DELIVERABLE D6.2

The Vistula Lagoon, the Ria de Aveiro Lagoon, the Mar Menor Lagoon and the Tyligulskyi Lagoon

Modelling results and recommendations

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Chapter 1

The Vistula Lagoon - Modelling results and recommendations

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1. Introduction

In this report calibration and validation results of models set up to answer specific questions related to the impact of different climate and socio-economic scenarios developed for the Vistula Lagoon will be presented.

The multi-model approach is used for the Vistula Lagoon to analyse a coastal lagoon dynamics on different time-scales - from seasonal variations to the climate scale variations (30 years) under natural and anthropogenic forcing.

Climate change and socio-economic impact on the transboundary Vistula Lagoon is analysed with the application of the two modelling suits: **1)** the **Delft3D** numerical model analysing response of the Vistula Lagoon to the climate and socio-economic impacts and **2) MIKE** modelling suite to answer a specific, however very important to Kaliningrad City, question: what will be the impact of climate changes on the salt intrusions into the Pregola River, polluting the city's fresh water uptakes.

The first numerical model of the Vistula Lagoon was set-up based on Delft3D software (Deltares 2010). Due to natural processes, mainly two-directional flow in the Baltiysk Strait responsible for water exchange between the lagoon and the Gulf of Gdańsk, it was decided to use a three dimensional approach to represent the Vistula Lagoon. The modelled area was covered by a curvilinear orthogonal grid in the horizontal plane (Fig. 1.1) and in the vertical by a system of layers using sigma coordinates (Table 1.1). In the hydrodynamic model spatial and temporal variations of water levels, currents and salinity were reproduced. Results from this model were coupled with the water quality model which takes into account such processes as nitrification, denitrification, algae growth, respiration and aeration, mineralization of particulate and dissolved organic matter; for more details on the models set-up see LAGOONS 2012b.

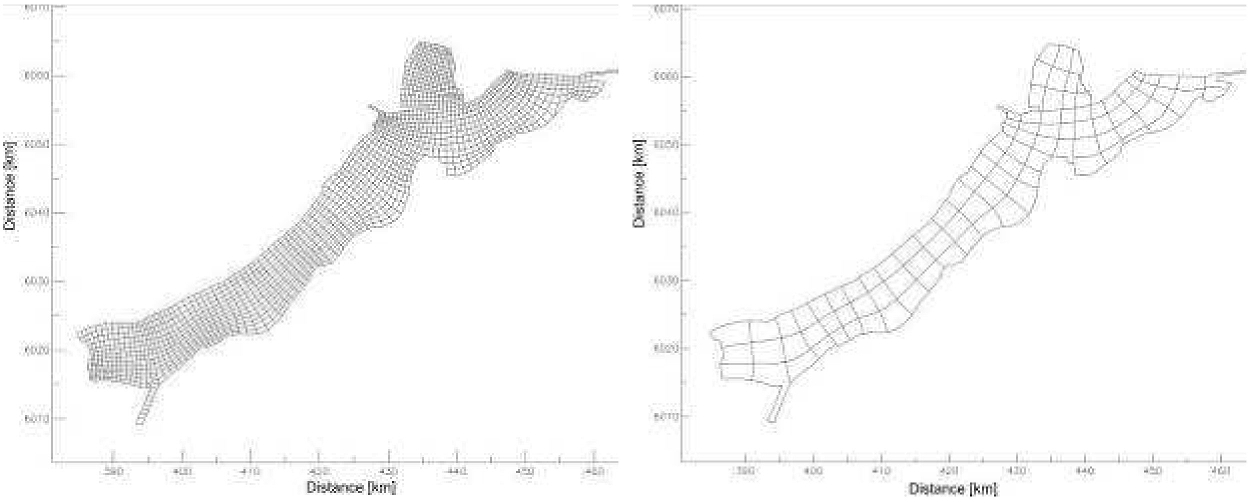


Fig. 1.1. Representation of Vistula Lagoon by curvilinear orthogonal grid: hydrodynamic model (left), and aggregated grid for water quality model (right).

Table 1.1. Discretization of Vistula Lagoon in vertical plane.

layer no	thickness [%]	layer no	thickness [%]
1	5	8	9
2	9	9	7
3	12	10	4
4-6	14	11	2
7	10		

The second numerical model of the Vistula Lagoon was set-up based on MIKE modelling suite (MIKE 21 & MIKE 3 Flow Model FM Hydrodynamic and Transport Module. 2005). The model will applied in order to carry out some supplementary simulations basing on specific data for the Russian part of the Vistula Lagoon to cover the whole spectra of the tasks related to the lagoon simulations of climate scenarios.

As it was mentioned in D61.1, the MIKE modelling system (also used in the MANTRA-East project in its 2D version) was used for the Vistula Lagoon in two versions: (1) regular grid (200 x 200 m) and 2-dimensional version, which was traditionally operated in Kaliningrad region and installed at end-users institutions, and (2) flexible mesh version (mesh size of 50-100 m in the river stream and of 1 – 1.5 km in the lagoon area), also in 2-dimensional mode, which is recently used for the scientific analysis.

Calibration of both 2-dimensional versions of the MIKE21 regular grid and the MIKE21 flexible mesh for the simulations of the Vistula Lagoon hydrology and an effect of salt wedge intrusion upstream the Pregolya River (to finalise preparation of the model set-up for future climate simulations) was made.

Table 1.2. Description of model set-ups for simulations on the basis of data for the Russian part of the Vistula Lagoon.

Model version	Grid size	Vistula Lagoon only	Vistula Lagoon and downstream of the Pregolya River	Results
Calibration/verification of salt wedge intrusion upstream the Pregolya River				
MIKE 21 (2-dimensional)	200 x 200 m	Period 09.04 – 20.11.1998, model warming 01.01– 09.04.98,	-	Salinity variations (one year) over the lagoon
MIKE 21 Flexible Mesh	Flexible mesh, triangular elements (mesh size is of 50-100 m in the river stream, and of 1 – 1.5 km in the lagoon area).	Vistula Lagoon was included into domain as adjacent water body	Short-term episodes: 29.09 – 11.10.12, 2 sec time step (calibration period)	Water level variations and salinity intrusion in the Pregolya. Calibration data of salinity in the river were collected for 06 - 08.10.2012. Verification period 13.08 - 15.09.2013. Exact data for verification – 04.09.2013.

2. DELFT 3D modelling suite

2.1 Data overview and analysis

Each numerical model requires its calibration and validation to confirm that processes modelled reproduce those observed in natural conditions. However, it is well known that any numerical model is not able to reproduce conditions observed in nature perfectly. From one side, the discretization of the modelled area introduces inaccuracies, on the other the existing knowledge on forcing phenomena is limited by data availability both in time and space. The main goal of the model calibration and validation is to estimate errors in representation of natural processes.

To calibrate the hydrodynamic and water quality models, data from three consecutive years 1998, 1999 and 2000 were applied. They were collected within EU FP5 “MANTRA–East” project (Bielecka et al., 2004). For the model validation purposes, data from the year 2009 were collected within the LAGOONS project.

Below an overview of data sets applied for both calibration and validation are presented.

2.1.1 Climate data

The Vistula Lagoon is an area where three basic climatic parameters influence hydrodynamics and water quality, namely wind, air temperature and precipitation.

Wind is the main forcing of water movement in the Vistula Lagoon; in natural conditions its direction and speed vary in time and space. Continuous measurements of wind conditions are limited to two stations in the Vistula Lagoon region (Baltiysk – on the Russian side, Frombork - on the Polish side). Based on earlier analysis (Bielecka et al. 2004) it was found that to reproduce hydrodynamic conditions in the Vistula Lagoon wind measurements from the coastal station Baltiysk can be assumed as representative for the area. Wind velocity and direction were measured for all analysed periods with a frequency of 3 hours by the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring (KCGMS), Russia. Comparison of wind roses for each year presented in Fig. 2.1 shows that in all analysed years the southern wind dominates; from that sector the maximum wind magnitude was usually observed. Eastern wind was observed rather frequently, however its magnitude hardly ever exceeded 4 m/s in the analysed years.

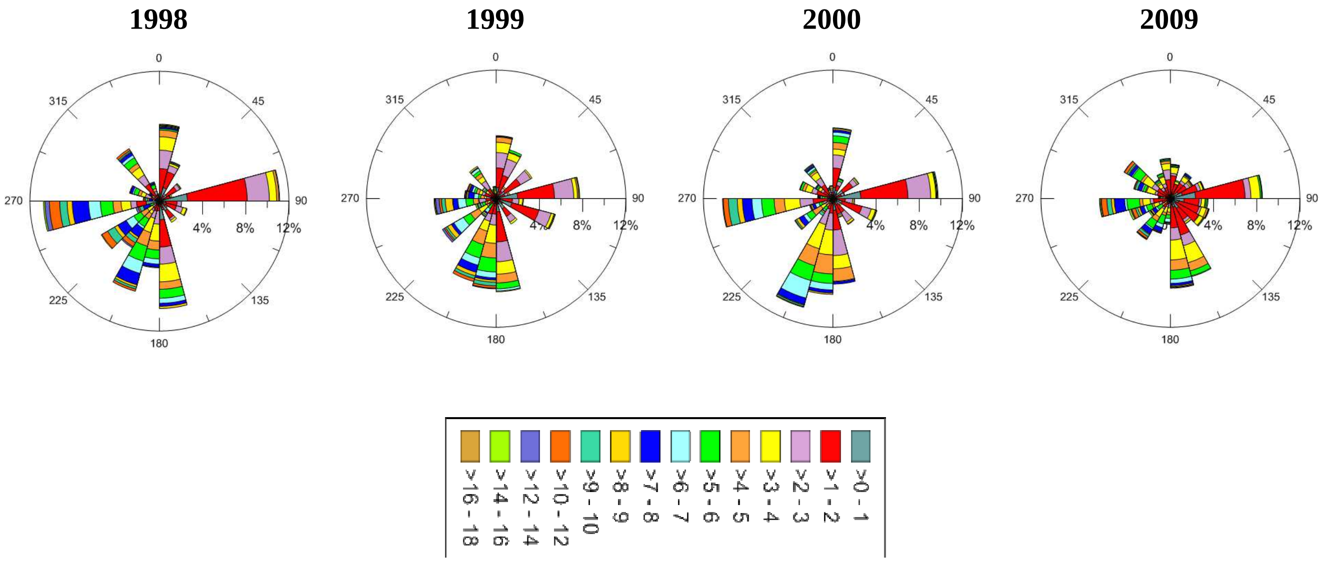


Fig. 2.1. Comparison of wind roses for the Baltiysk station for years 1998-2000 and 2009.

Air temperature and precipitation are very important parameters characterising climate in the drainage basin of the Vistula Lagoon. They are directly related to amount and temperature of water discharged by rivers into the lagoon. Both parameters were analysed in details in Chapter 6.1 of D5.1 Report (LAGOONS 2013).

2.1.2 Hydrological data

Hydrology in the Vistula Lagoon basin is crucial from the point of view of lagoon's hydrodynamics and water quality. Inflow of riverine water into the lagoon modifies the general water circulation pattern created by meteorological conditions. In the same time riverine water

carries dissolved chemical elements playing an important role in water quality processes in the lagoon.

From the modelling point of view the following hydrological parameters are important:

river discharge and water temperature;

water levels;

water exchange through the Baltiysk Strait.

