Baltic Sea) in a view of hydrodynamic numerical modelling. *Baltica, Vol. 18 (2), 56-67.* Vilnius. ISSN 0067-3064.

Abstract Comparative description of two coastal lagoons of the Baltic Sea is presented in terms of numerical parameters revealing morphometric and hydrological features of these non-tidal lagoons. An overview of problems, already solved by using a hydrodynamic modelling for both lagoons, is presented. Recommendations on modelling approaches of different spatial dimensionality are formulated for different groups of problems (hydrodynamics, sediment transport, water quality and operational delling).

Keywords *Lagoons, numerical modelling, hydrodynamics, Baltic Sea, Darss-Zingst Bodden Chain, Vistula Lagoon.*

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INTRODUCTION

Before entering the Baltic Sea, waters of some main and medium rivers of its southern and eastern coast pass through flat semi-enclosed coastal water bodies, which serve as natural filters for seaward terrestrial flow of sediments, nutrients and chemical pollutants. Namely, the following water bodies are to be mentioned (from South to North): the Darss-Zingst Bodden Chain, the Odra Lagoon (or the Odra Estuary), the Vistula Lagoon, the Curonian Lagoon, the Matsalu Bay, and the Neva Bay.

The Vistula Lagoon (VL) and Darss-Zingst Bodden Chain (DZBC), in contrast to others, are rather similar and are to be equally considered in numerical modelling applications. For the DZBC a box model was applied in (Correns 1978), while plane models were used in (Sundermann 1966, Vietinghoff et al. 1975, Raabe & Baudler 1988, Hinkelmann & Zielke 1991&1993, Stückard et al. 1995, Schönfeldt et al. 1996, Schönfeld 1997). For the Vistula Lagoon the plane two-dimensional model was applied in (Catewicz & Jankowski 1983; Kolodko et al. 1983; Szymkiewicz 1992; Kapinski & Robakiewicz 1993; Staskiewicz & Lewandowski 1994, Chubarenko & Chubarenko 1995, 1997, 2003; Kwiatkowski et al. 1997, Rasmussen 1998, I.Chubarenko 1998a,b, I.Chubarenko & Tchepikova 2000, Bielecka & Kazmierski 2003). Analysis of water level variations (including extreme storm surges), water exchange with the Baltic Sea, role of navigable channels and passes between lagoon sub-basins, structure of currents, influence of dams, harbour constructions and dredging, water quality problems were discussed in the above mentioned papers.

Every model application presupposes a certain physical assumptions. Typically, papers on modelling thoroughly present the equations and results but pay less attention to analytical pre-modelling stage. Our paper presents a pre-modelling analysis of recent morphometric and hydrological features of DZBC and VL with the aim to discuss a scope of application of hydrodynamic numerical models of different dimensionality to reveal a water dynamics and related variations in water quality in both short-term and inter-annual time scales. Morphodynamics is not considered here, since it is more a long-term process, which affects the basic lagoon morphometry.

AREA DESCRIPTION

The both coastal water bodies are located at the southern coast of the Baltic Sea (Fig. 1). The river discharge largely influences the lagoon hydrology, and, therefore, DZBC and VL can be classified as estuarine lagoons (*Davies 1973)* or plane estuaries (*Kjerfve 1994*); the DZBC can also be considered as choked lagoon, whilst the VL is intermediate between chocked and restricted ones. These lagoons are non-tidal ones, level variations and local wind are the main driving forces (Chubarenko & Chubarenko 2002).

The basic morphometric and hydrological characteristics of both lagoons were collected from the works published by Schlungbaum & Voigt (2001), Hinkelmann & Zielke (1993), Seehandbuch (1979), Schlungbaum et al. (1995), Schlungbaum & Baudler (2001), Lazarenko & Maewski (1971), Chubarenko et al. (1998), Baudler & Müller (2003), and Schumann et al. (2005). The volume of water body equals ca. 0.4 km^3 (DZBC) and 2.3 (VL) km^3. Mean area of the lagoon surface is ca. 197 (DZBC) and 838 (VL) km^2. Mean and maximum lagoon depths (excluding channels) are ca. 2 and 4 m (DZBC), and 2.7 and 5.2 m (VL). The length of inner shoreline equals to 120 (DZBC) and 270 (VL) km. The lagoons have an elongated shape, are separated from the sea by sandy barriers covered by forest. The lengths of the lagoons along the longitudinal axis are 55 (DZBC) and 91 (VL) km. Both lagoons have one inlet. The characteristic lengths and widths are ca. 10 km and 400 m (DZBC) and 2 km and 400 m (VL), while the minimal vertical cross-sections equal ca. 900 m^2 (DZBC) and 4200 m^2 (VL). The DZBC is subdivided into several sub-basins (Boddens), which are connected with each other by narrow passes. Cross-sectional areas of natural bottlenecks in the DZBC and VL are 250–1300 m^2 and 4500–19500 m^2 respectively.

DZBC has a wide rush areas spreading up to 1.2-1.5 m depth in contrast to the VL, where rush coverage is much less. The portion of area covered with rooted vegetation ranges between 5-30% and 0.3-0.5% for different sub-basins of DZBC and VL respectively. Muddy sediments cover most part of the lagoons bottom, marine originated sandy sediments are found in the area adjacent to the inlet only. The absolute value of nutrient load is higher for the VL (Fig. 1c). According to the estimation of the specific load (ton per year per