River discharge and its temperature

River discharges play an important role in the modification of hydrodynamic conditions in the Vistula Lagoon, especially in the river mouth regions. As shown in Table 2.1 (in Appendix 1), measurements were done regularly on most rivers incorporated in the model, however their frequency varies from 1/day till 1/month. For two inflows (sewage collector, Prokhladnaya) direct measurements were not carried out; in those cases estimated values were introduced.

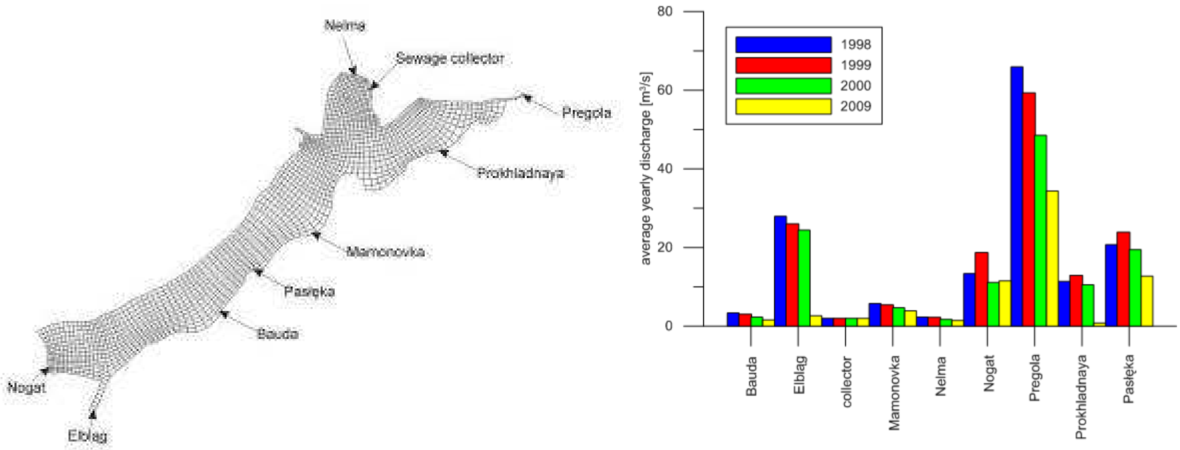


Fig. 2.2. Location of discharge points (left) and average discharges in years 1998, 1999, 2000 and 2009 introduced into the model.

In the Vistula Lagoon drainage basin discharge from the Pregola River dominates on the scale of a year. Its average discharge reached 66 m^3/s in the year 1998, ~60 m^3/s in the year 1999 and ~48.5 m^3/s in the year 2000, while in the year 2009 it was only ~34 m^3/s. Much bigger differences for Pregola River are observed in the scale of seasons. The most wet was the first quarter of the year (months I-III) when the average discharge for the Pregola in all analyzed years exceeded 110 m^3/s, with the maximum value of 134 m^3/s in the year 2000.

The Pasłęka River, located in the central part of lagoon in the vicinity of the Polish-Russian border, is characterized by low average discharge (19 - 24 m^3/s) in years 1998 - 2000, and even lower discharge (12.7 m^3/s) in the year 2009.

It is very characteristic that discharge in the Elbląg River was found relatively high in the years 1998-2000 when data were available only 1/month; for the year 2009 when data were available 1/day much lower average discharge was found.

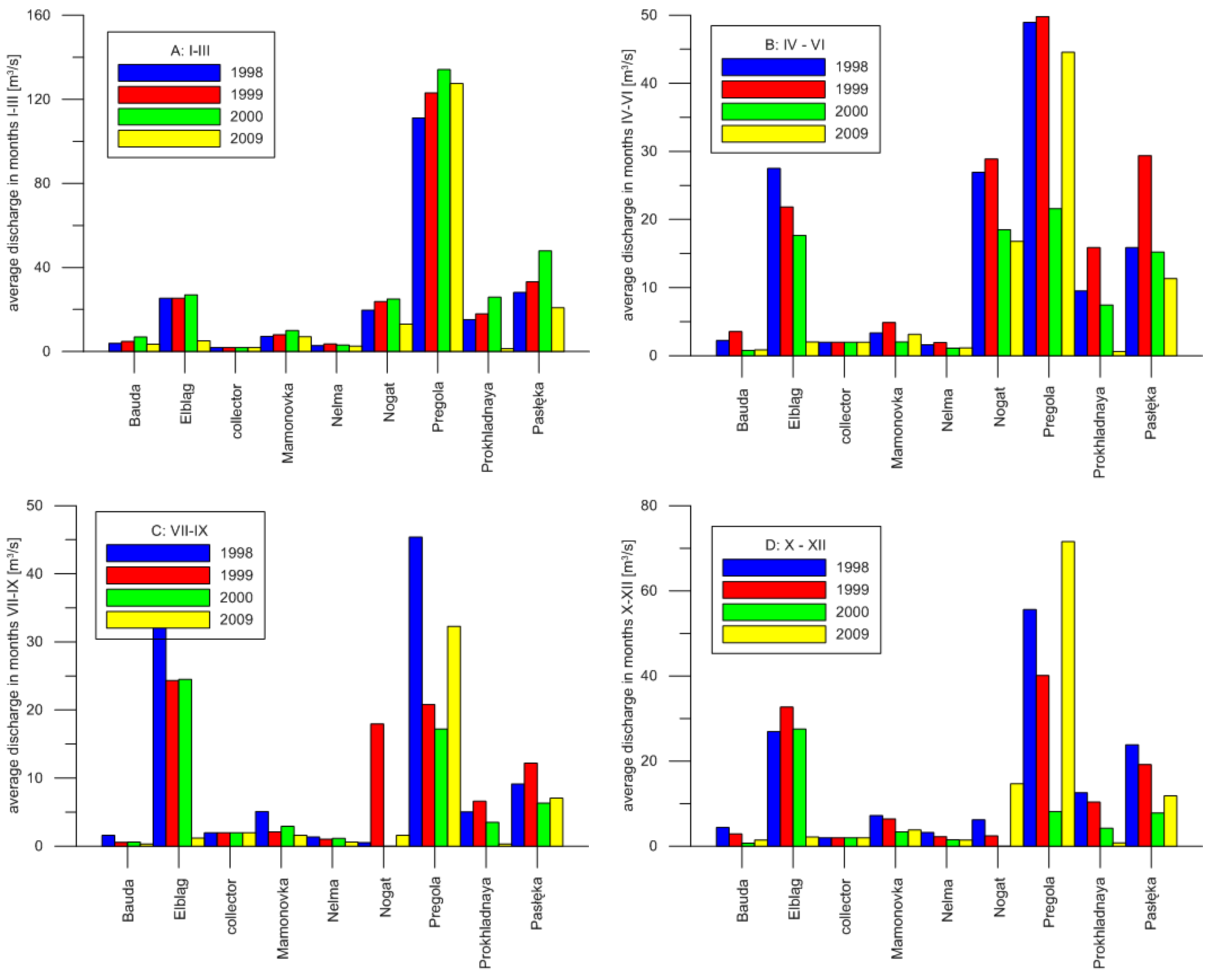


Fig. 2.3. Average discharges into the Vistula Lagoon in division into three months periods.

Water levels

Water levels were measured at several coastal stations of the Vistula Lagoon with different frequencies, for details see Table 2.2 (Appendix 1). Those data were in use for the calibration and verification of hydrodynamic model. Data from the Baltiysk station played a special role; they were applied as model boundary conditions. Detailed analysis of water levels will be presented in Section 2.3.

Water temperature and salinity in the lagoon

Water temperature and salinity were measured continuously at a few coastal stations at the Vistula Lagoon (Tables 2.3, 2.4 - Appendix 1). Additionally, those parameters were measured at vertical profiles (CTD measurements) in a number of locations in the lagoon. Overview of

collected data is given in Table 2.5 (Appendix 1) for the Polish part, and Tables 2.6 and 2.7 (Appendix 1) for the Russian part. In Fig. 2.4 the location of measurements is given.

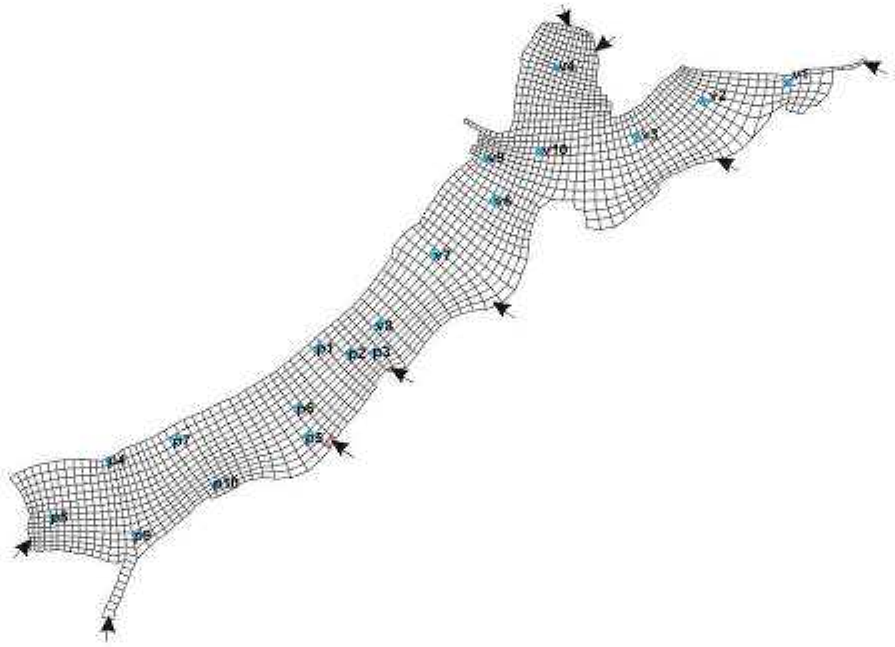


Fig. 2.4. Location of CTD measurements in years 1998-2000.

2.1.3 Ecological data

Data for calibration

The hydro-meteorological data and measurement sites which were adopted for reconstruction of nutrient cycling during the calibration procedure are presented in Fig. 2.5, whereas parameters and frequency of measurements are presented in Table 2.8 (Appendix 1). Four Polish rivers: Pasłęka, Elbląg, Bauda, and Nogat and Szkarpawa (taken together) were considered in the model of the Vistula Lagoon ecosystem. In the Russian part of the lagoon four rivers were incorporated: Pregoła (with the largest water outflow to the Vistula Lagoon), Nelma, Prokhladnaya and Mamonovka (Fig. 2.6, Table 2.9 - Appendix 1). Data on nutrient concentrations as well as organic matter content were gathered within the EU Project MANTRA-East (http://mantraeast.ibwpan.gda.pl/). The data used in the modelling are mainly from monitoring programs carried out by the state administration and scientific institutions in Poland and Russia. Data for the Gulf of Gdansk were elaborated based on publically available Baltic Environmental Database (http://nest.su.se/bed/). The data sources and frequency of measurements are presented in Tables 2.10 and 2.11 (Appendix 1).

For the years 1998-2000 and for the Vistula Lagoon, data from 43 sampling points: 25 in the Polish part and 18 in the Russian part of the lagoon, were used. The measurement stations are presented in Fig. 2.7.

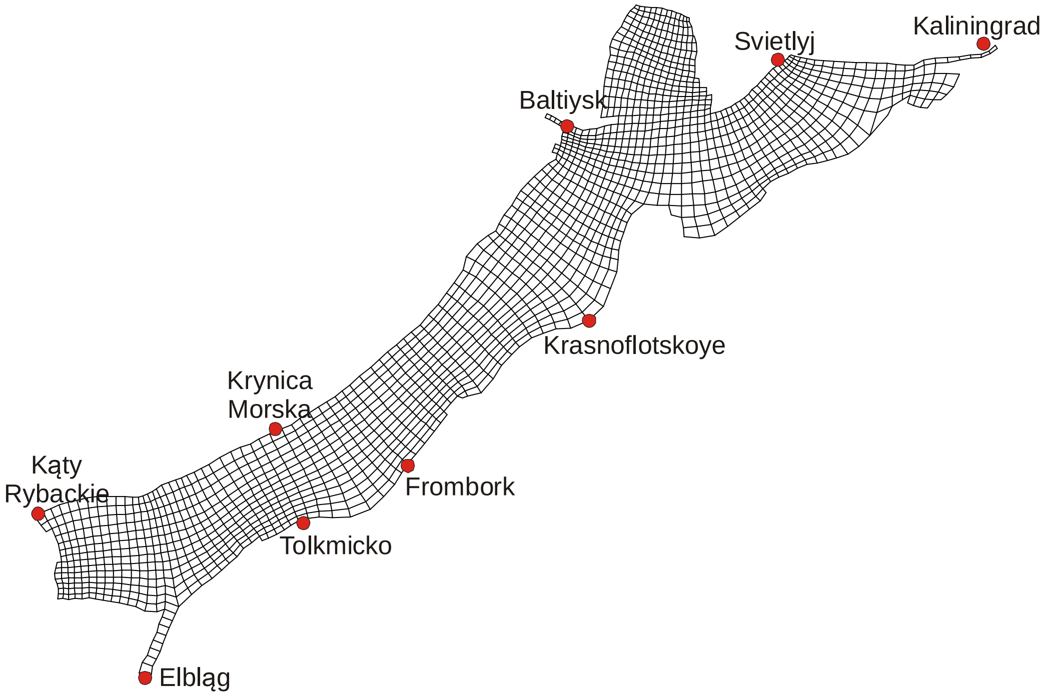


Fig. 2.5. Location of hydro-meteorological measurement stations in the Vistula Lagoon.

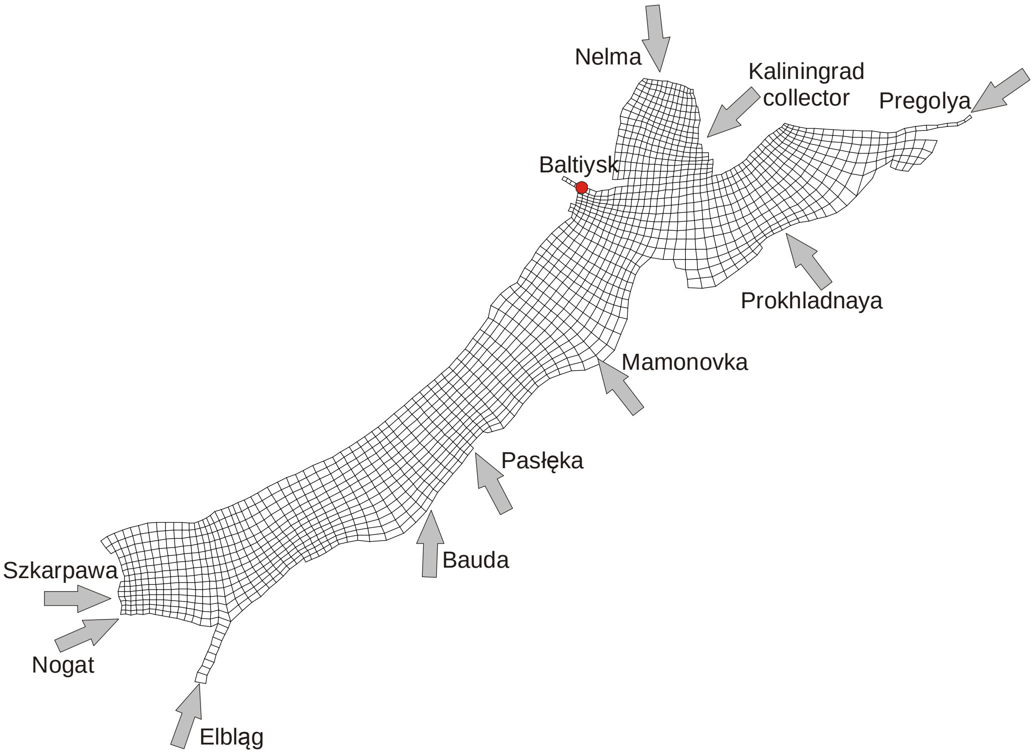


Fig. 2.6. Rivers entering the Vistula Lagoon which were applied in the model.

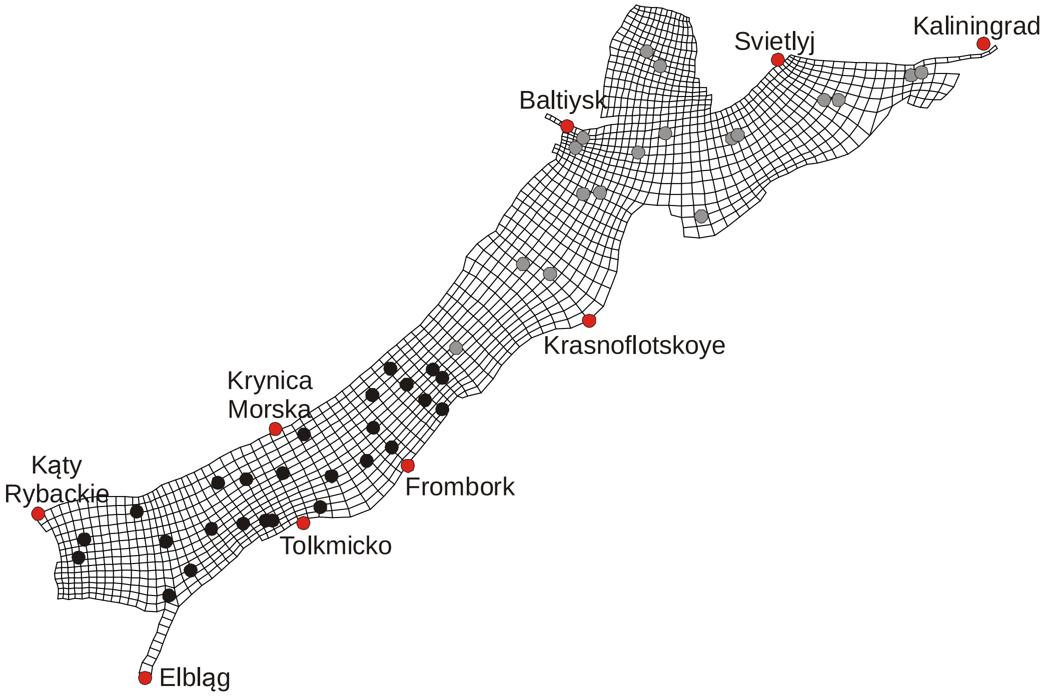


Fig. 2.7. Locations of measurement stations in the Vistula Lagoon (black dots – location of measurement points in Polish part of the lagoon; grey dots – Russian part of the lagoon).

<u>Data for validation</u>

In the present work, data from 2009 were used for validation of the model used in the Vistula Lagoon. The frequency and data sources of hydro-meteorological are presented in Table 2.11 (Appendix 1).

Similarly to the calibration procedure, in the validation procedure four rivers on the Polish side and four rivers on the Russian side were taken into account. The outcome from the monitoring programs conducted by the regional administration was the main source of measurement data. All available data on nutrients and organic matter concentrations in the rivers entering the lagoon and concentrations in the lagoon's water for the year 2009 are presented in Tables 2.12 and 2.13 (Appendix 1).

2.2 Hydrodynamic model calibration and validation

2.2.1 Calibration methodology and results

The hydrodynamic model of the Vistula Lagoon is constructed based on Delft3D-FLOW software. Taking into account the specific characteristic features of the area, a curvilinear orthogonal grid in the horizontal plane (Fig. 1.1) and 11 layers in the vertical, using sigma coordinates, were introduced (Table 1.1). In the hydrodynamic model, water levels, water currents and salinity changes in time and space were calculated. The calibration was carried out using data from three consecutive years 1998, 1999 and 2000. Water currents in the Vistula Lagoon are mainly wind driven, modified by inflow of rivers and water exchange with the Baltic Sea through the Baltiysk Strait. Due to data limitation, time varying and spatial uniform wind conditions as measured at the coastal station Baltiysk were applied.

Initial conditions

Based on available data, the initial conditions were created using the following procedure:

- preparation of salinity spatial distribution in layers based on available historical data;
- run of the model with a steady wind, rivers inflow and water level conditions as on the 20th December 1997;
- continuous run of the model with time varying boundary conditions till 1st January 1998.

Boundary conditions

To run the Vistula Lagoon model the following data were taken into account:

- wind velocity and direction from Baltiysk station – years 1998-2000, frequency 6 h (Fig. 2.8);
- water levels (Fig. 2.9; freq. - 3 h) and salinity (Fig. 2.10– freq. 1 day) in the Baltiysk Strait – years 1998-2000;
- inflow of rivers – years 1998-2000, frequency as in Table 2.1 (Appendix 1) (Fig. 2.11).

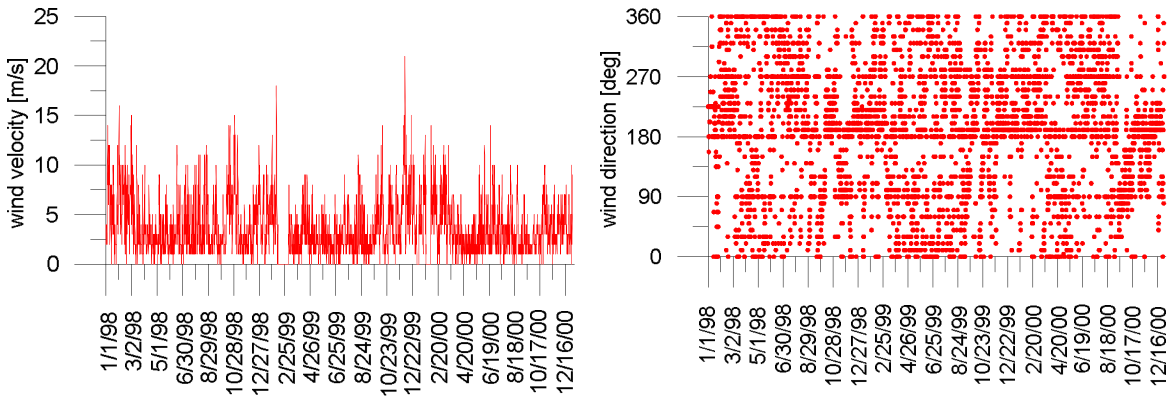


Fig. 2.8. Wind velocity (left) and direction (right) at the Baltiysk coastal station in years 1998-2000.