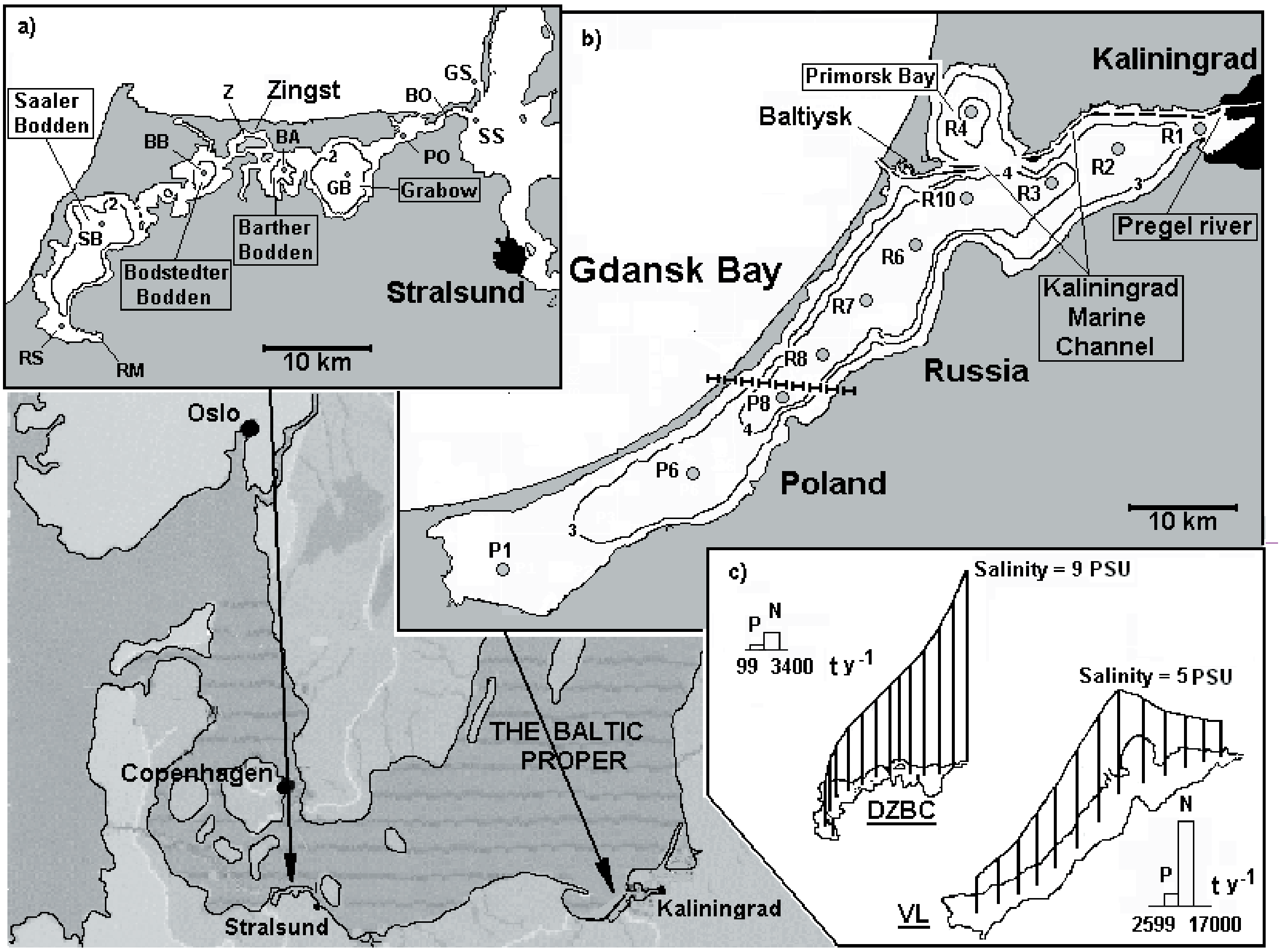

Fig 1. Locations of the Darss-Zingst Bodden Chain (a) and the Vistula Lagoon (b) in the Baltic Sea. The net of monitoring stations and lines of constant depth are indicated. The average distribution of salinity along the lagoons and general average annual nutrient load are presented in the incut (c).

lagoon volume) the VL ecosystem is under 5 times higher phosphorus load, while nitrogen load for the DZBC is ca. 10% higher than for the VL.

METHOD

To reveal similarities and differences in the lagoon's environment we follow a pre-modelling analysis approach (Chubarenko et al. 2004) and use the following set of parameters:

- *Parameter of orientation* equals to a ratio of alongseashore lagoon size to cross-seashore one. It shows the lagoon orientation against the sea shoreline.

- *Width-to-depth ratio* (km m^{-1}), common for estuary classifications (Martin & McCutcheon 1999).

- *Depths ratio* is a ratio of maximum lagoon depth to the mean one.

- *Ditch ratio* equals to a ratio of mean depth in the artificial navigable channels to the maximum lagoon depth.

- *Restriction parameter* (m km^{-1}) is defined as a ratio of total width of the lagoon entrance (m) to the total length of the lagoon shore (km).

- *Openness ratio* (m^2 km^{-2}) is a ratio of area of the lagoon inlet transversal transect (m^2) to the lagoon surface area (km^2). The bigger is its value the larger is a potential influence of the sea.

- *Parameter of inlet resistance* (m^{-1}) equals to a ratio of inlet length (m) to area of inlet transversal transect (m^2). The bigger is the ratio the larger hydraulic resistance has the lagoon inlet, and the response of the lagoon volume to incoming water fluxes is longer in time.

- *Parameter of shore-line development* is a ratio of the lagoon coast length *L* to a circumference of a circle with area equal to that of the lagoon water surface (S_{lag}): $P_{shore} = L\cdot(4\cdot\pi\cdot S_{lag})^{-0.5}$.

- *Macrophite ratio* equals to a ratio of the area of vegetation coverage to the lagoon surface area.

- *Watershed parameter* (m y^{-1}), shows the specific freshwater capacity of a catchment and equals to a ratio of freshwater river runoff (m^3 y^{-1}) to catchment area (m^2).

- *Specific values of water budget components* (m y^{-1}) equal to a ratios of each budget component (m^3 y^{-1}) to lagoon surface area (m^2), and characterise their individual impact on lagoon water volume.

- *Salting factor (F_s)* equals to a ratio of marine water annual inflow to total water annual gain (net fresh water gain minus evaporation and plus marine water inflow) illustrates the general lagoon hydrological behaviour: if $F_s < 0.5$, the fresh water influx is bigger than the sea water inflow and a lagoon is under larger terrestrial influence. A salting factor between $0.5 < F_s < 1$ indicates that the lagoon is predominantly under the influence of the sea.