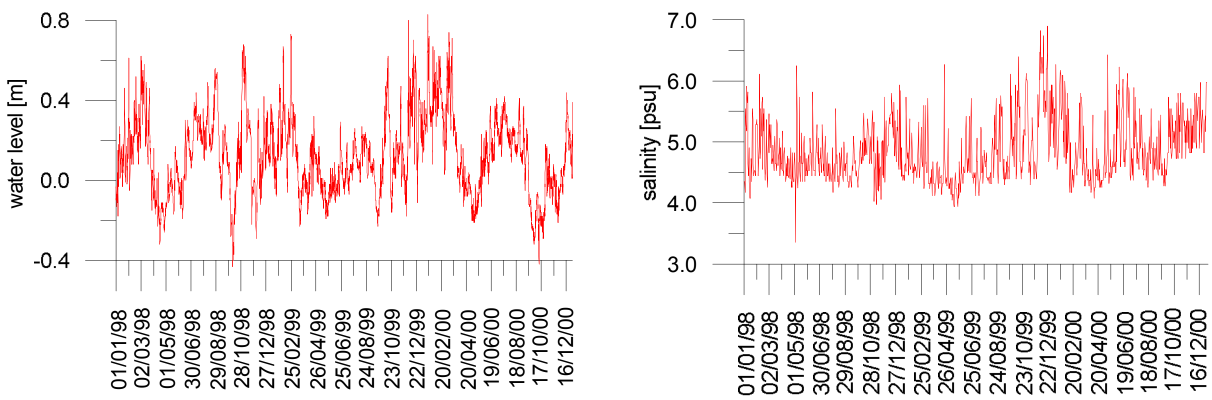


Fig. 2.9. Open boundary conditions - water level variations (left) and salinity variations (right) in Baltiysk Strait in years 1998 – 2000.

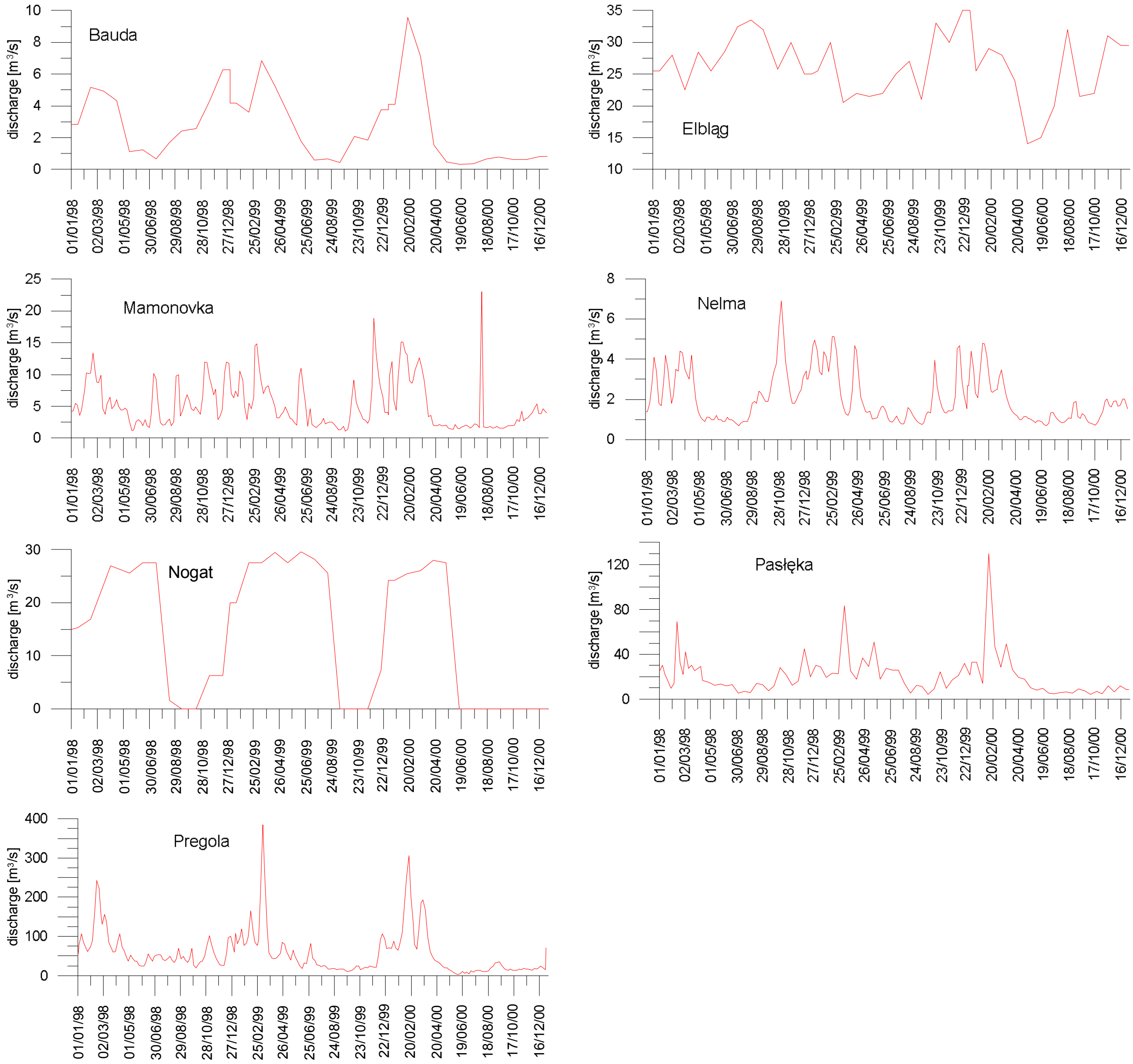


Fig. 2.10. River discharges in years 1998-2000 in the main inflows to Vistula Lagoon.

To calibrate the model, several runs using a variery of numerical parameters were carried out. Below, the results from the best run are presented. In that case the following numerical parameters were applied:

Manning roughness coefficient C_D:	0.015
Horizontal eddy viscosity:	0.1 m^2/s
Horizontal eddy diffusivity:	1 m^2/s
Vertical eddy viscosity :	0 m^2/s
Vertical eddy diffusivity:	0 m^2/s
Wind drag coefficient:	0.0025

Results

Comparison of measured and modelled values will be presented for all parameters in the same manner:

- graphically;
- using two evaluation criteria: Nash and Sutcliffe efficiency (NSE), and Deviation in Balance (DB).

Nash and Sutcliffe efficiency (Nash, Sutcliffe, 1970) is a non-dimensional measure describing the squared difference between the simulated and observed values. It is defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(obs_i - sim_i)^2}{\sum_{i=1}^{n}(obs_i - obs_{av})^2}$$

where: obs_i - observed value;

sim_i – simulated value.

The efficiency can vary from minus infinity to 1. In case NSE<0 the observed mean value (obs_{av}) is a better predictor than the model, while for NSE>0 the model is a better predictor than the observed mean.

Deviation in balance (DB) is a measure which describes the quality of simulated model results as the difference of observed values against the simulated ones. It is defined as:

$$DB = \frac{sim_{av} - obs_{av}}{obs_{av}} \times 100$$

where: sim_{av} - mean value of simulated data;

obs_{av} - mean value of observed data.

Comparison of model results with *in situ* measurements covered the following parameters:

- water level variations in time at coastal stations (graphical comparison - Fig. 2.11; NSE and DB evaluation criteria – Fig. 2.15);
- salinity variations in the lagoon (graphical comparison: Figs. 2.13, Fig. 2.14; NSE and DB evaluation criteria – Figs. 2.15, 2.16, 2.17; comparison of averages in verticals – Figs. 2.18, 2.19).

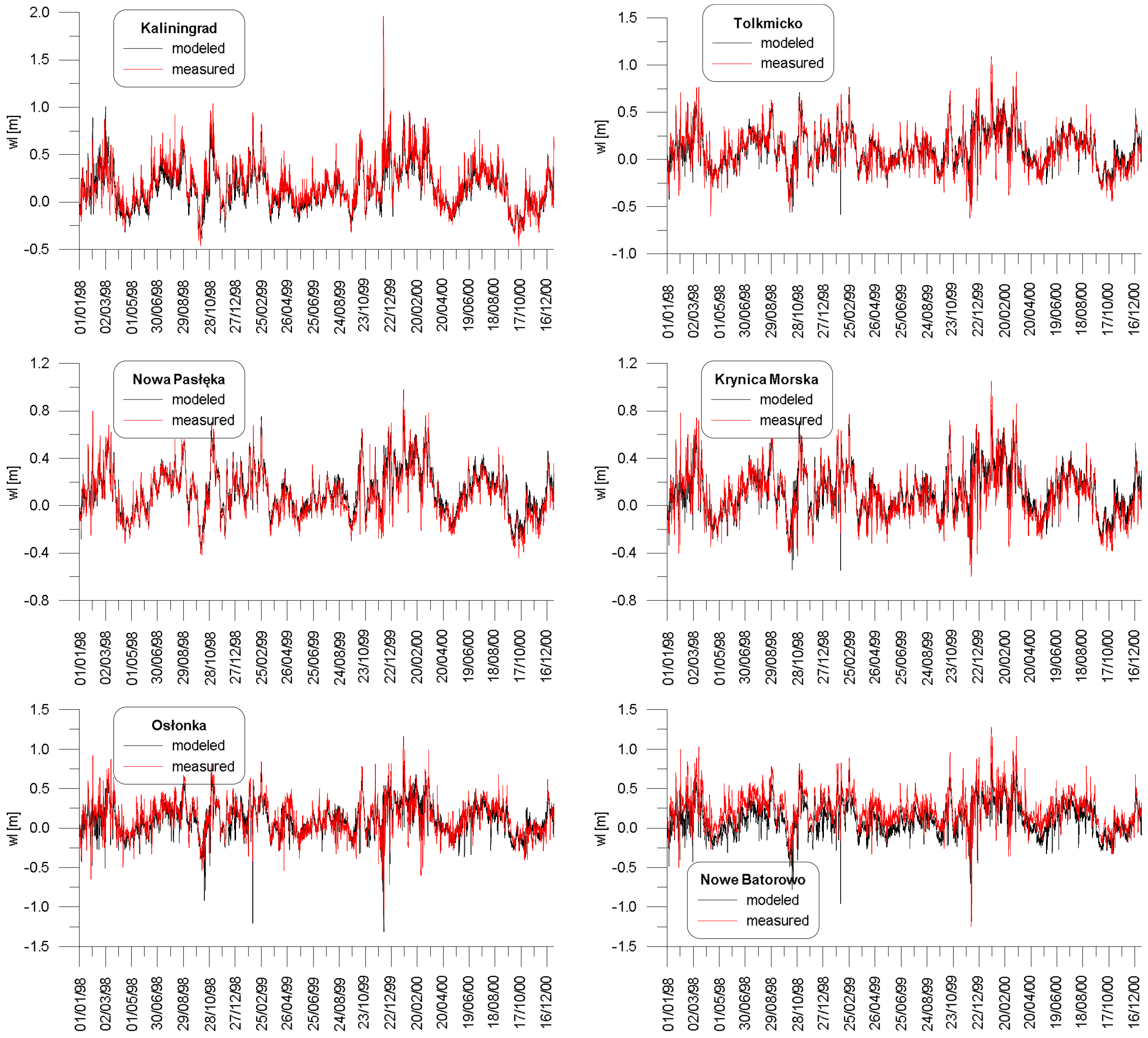


Fig. 2.11. Water level variations in time at stations located at Vistula Lagoon coast – comparison between measurements and modelled values – 1998-2000.

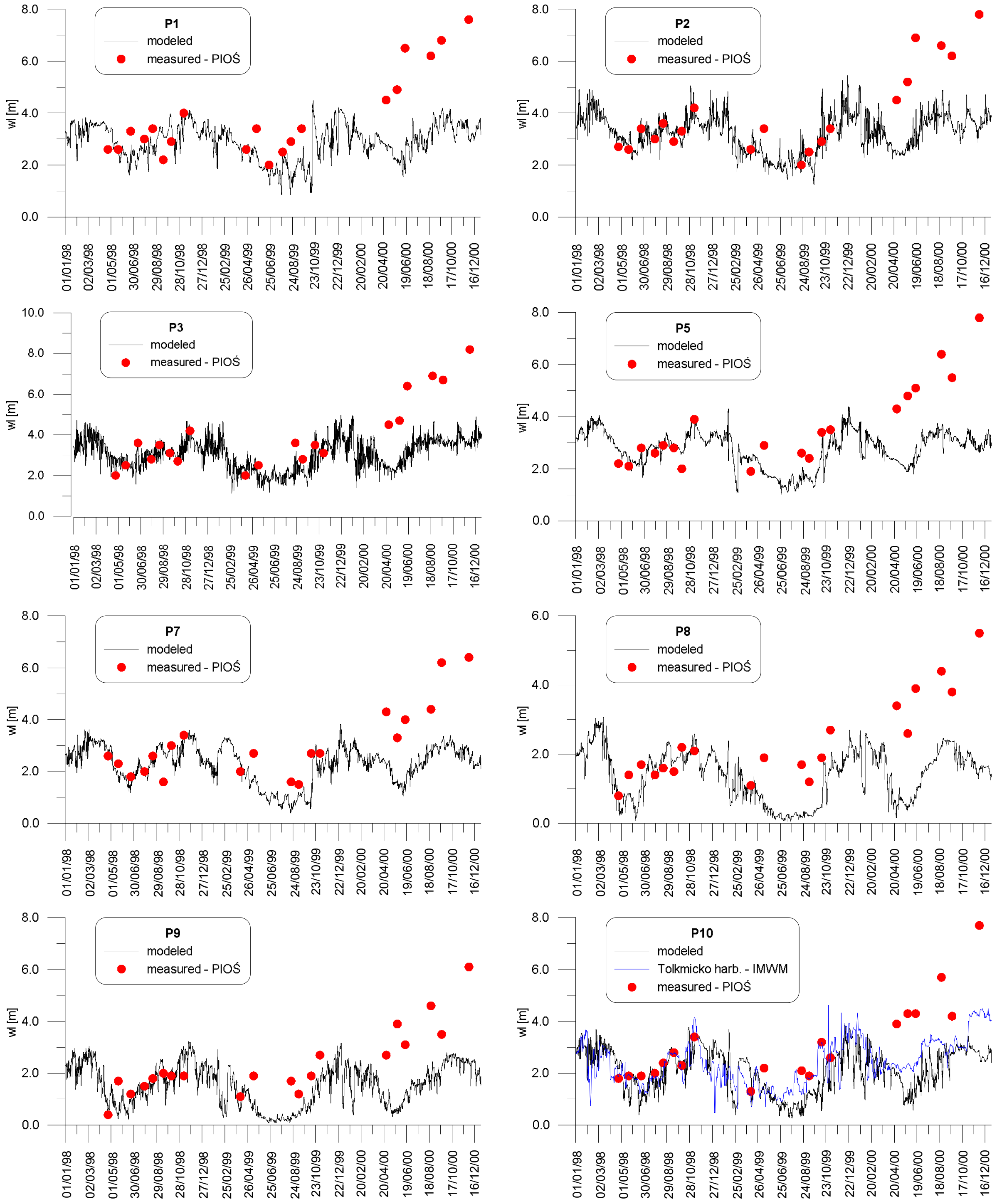


Fig. 2.12. Salinity variations in time at chosen locations in the Polish part of Vistula Lagoon – modelled versus measured data – 1998-2000.

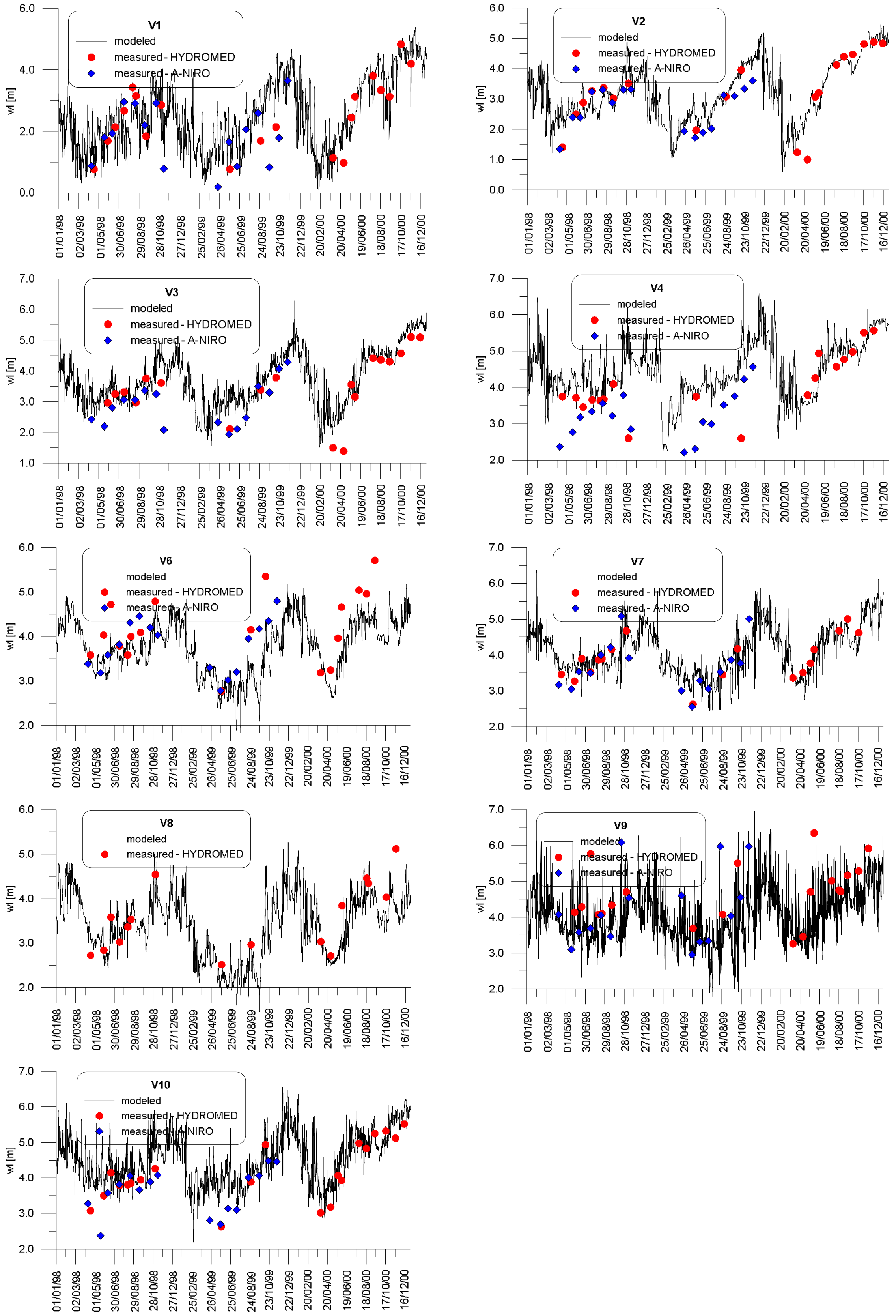


Fig. 2.13. Salinity variations in time at chosen locations in the Russian part of Vistula Lagoon – modelled versus measured data.

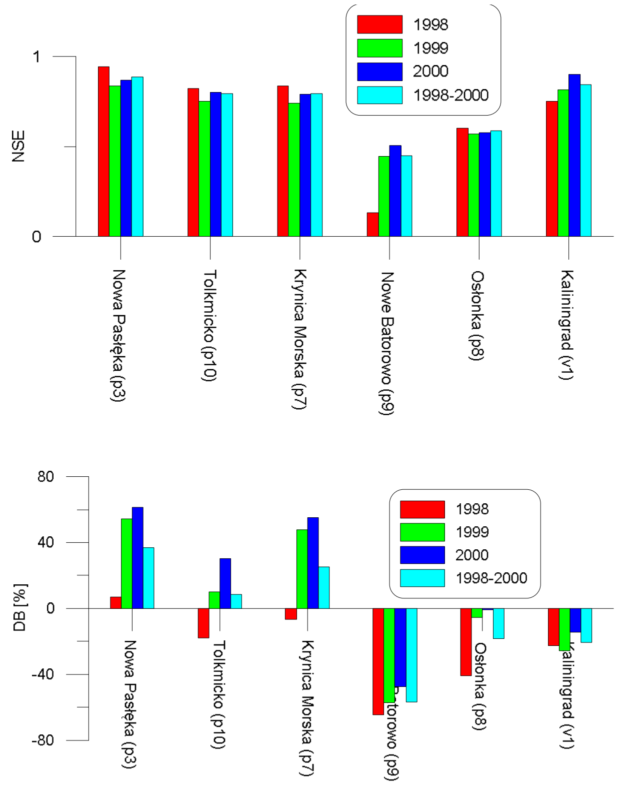


Fig. 2.14. Evaluation of water level variation at chosen locations in years 1998-2000: top – NSE; bottom – DB.

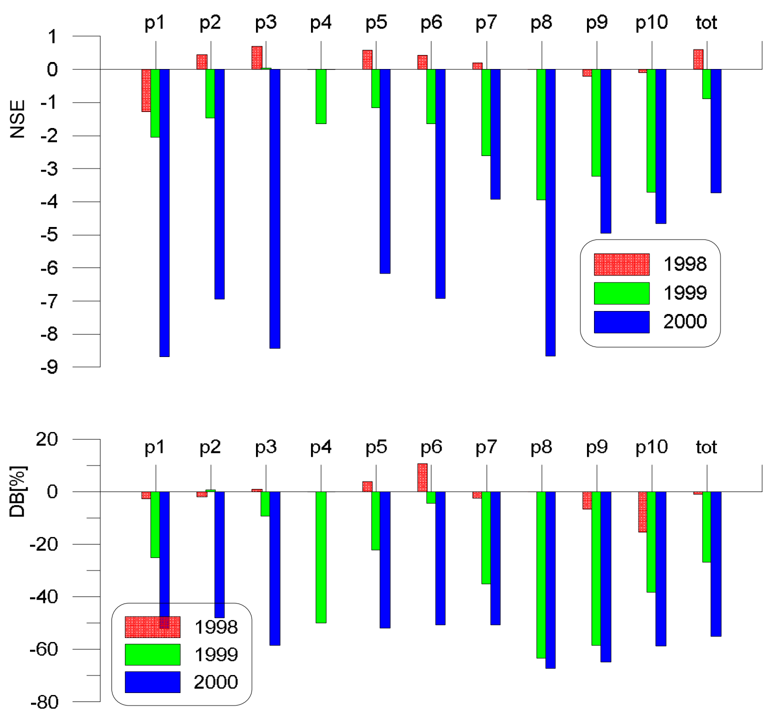


Fig. 2.15. Evaluation of salinity variation at chosen locations in the Polish part of Vistula Lagoon in years 1998-2000: top – NSE; bottom – DB.