In order to estimate a significance of water stratification in both lagoons the following parameters were used:

- *Stratification parameter* (Hansen & Rattray 1966), $P_{str} = (s_{bot}^{aver} - s_{surf}^{aver})\cdot s_{mean}^{-1}$, where $s_{surf}^{aver}, s_{bot}^{aver}, s_{mean}$ are characteristic surface, near bottom and vertically averaged salinity.

- *Circulation parameter* (Hansen & Rattray 1966), $P_{cir} = U_s\cdot U_f^{-1}$, where U_s and U_f are a net non-tidal surface characteristic velocity and characteristic freshwater velocity.

- *Estuary number* (Thatcher & Harleman 1972), $Ed=u_m\cdot[\Delta\rho/\rho]^{-1}\cdot(gh_0\, u_{riv}\, \pi)^{-1}$, where u_m and u_{riv} are the amplitudes of profile-averaged tidal velocity at the mouth of the estuary and in the river, h_0 is the depth of mouth of estuary, $\Delta\rho$ is a difference in density between seawater and river water and ρ is a density of seawater, g is an acceleration of gravity (9.8 m s^{-2}).

- *Estuarine Richardson Number* (Martin & McCutcheon 1999, Fischer et el. 1979) indicates the vertical mixing potential: $R=\Delta\rho\cdot g\cdot Q_{fresh}\cdot(\rho\cdot W\cdot u_t^3)^{-1}$, where Q_{fresh} is a freshwater gain, W is a basin width, u_t is the root-mean-square current speed, $\Delta\rho$, ρ, g, were describe right above.

- *Rossby number* $R=U\cdot(f\cdot L)^{-1}$, where $f=2\cdot\Omega\cdot Sin(\varphi)$ is the Coriolis parameter, Ω is the frequency of the Earth rotation ($\approx 7.2921\cdot 10^{-5}$ s^{-1}) and φ is geographic latitude; L and U are horizontal length scale and mean velocity. The Coriolis effect is considered to be important for Rossby numbers $Ro<0.1$ (Martin & McCutcheon 1999, Fischer et al. 1979). The ranges of latitudes for DZBC and the VL are (54°15'- 54°25') and (54°15.3'-54°43.7') respectively, and inertial period $T=2\pi f^{1}$ makes up approximately 14.7 hours for both lagoons.

DISCUSSION OF MORPHOMETRIC AND HYDROLOGICAL FEATURES

Morphometry of the lagoons

The lagoons are rather shore-elongated, their parameters of orientation (Table 1) are significantly bigger than 1 (15 for DZBC and 10 for the VL). The both are shallow, and width-to-depth ratios have the same order: (1.8-27.5) km per 1m for the DZBC, and (3.4-33.7) km per 1m for the VL. The ratio between maximum lagoon depth and average one for both lagoons is practically the same (1.9 and 2).

Both lagoons have navigable channels. The fairway in the DZBC (average depth of 3-3.5 m) passes along the deepest places in sub-basins. It is shaped as a ditch in the bottom (a width of 30-50 m) only in the shallow inlet bottleneck of the lagoon or shallow narrowness between sub-basins. Strong currents do not only support the channel depth in such narrowness but also make it deeper, and there are several places where the depth of the channel is as big as 7-8 or even 16.5 m. The total length of fairway from inlet to remote lagoon end of the DZBC is of 63 km, and it mostly follows the central axis of the lagoon. In the VL, the channel

Table 1. Parameters for comparison description of the Darss-Zingst Bodden Chain and the Vistula Lagoon.

Parameter	Physical dimension	Darss-Zingst Bodden Chain	Vistula Lagoon
Parameter of orientation	Dimensionless	15	10
Width-to-depth ratio	km m^{-1}	1.8 – 27.5	3.5 - 34
Depths ratio	Dimensionless	2	1.9
Ditch ratio	Dimensionless	0.75	1.6
Restriction parameter	m km^{-1}	8.5	1.5
Openness ratio	m^2 km^{-2}	4.5	5
Parameter of inlet resistance	m^{-1}	11	0.5
Parameter of shore-line development	Dimensionless	2.4	1.2
Macrophite ratio	Dimensionless	0.05 - 0.3	0.001÷0.005
Watershed parameter	m y^{-1}	0.18	0.15
Salting factor	Dimensionless	0.91	0.83
Stratification parameter	Dimensionless	0.1	0.7
Circulation parameter	Dimensionless	50	25
Estuary number	s^2 m^{-2}	30-35	5-10
Estuarine Richardson Number	Dimensionless	0.001	0.002
Rossby number	Dimensionless	$(3.2 – 140) \cdot 10^{-3}$	$(5.5 – 56) \cdot 10^{-3}$

passes along the northern shore (35 km), from the lagoon inlet to the Pregel River mouth. 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 was built 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. The ratio between predominant depth in the channel and the maximum lagoon depth (0.75 for the DZBC and 1.6 for the VL) shows that channels in DZBC play only a local role, namely in the shallow isthmuses between the main sub-basins. For the VL, the channel is significantly deeper than the lagoon itself, and so it is very important for the lagoon hydrodynamics.

The both lagoons have limited connection with the sea. A geometric restriction parameter shows that the DZBC (8.5 m per km), is relatively more open than VL (1.5 m per km), but the openness ratios are similar (4.5-5 m^2 km^{-2}), and therefore the Baltic Sea influence is equal for both lagoons.

The parameter of inlet resistance for DZBC and VL is 11 and 2, respectively. It reflects much longer response of the DZBC to water level variations in its inlet (Schönfeldt 1997) than that of the VL.

The DZBC is highly structured (Schönfeldt 1997) and divided into several wide sub-basins connected by narrow passes. Such a shape favours the internal wind-induced circulation in the sub-basins, independent from the water exchange between them. In contrast, for the VL, the whole-basin circulation is the main characteristic feature.