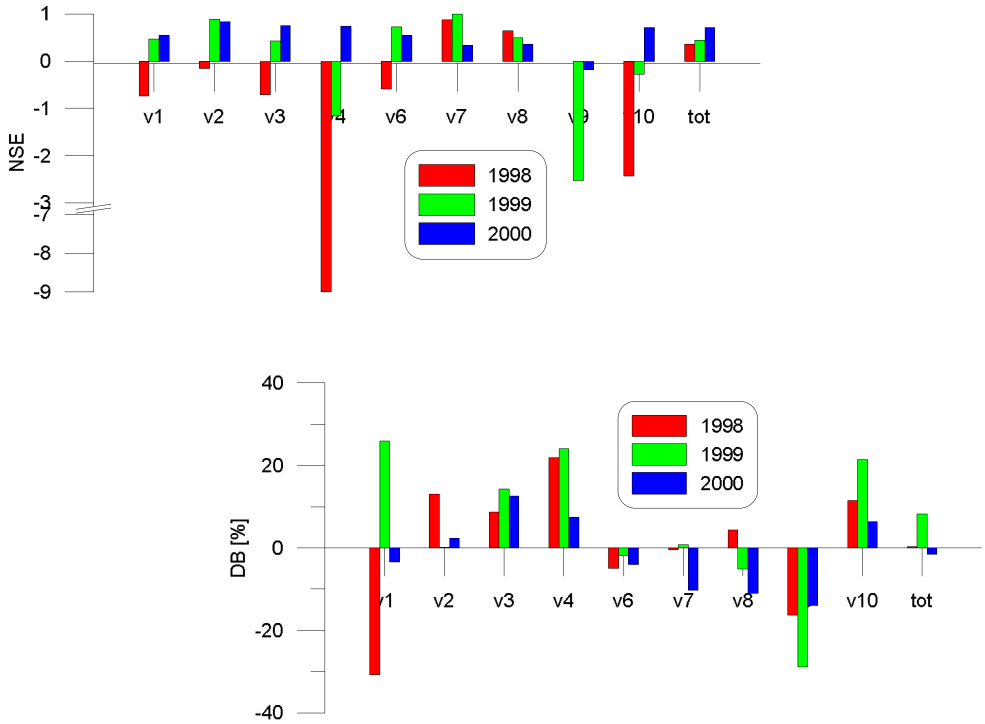


Fig. 2.16. Evaluation of salinity variation at chosen locations in the Russian part of Vistula Lagoon in years 1998-2000: top – NSE; bottom – DB.

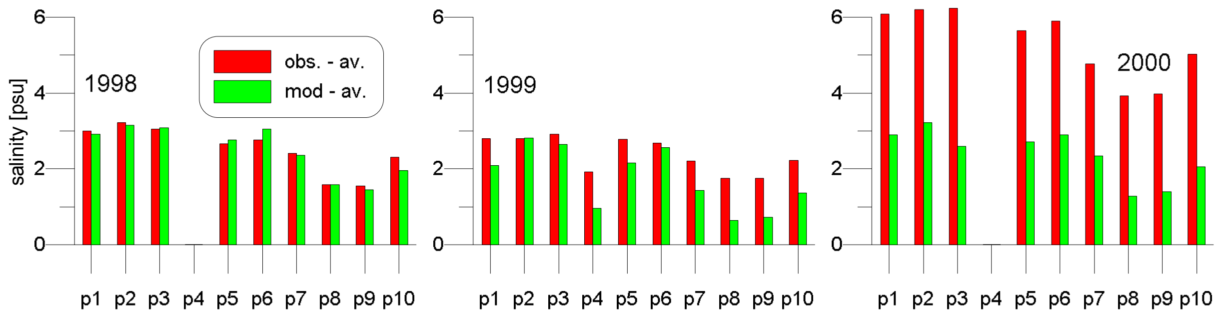


Fig. 2.17. Comparison of salinity averaged values at verticals in the Polish part of Vistula Lagoon in years 1998, 1999 and 2000

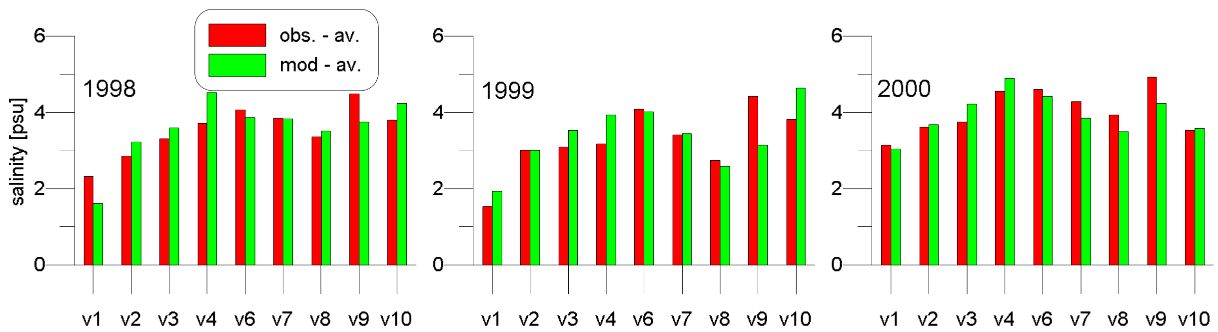


Fig. 2.18. Comparison of salinity averaged values at verticals in the Russian part of Vistula Lagoon in years 1998, 1999 and 2000.

Comparison of model results using both graphical presentation and evaluation measures leads to the following conclusions:

- water level variations at coastal stations are reproduced by the model with high accuracy in most locations taking into account graphical comparison and NSE measure. The lowest efficiency was observed at Nowe Batorowo, close to the Elbląg river inflow to the lagoon. This discrepancy can be explained by probable low accuracy of discharge for the Elbląg river in years 1998-2000 (see Section 2.2.1). Usage of DB measure for averaged measured and modelled values leads to errors up to 60%. However, it has to be noted that variations of water level around the reference level were taken into account;
- salinity variations were analysed separately in the Polish and Russian parts of the lagoon due to different data sources. In the Polish part (Fig.2.15) a substantial difference is observed between the results from the year 1998, when the agreement was good, and years 1999-2000 for which the agreement was lower. In the Russian part (Fig. 2.16) quite opposite situation can be observed. In both parts the accuracy of the modelled salinity is lower than for water levels as a consequence of much lower accuracy of input data. Comparison of the averaged observed and measured salinity values (Fig. 2.17, 2.18) shows rather good agreement with the exception of the year 2000 in the Polish part. The measured values are much higher than those measured earlier and later; it seems that a systematic measurement error occurred.

2.2.2 Validation methodology and results

Model validation was carried out for the year 2009 using all numerical parameters as derived in the calibration process.

Initial conditions

Similarly as for the calibration, also for the validation purposes it was not possible to create initial conditions using the *in situ* data. In such circumstances, the procedure to create initial conditions was as follows:

- salinity spatial distribution in layers were prepared based on available historical data (the same as for the calibration);
- run of the model as steady state for the 20th December 2008 to reach the steady state;
- continuous running of the model as time varying (time varying boundary conditions) till 1st January 2009.

Boundary conditions

To run the Vistula Lagoon model the following data were provided:

- wind velocity and direction from Baltiysk station– year 2009, freq. 3 h (Fig. 2.19);
- water levels (Fig. 2.20; freq. - 3 h) and salinity (Fig. 2.20– freq. 1 day) in the Baltiysk Strait – year 2009,
- inflow of 9 rivers/discharges – year 2009, frequency as in Fig. 2.21.

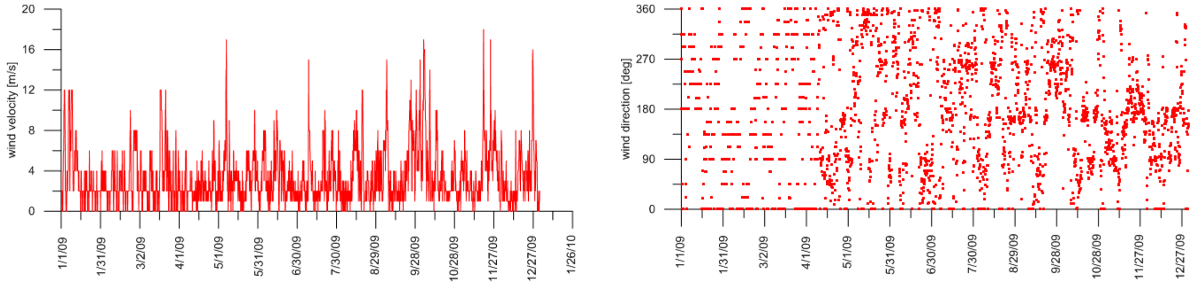


Fig. 2.19. Wind velocity (left) and direction (right) at the Baltiysk coastal station in 2009.

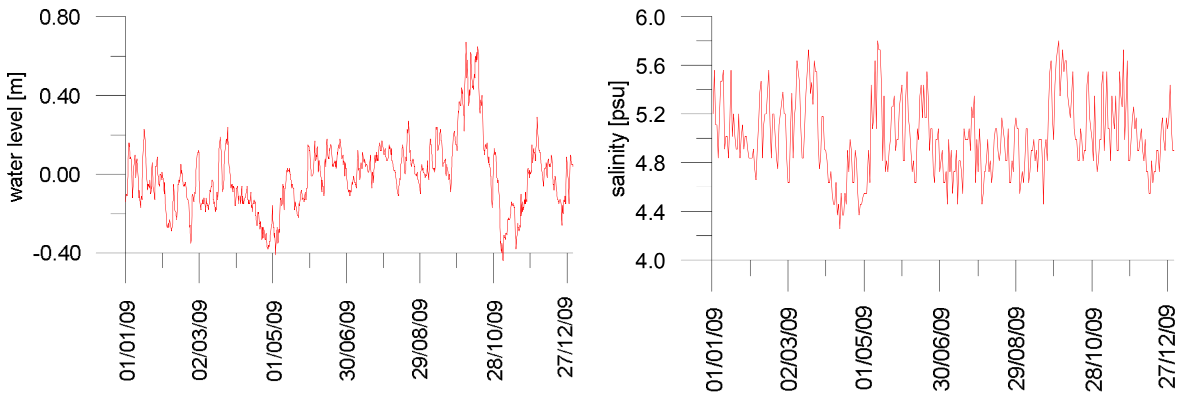
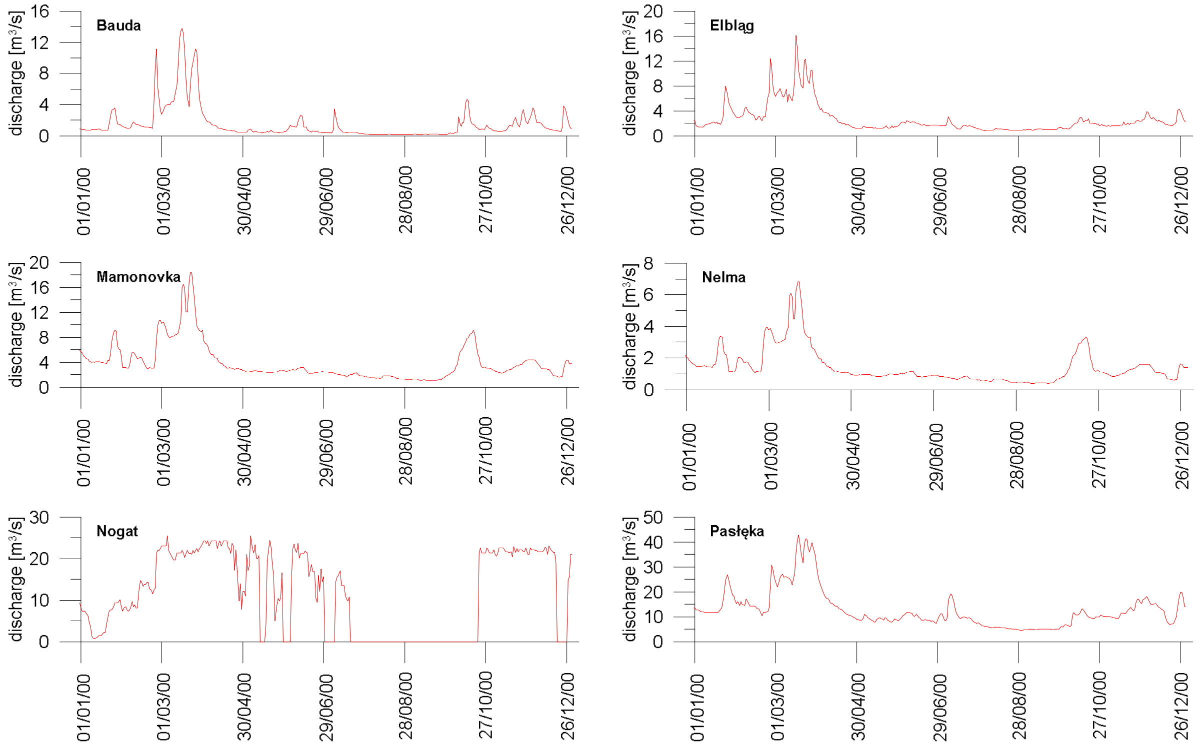


Fig. 2.20. Open boundary conditions – water level variations (left) and salinity variations (right) in Baltiysk Strait in year 2009.