The shore development parameter for the DZBC is two times higher than for the VL, 2.4 and 1.2 respectively. Microphyte ratio for DZBC (0.05-0.3) actually 10 times higher than for the VL (0.001-0.005).

Water budget

Water inflow from the Baltic and freshwater river run-off are the main components of water budget for both lagoons (Table 2). These terms comprise together 96.2 % and 97.3 % of water budget, and make up 2.76 and 0.29 km^3 y^{-1}, 17 and 3.68 km^3 y^{-1} respectively for DZBC and VL. Evaporation exceeds precipitation in 1.3-1.4 times for both lagoons. The role of groundwater infiltration is approximately the same for both lagoons (0.6 % and 0.3 % of water budget). Seepage and infiltration through the sandy barrier between the lagoon and the Baltic Sea are unknown for both lagoons.

The VL has a catchment area (23 870 km^2) 15 times bigger than that of the DZBC (1578 km^2). More wet climate of DZBC is the cause of higher specific watershed freshwater capacity: the ratio of fresh water gain to watershed surface is 17 % higher for the DZBC (18 cm y^{-1}) than that for the VL (15 cm y^{-1}). The absolute annual influx from the Baltic Sea to the VL is 6 times higher than to DZBC, this is the result of lower inlet hydraulic resistance and synergetic action of main driving forces.

The annual variations of the negative and positive components of water balance for both lagoons are characterised by one minimum and one maximum (Fig. 2) and are controlled by seasonal variations of water exchange with the Baltic Sea. The maximum of total water gain is less in wintertime, the minimum is in summer months when weather is calm and intensity of water level variations is low.

Table 2. Water balance components for the Darss Zingst Bodden Chain and the Vistula Lagoon in terms of its absolute (Lazarenko & Maewski 1971; Schlungbaum & Baudler 2001) and specific (a discharge per lagoon area, m y^{-1}) values, as well as percentages of total gain or loss, and eigen retention times (year) equals to the ratio of the lagoon volume to appropriate term of water balance.

Water balance components	**Darss-Zingst Bodden Chain**				**Vistula Lagoon**			
	[km^3 y^{-1}]	[m y^{-1}]	[%]	[year]	[km^3 y^{-1}]	[m y^{-1}]	[%]	[year]
River discharge	0.29	1.47	9.1	1.4	3.68	4.39	17.3	0.6
Underground discharge	0.02	0.1	0.6	20	0.07	0.08	0.3	33
Precipitation	0.10	0.51	3.2	4	0.50	0.60	2.4	4.6
Inflow of the marine water	2.76	14.01	87.1	0.14	17.0	20.29	80.0	0.14
Total annual water gain	3.17		100		21.25		100	
Evaporation	0.14	0.71	4.4	2.8	0.65	0.78	3.1	3.5
Outflow toward the sea	3.03	15.38	95.6	0.13	20.6	24.78	96.9	0.11
Total annual water loss	3.17		100		21.25		100	

Thermal variability

The VL is practically uniform in its thermal structure (Chubarenko et al. 1998). The annual dynamics of water temperature (from -0.2 up to 25°C) is governed by solar heating. Maximum temperature is typically observed at the beginning of August, which is about one-two week later than the maximum in the air temperature. Instant horizontal and vertical variations in water temperature are insignificant in comparison with the daily ones. In the DZBC, water is mostly homogeneous in vertical (Baudler 2002). During calm weather, temperature difference between two distant ends of the lagoon may reach up to 0.5-2.5°C, but this difference disappears when wind starts blowing. The seasonal variations of temperature are similar to those of the VL: the maximum of solar radiation is observed in June-July, whilst the water temperature reaches its maximum in August. Such uniform temperature behaviour is the reason to recommend the zero-dimensional, or one-box, approach to model the thermal variations in both lagoons.

Salinity variability

The salinity field in the VL (Fig. 3) is characterised by salinity decrease eastward and southward from the lagoon inlet. The maximum range of annual variations is observed at the Pregel River mouth (0.5-5.0 psu), the minimum one is near the lagoon inlet (3.5-6.5 psu). All these variations are caused by seasonal changes. The maximum spatial variations over the lagoon area are observed in spring, when salinity is low in average. Salinity starts rising in summer because of intensification of periodic marine water inflows, and leads to more spatially uniform situation in autumn, with spatial differences between 3.5 psu in the Pregel River and 6.0 psu in the inlet, on average.

The DZBC has permanent salinity gradient from its inlet towards the western end of the lagoon (Fig. 3a). Both seasonal and year-to-year variations contribute almost equally to this variability. Salinity at the lagoon entrance is rather stable. In contrast, spatial distribution of salinity inside the lagoon varies from year to year significantly (Schumann et al. 2005), because both,

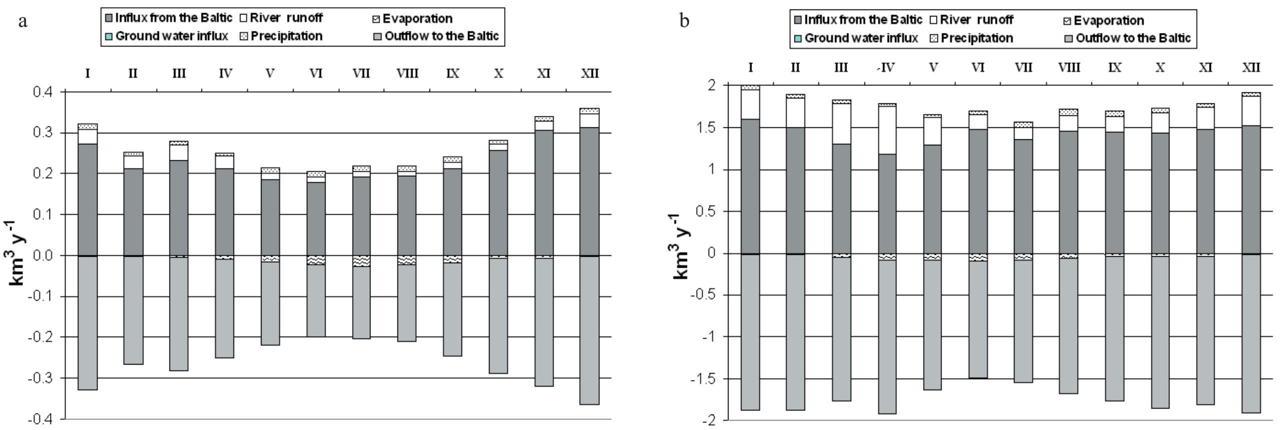

Fig 2. Seasonal dynamics of water budget components for the Darss-Zingst Bodden Chain (a) and the Vistula Lagoon (b). Marine water influx and fresh water gain from rivers are the most significant positive terms of the budget. Ground water influx is not visible on the diagram due to its small value. Outflow to the Baltic Sea and evaporation are negative terms of the budget.

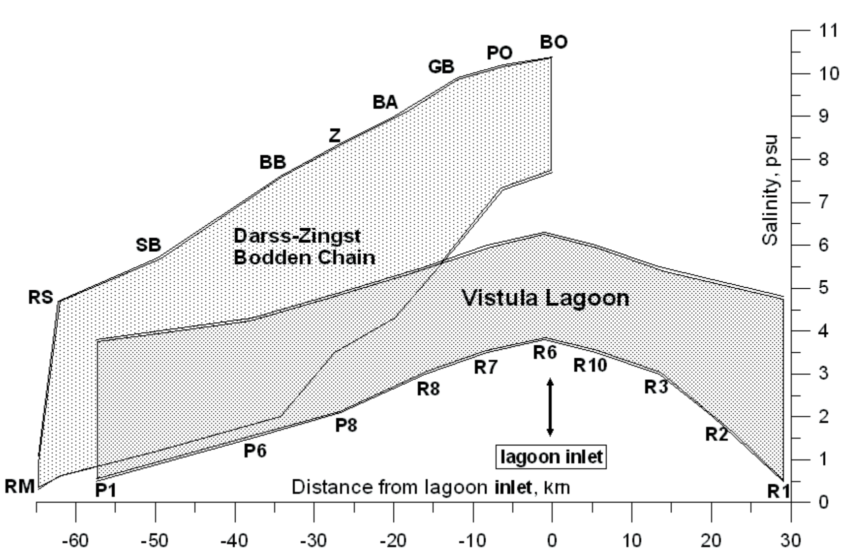

Fig. 3. Range of seasonal variations of monthly average values of salinity along the Darss-Zingst Bodden Chain and the Vistula Lagoon with indication of names of monitoring stations (indicated on Fig. 1). The peaks of plots corresponded to lagoon inlets are coincided.

water inflow from the Baltic Sea and river runoff, also vary from year to year.

Since spatial salinity differences are well pronounced and vary temporary in both lagoons, the one-dimensional in space model may be applied to resolve the salinity structure along the lagoon lengthwise axis; to resolve seasonal spatial pattern of salinity in the lagoons, two-dimensional model can be used.

Although both lagoons are, on average, vertically mixed, the salinity stratification is observed near lagoon inlets and main river mouths mostly at the spring and autumn periods (Chubarenko et. al. 1998). Therefore, a three-dimensional hydraulic model is required to simulate the real dynamics of salty water penetration into the lagoon as well as spreading the fresh river waters over the lagoon surface.

Salting and desalinisation

The instant value of salting factor reflects the current tendency of the hydrological changes in the lagoon: the lagoon tends to be less salty than the adjacent marine water if current value of F_s is less than 0.5 ($F_s < 0.5$), and saltier if it is bigger than 0.5 ($F_s > 0.5$) (Chubarenko et al. 2004). Since the values of salting factor F_s is bigger than 0.5 (Fig. 4), both lagoons are under predominant marine influence, but the DZBC depends on the marine influx stronger than the VL does.

The monthly-averaged salting factor for the VL varies in the range of 0.68-0.92 during a year and has a minimum in spring (corresponding to maximum river runoff) and maximum in summer, coming before the rainy season. The lagoon is intensively salting from May till July, and then experiences less rate of salting until wintertime, then temporal equilibrium comes, and finally an increasing of the fresh river runoff in spring leads to lagoon desalinisation (Fig. 4).

For the DZBC, the annual dynamics of salting factor is less pronounced. It is also characterised by one minimum and one maximum, however they are not as sharp as for the VL, and do not contemporise with extremes in river runoff (Fig. 4). Salting is controlled by inflow from the Baltic and continuously proceeds from January to August. Then, process changes to general desalinisation. In contrast to the VL, the duration of salting in the DZBC is longer than desalinisation, and there is no period of equilibrium.

Both lagoons are characterised by TS loop-shaped diagram (to pass clockwise in Fig. 5a,b), that is typical for lagoons, where annual dynamics of salinity and temperature variations are correlated; the both have one maximum and one minimum during a year, and are partly shifted in time (Chubarenko et. al. 2004). This diagram well indicates the periods of stratification. For example, for the VL the upper-layer and near-bottom conditions are different during spring and autumn periods (Fig. 5b).

Retention time

Each water gain component determines an individual input into general retention time of the estuarine lagoon (Chubarenko et.al. 2004). For DZBC and VL (Table 2), the river runoff and marine influx are the

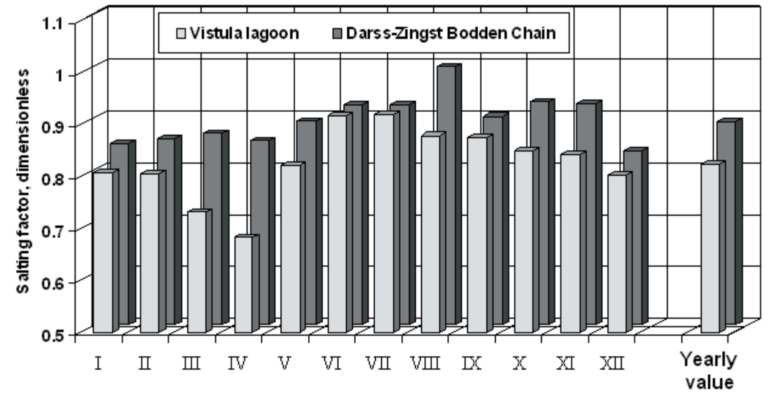

Fig. 4. Annual variations of salting factor for the Darss-Zingst Bodden Chain and the Vistula Lagoon: average monthly values and average annual value.

main contributors of flushing of the lagoon volumes. The resulting *retention time*, which is also called the *residence* or *flushing* time, is about 45 days for DZBC and 40 days for the VL. Therefore hydraulic capacity for restoration is similar for the both lagoons.