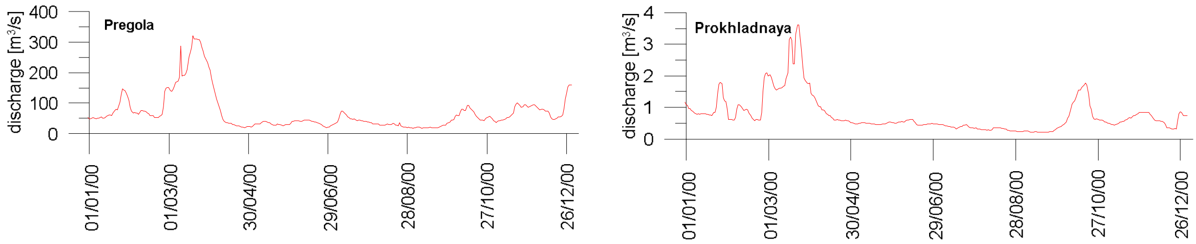


Fig. 2.21. River discharges in year 2009 in the main inflows to Vistula Lagoon.

Results

Comparison of the model results with *in situ* measurements covered the following parameters:

- water levels variations in time at coastal stations (graphical comparison – Fig. 2.22; NSE and DB evaluation criteria – Fig. 2.25)
- salinity variations in the lagoon (graphical comparison: for the Polish part – Fig. 2.23, for the Russian part – Fig. 2.24; NSE and DB evaluation criteria – Fig. 2.26 and 2.27; comparison of averages at verticals – Figs. 2.28, 2.29) .

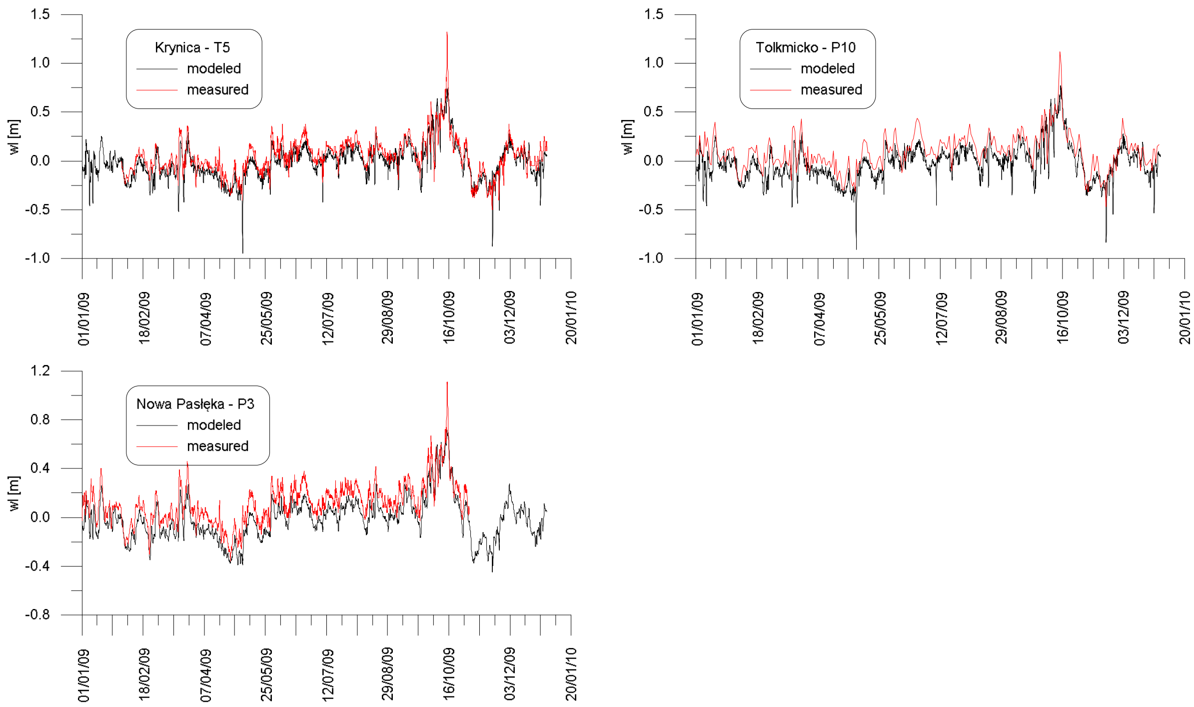


Fig. 2.22. Water level variations in time at stations located at Vistula Lagoon coast – comparison between measurements and modelled values – 2009.

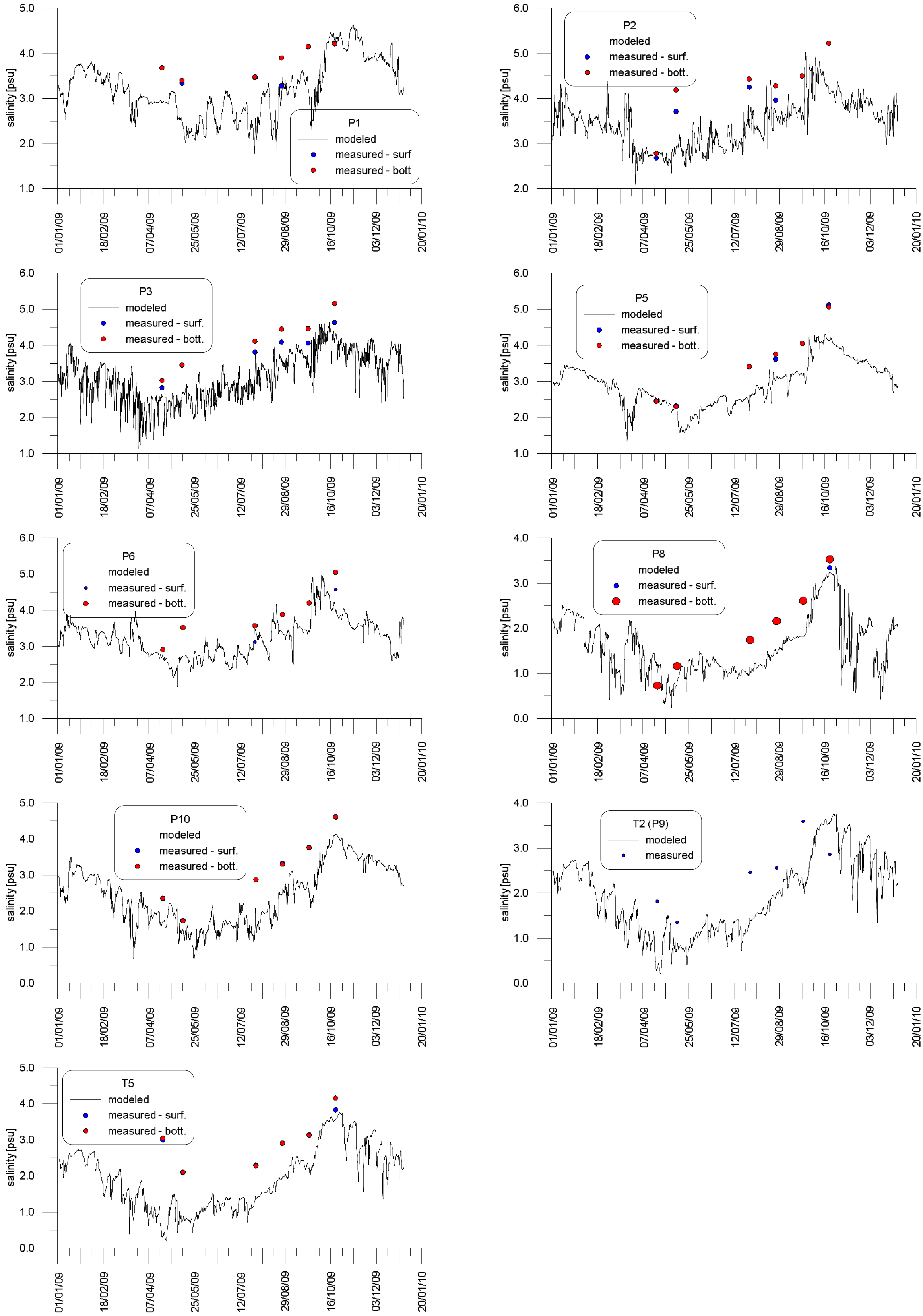


Fig. 2.23. Salinity variations in time at chosen locations in the Polish part of Vistula Lagoon, modelled versus measured data – 2009.