Response to level variations at the inlet and water exchange through the inlet

For both lagoons, the difference of water level between the lagoon and adjacent marine waters is the main driving force for water exchange, which intensity, in its turn, depends on hydraulic resistance in the inlet and channels between sub-basins. It was mentioned in (Schönfeldt 1997), that during a storm surge, mean water level in the DZBC is almost always lower than that in the adjacent Baltic Sea, because of considerable time lag between set-up of maximum water levels in the Baltic Sea and in the inner sub-basins. The elevation of the level in the Baltic Sea, which causes the level rise in the inner lagoon sub-basins, normally has already begun falling down, when the maximum levels are reached in the very lagoon (Schönfeldt 1997, Brosin 1965).

The induced water level variation at the distinct ends of the VL starts 3-4 hours after the imposed one occurs in the inlet. The lag between maximum values of inducing and responding signals is usually 10-12 hours; water exchange flux significantly influences on current velocities at the area close to the inlet (5-8 km), the river runoff is manifested even in less area (Szymkiewicz 1992). A wind is the only main driving force for the velocity pattern in the lagoon in a whole.

Since the level variations in the inlet, which could change rapidly (up to 4÷5 cm per hour), control the water exchange process, the fluxes through the inlets vary frequently, together with water level. Short-term variations (1÷4 hours) do not actually influence water exchange between volume of both lagoons and marine zone, because it is the same mixed water, which is to go back and forth, and it does not penetrate deep into the lagoons. Imposed level rise initiates the marine water intrusion passing along the bottom toward a lagoon deep, but shallow and long inlet in the DZBC, and inner sandy bar in the VL significantly limit the intrusion propagation. If only the amount of incoming water increases some certain value, i.e. the level rise has relatively long duration, the actual intrusion of saline water will happen. For example, it takes more than 6 hours for salt-water intrusion to overflow the bar towards the lagoon deep in the VL.

In general, velocity in the VL lagoon inlet is approximately 20% stronger than that in the DZBC. Inflow/outflow currents are observed to be uniform in 74.9% of situations; re-organisation process leads to two-layer currents (influx at the bottom and outflow at the surface) – 11.7%, or two-stream currents - 13.4%. The maximum currents of 1.34 ms^{-1} and 1.38 ms^{-1} were observed during instrumental measurements in the 1970s for inflow and outflow respectively. According to historical records the inflow current of 2 ms^{-1} was observed once in 18th century. The observed average velocity for one-direction flow through the whole inlet ranges between 0.06 and 0.95 ms^{-1}. The average currents for the two-layer or two-stream regimes are usually in the range of 0.1 – 0.2 ms^{-1}. (Lazarenko and Majewski 1971).

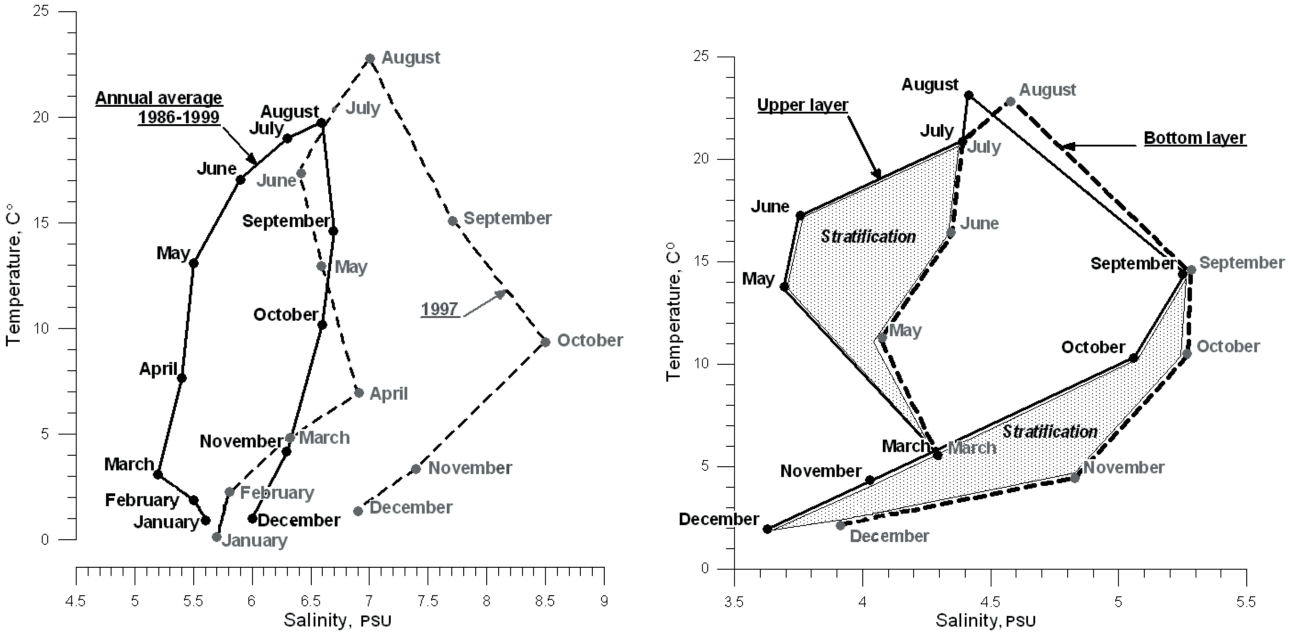

Fig 5. Monthly average values of TS index for Darss-Zingst Bodden Chain averaged over the years (1986-1999) and their values for 1997 (a); monthly mean values of spatially averaged TS index for upper (solid line) and bottom (dashed line) layers for the Vistula Lagoon in 1997 (b).

Wind action

Wind action is of specific importance for the lagoon water dynamics because it (i) directly generates water currents and (ii) establishes (with time) water level inclination, which is a reason for compensative near-bottom flows. Wind-induced currents in both lagoons are typically of 0.05-0.15 m s^{-1}, with a stormy maximum of 0.2-0.5 m s^{-1}. As for return flow, it develops in the VL in about 5 hours for lengthwise winds and 0.5-1 hour for transversal winds. According to (Lazarenko & Majewski 1971) the level rise at the remote end of the VL begins in 2-4 hours after wind starts blowing, the maximums of level rise rate comes in 5-6 hours, the maximum level is established in 6-12 hours after permanent wind blowing. The DZBC is divided into several sub-basins with shorter length scale each, and the time to get inclined and develop the return bottom flow is shorter: 0.5-1 hour for lengthwise winds and 12-30 minutes for transversal winds.

In the VL the inlet is located in the central part of the lagoon. The inlet has small hydraulic resistance. The lagoon has no narrowness in its shape. So, the level at any point of the VL can be presented as arithmetic sum of the level at the inlet and wind induced deviation, variable over the lagoon area. Extreme values of level changes at remote end of the VL are of 1.3-1.7 m, while 0.9-1.1 m of it is the contribution of wind induced level set-up. The difference in water levels between remote ends in stormy period usually is about 0.5-0.7 m, but can exceed even 1.5-1.7 m (Lazarenko & Majewski 1971).

The Baltic Sea water level variations are larger near the DZBC inlet than near the VL one, but the inner shore of the DZBC is better protected from flooding than that of the VL, because narrow and shallow lagoon inlet dumps the flow of marine waters into the lagoon. In addition, apparently in the DZBC, the narrows between its sub-basins, and especially the pass between Bodstedter Bodden and Barther Bodden, block the penetration of water along the lagoon.

Stratification and circulation classification

Stratification parameter estimated for the main river mouths and lagoon inlets gave respectively 0.02 and 0.1 for the DZBC and 0.2 and 0.7 for the VL. Circulation parameter equals 50 for DZBC and 25 for VL. This means that both lagoons belong to the estuaries (according the stratification-circulation diagram (Hansen and Rattray 1966), which are partly well mixed and have flow reversal with a depth. High values of circulation parameter for both lagoons manifest the low contribution of river drain to actual water movement in the lagoon body.

Estimation of estuary number gives values of 30-35 for the DZBC and 5-10 for the VL, and according to classification of Abraham (1988) and Harleman and Ippen (1967) this means that the DZBC is a well mixed water body (its estuarine number E_d is higher than 8), and the VL is in-between the well mixed and partly mixed types of coastal water bodies. However, an estimation of Estuarine Richardson Number (Fischer et al. 1979) for both lagoons gives values less than 0.08 (R equals 0.01 for DZBC and 0.002 for VL), which means that our lagoons are well mixed and the vertical density variation is negligible.

Such estimations of physical numbers provide a basis to consider generally our lagoons as vertically well mixed plane estuarine lagoons having predominantly horizontal spatial gradients of characteristics. And this means that two-dimensional plane modelling approach is able to reproduce their main behaviour correctly. However, if to estimate the described above parameters for some part of lagoon (e.g., an inlet area), the significance of stratification and importance of baroclinic effects will be evident.

According to (Martin and McCutcheon 1999; Fischer et al. 1979), the Coriolis effect is considered as important for Rossby numbers Ro<0.1. Rossby number for DZBC and VL is 0.003-0.14 and 0.005-0.056 respectively. It indicates that the Coriolis effect is important for the general water dynamics in the VL, while for the DZBC the Coriolis force considerably influences the water dynamics in the biggest Saaler Bodden only. Going into details, the Coriolis force acts in any basin for any movements (Chubarenko et.al 2004) and becomes significant when characteristic time of motion is of order of inertial period, which makes up approximately 14.7 hours for both lagoons. Thus, for the both lagoons, the role of the Coriolis force is still to be clarified more deeply, because the estimations above are not in the agreement, for example, with the previous statements on insignificance of the Coriolis force, made by Schönfeldt (1997) and Szymkiewicz (1992).

DISCUSSION ON MODEL SELECTION VERSUS RESEARCH GOAL

Zero-dimensional approach (0D)

Water inflow and outflow are mostly controlled by water level variations at the inlets of the lagoons. For this reason, a zero-dimensional (in space), or box, model is applicable for purposes to estimate a temporal dynamics of the water exchange between the lagoons and the Baltic Sea with a time scale of weeks, months or years. If the VL can be presented as one well-mixed box, the DZBC has to be approximated as a cascade of linearly connected boxes (Correns 1978*)*. Since water salinity and temperature are the state variables, precipitation, evaporation, river and underground run-offs and, of main importance, the level variations at the inlet are to be treated like forcing factors, as well as temperatures of air, river and marine waters and solar heating. Evaporation is typically parameterised through the difference between water and air temperature and wind. Incorporation of the chemical and biological cycles in such a model allows simulation of a seasonal dynamics of multitude parameters of water quality. To avoid an overestimation of lagoon flushing by marine waters, the most frequent water level variations (when the same water is coming back and forth through the inlet) have to be filtered. And it is the vary point of model calibration versus salinity: which amplitude and duration of level rise do actually bring marine salty water intrusions into the entire lagoon.

One-dimensional approach (1D)

The both lagoons are elongated and the main rivers inflow into their remote ends. Vertical stratification is weak or localised in limited areas. Therefore, the one-dimensional model with the spatial lengthwise extension could reasonably simulate the longitudinal variations of salinity, temperature or any other parameter in the lagoon. It is expected that the deep navigable channel in the VL can be described as additional brunch in one-dimensional computational grid. If for the DZBC the open marine boundary is to be placed at the one end of 1D-grid, for the VL it should be in the middle of it. Model has to be driven by river discharges, marine level variations and by wind. This approach is good enough to simulate correctly any wind surge in case of evaluation of risk of flooding at the settlements at the distant ends of the lagoons.

Two-dimensional approach (2D)

Two-dimensional modelling has already proved its applicability for different problems (Catewicz & Jankowski 1983, Kolodko et al. 1983, Karpinski & Robakiewicz 1993, and other cited below). It gave very precise solution for water level variations in case of extreme stormy events (Szymkiewicz 1992). To get more reliable results for the entrance of the DZBC boarded by low flooded land the simulation area was extended to east from the inlet (Schönfeldt 1997), and that permitted to reveal a lag between the maximum water levels in the individual “Boddens”. The 2D model for the VL was completely prepared (Staskiewicz & Lewandowski 1994, Rasmussen 1998) for practical use in problems of (i) variations of the water level and fluxes (hydrodynamics), (ii) transport of ‘passive’ tracers like salinity (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 (I.Chubarenko 1998a) or artificially established new entrances in the lagoon (I.Chubarenko & Tchepikova 2000). Analyses of currents and sediment transport by 2D model was made by Hinkelmann & Zielke (1993) for harbour of city of Barth in the DZBC, and by Jurgensen et al. (2004) for city of Baltiysk in VL. The above success in using 2D models for practical problems is ensured by a principal peculiarity of 2D approach – it gives rather precise solution for water fluxes between parts of elongated basin (Chubarenko et al. 2000).

Three-dimensional approach (3D)

Three-dimensional modelling is required to study the real physical processes taking place in both lagoons, e.g. near-bottom penetration of marine water intrusion into the VL (I.Chubarenko 1998b) or local upwelling-downwelling zones, which permanently exist along the lines of high depths gradients in the DZBC. Real three-dimensionality of currents in the VL was proved by direct measurements in 1994-1995 (Chubarenko & Chubarenko 2003), and emphasised in the works of Kazmierski (2001), Chubarenko & Chubarenko (2002), and Jasinska et al. (2003). First result of 3D modelling for the Vistula Lagoon is presented in Bielecka & Kazmierski (2003), where a curvilinear orthogonal grid with minimum and maximum cell size of 200 and 1300 m respectively and 11 levels in vertical direction was used. The simulations have demonstrated vertical differences in velocity and salinity distributions in the lagoon. It was mentioned that the correct accounting of vertical stratification at the open boundary of the lagoon inlet is a crucial point for proper simulation of currents and salinity.

The use of 3D model is recommended when the conditions for benthic or pelagic aquaculture are studied, or sediment transport is investigated in the vicinity of the considerable local depth variations like dredging areas. Finally, the simulation tasks involving short-term forecasts for accidental oil or other chemicals spills, which fractions partly spread over the surface and partly sink, definitely require the 3D approach for the hydrodynamic and transport problems because of possible different directions in advective transports at different depths.

CONCLUSIONS

A set of parameters was introduced for pre-modelling comparative description of the morphometry and hydrology of the selected lagoons. Quantitative estimation of these parameters is very helpful in understanding of main features (as well as similarity and differences) of studied domains before the numerical modelling will start, but no formal procedure was proposed so far to deduce from values of these parameters which type of numerical model is to be applied. To answer this question, the purposes of modelling study should be considered rather than the physical characteristics.

The reviewed publications show that models of different dimensionality can be applied for revealing the appropriate features in lagoon hydrodynamics at different spatial and temporal scales. Even though it is used to apply the zero- and one-dimensional approaches to analyse the water level variations and even the salinity gradients in the lagoons, the two-dimensional plane (2D) modelling approach is more efficient and reasonable for DZBC and VL.

Two principal types of problems can be solved using 2D-approach (with an accuracy sufficient for practical purposes), namely, the simulation of water level variations with time scale of hours, and water quality variations with time scale of months. 2D models are good platform to analyse different scenarios of economic activity in the lagoon watershed area (Bielecka et al. 2003).

The 3D modelling approach accounting for the Coriolis force is required for successful simulation of real currents in DZBC and VL lagoons as well as in other estuarine lagoons, especially in case of operational forecast during incidents. The weakest point of 3D modelling is the huge amount of data required.

Even though the real current structure in the lagoons should be simulated only by 3D-model, some simplification is possible because in many tasks the solution for current itself is not required. For instance, the ecological modules need only the fluxes between lagoon sub-basins, and these fluxes are the direct output from 2D model. For tasks involving lagoon water quality, 2D hydrodynamic and transport models are usually sufficient to resolve the seasonal variations of simulated parameters, and, in this case, it should be calibrated using some conservative tracer such as salinity. The 2D time-dependent hydrodynamic approach is also sufficient to simulate wind surges and water exchange between a lagoon and adjacent marine coastal waters. Finally, the tasks involving the study of water exchange between the sub-basins of the lagoons should be solved in 3D approach for precise short-term simulations and in 2D one - for simulation of seasonal variations.

The comparison of characteristic features of two Baltic non-tidal estuarine lagoons, the Drass-Zingst Bodden Chain and the Vistula Lagoon, showed, that even though there is a considerable similarity in their general hydrodynamic behaviour, the lagoons possess very individual features influencing upon their hydraulic and mixing process. Especial effect is caused by existence of deep navigable channels.

Acknowledgements

The authors thank Prof. Ulf Carsten, for his valuable remarks and Mr. W. S. Hess (both – Germany) for his attentive reading of the text. Authors very appreciate constructive remarks and advises of Prof. Jan Harff, Germany, and Prof. Zbigniew Pruszak, Poland. Paper was prepared under cooperation program "Investigation of Coastal Waters of the Baltic Sea" between Institute for Aquatic Ecology (University of Rostock) and Atlantic Branch of P. P. Shirshov Institute of Oceanology, Kaliningrad, during the workshops at the Field Station Zingst of the University of Rostock financed by the University in 2003-2005.

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