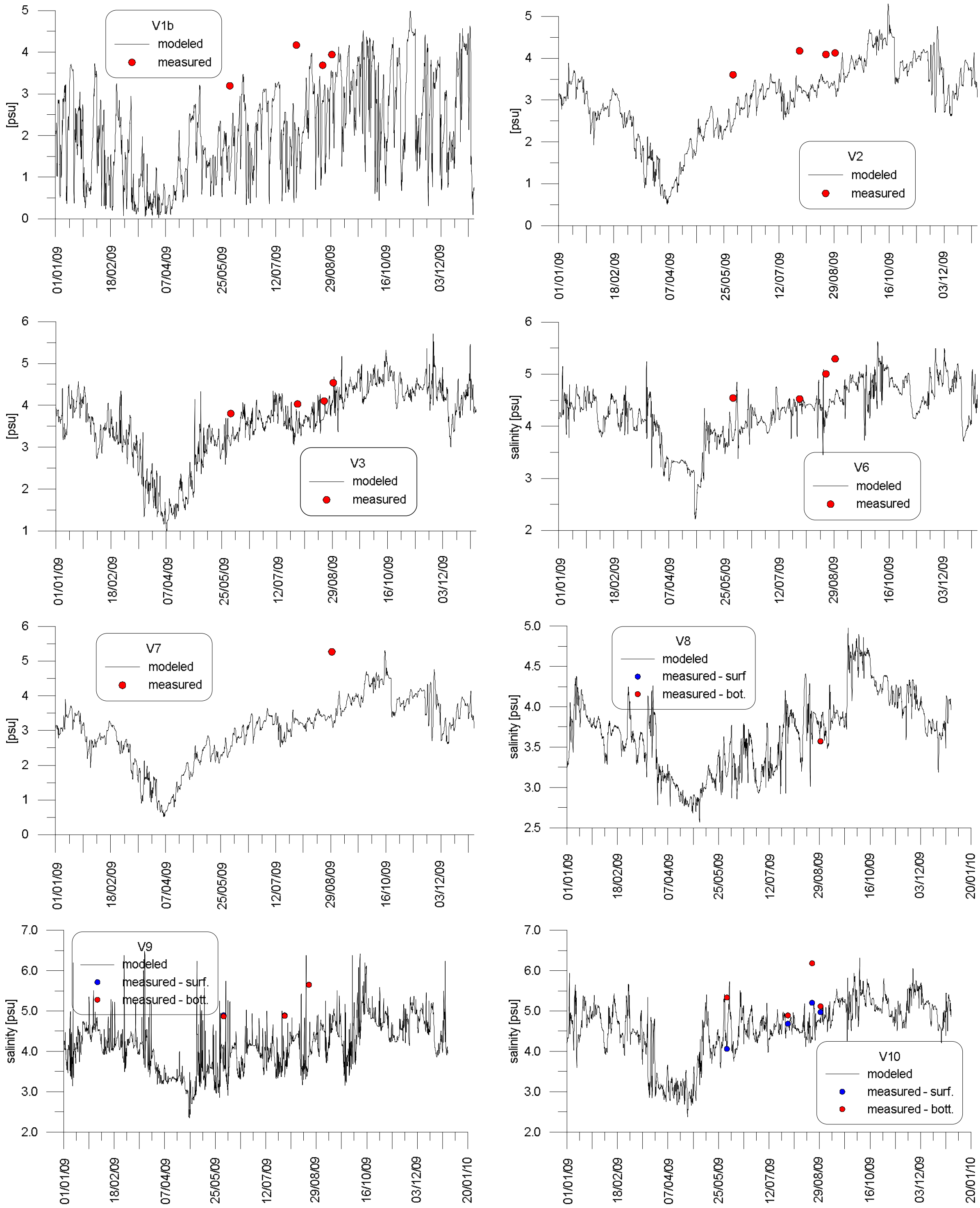


Fig. 2.24. Salinity variations in time at chosen locations in the Russian part of Vistula Lagoon, modelled versus measured data – 2009.

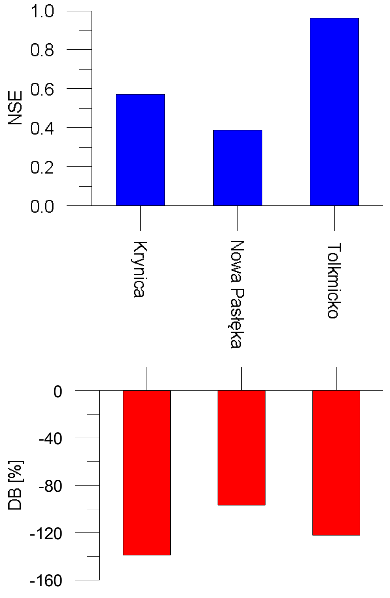


Fig. 2.25. Evaluation of water level variation at chosen locations in year 2009: top – NSE; bottom – DB.

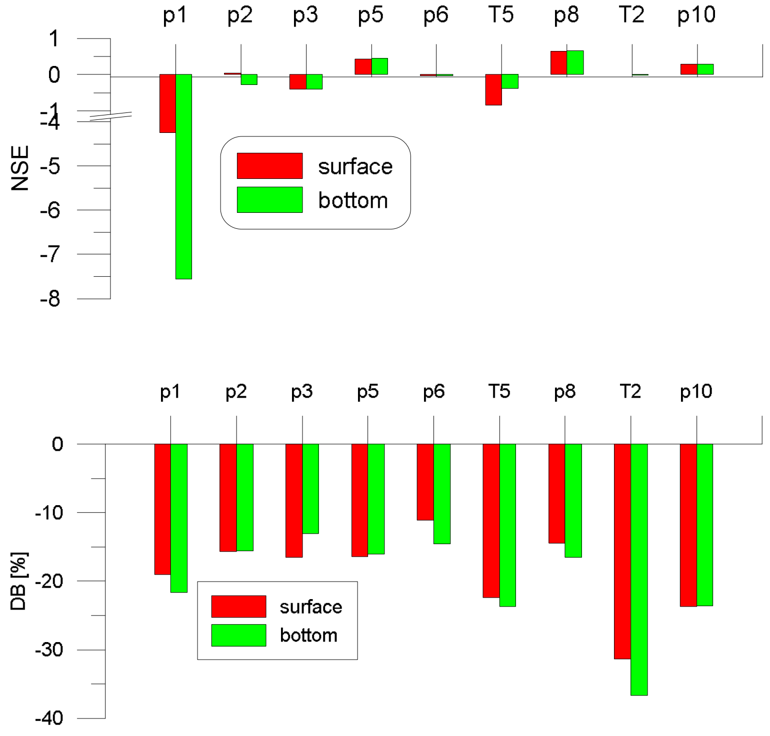


Fig. 2.26. Evaluation of salinity variation at chosen locations in the Polish part of Vistula Lagoon in year 2009 for surface and bottom layers: top – NSE; bottom – DB.

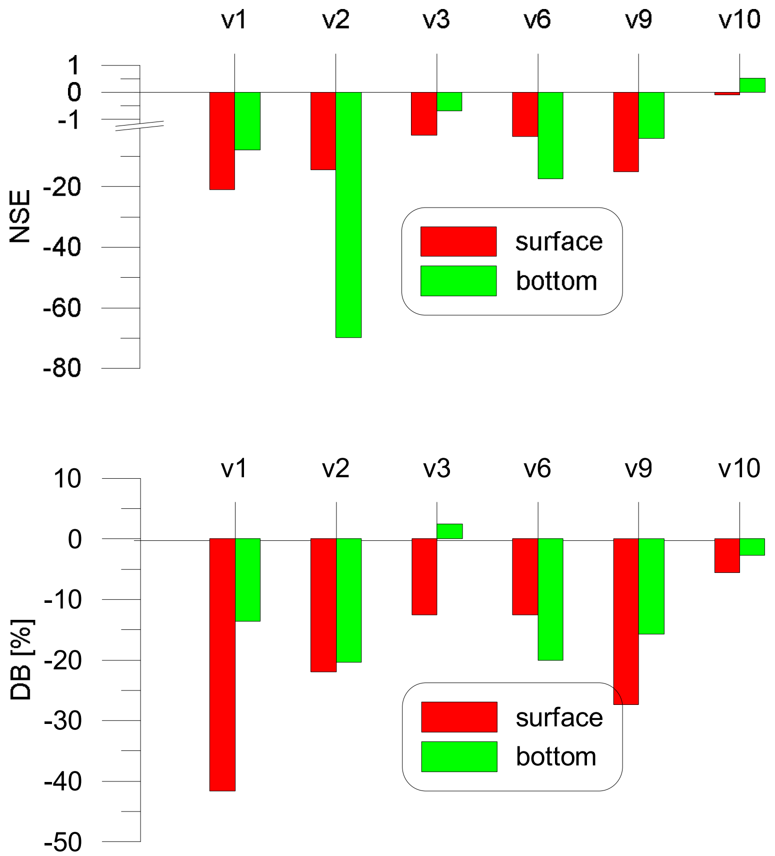


Fig. 2.27. Evaluation of salinity variation at chosen locations in the Polish part of Vistula Lagoon in year 2009 for surface and bottom layers: top – NSE; bottom – DB.

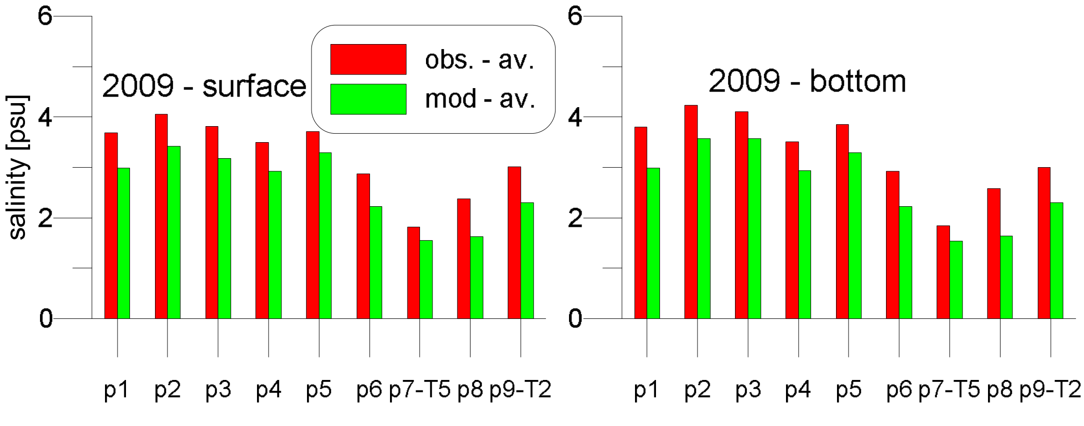


Fig. 2.28. Comparison of salinity averaged values at verticals in the Polish part of Vistula Lagoon in year 2009 in the surface and bottom layers.

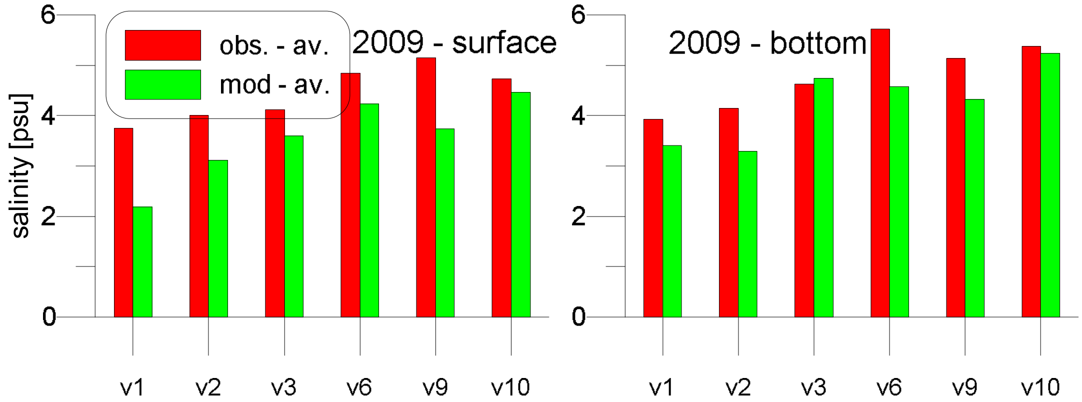


Fig. 2.29. Comparison of salinity averaged values at verticals in the Russian part of Vistula Lagoon in year 2009 in the surface and bottom layers.

The validation of the model, using the data set from the year 2009, leads to the following conclusions:

- water levels were reproduced by the model with a similar accuracy as achieved in the calibration; for comparison only 3 coastal stations were available;
- salinity variations were reproduced by the model with a comparable accuracy as the calibration. Better agreement was achieved in the Polish part of the lagoon. Comparison of the averaged values of salinity at verticals (Fig. 2.28, 2.29) shows good agreement with regard to tendencies; in nearly all cases the model underestimates the salinity. This situation can result from relatively poor information on water exchange between the lagoon and the Gulf of Gdańsk.

2.3 Ecological model calibration and validation

2.3.1 Calibration methodology and results

Below the data used to calibrate the water quality model and results achieved are described in detail.

Water temperature conditions

The daily measurements of water temperature in the Vistula Lagoon showed relatively small differences among the measurement sites in harbours: Tolkmicko, Krasnoflotskoye, Bałtiysk and Kaliningrad (Pregola outlet). Although the average difference did not exceed 1,5^{o}C, in the winter and summer season the difference between the measurement sites would even reach 5-6^{o}C. In the summer season of 1998, water temperature was above 20^{o} C, and the maximum value on the level 21,2^{o} C was observed only during 12 days. In contrast, water temperature in 1999 above 20^{o}C was observed for 58 days and the maximum reached 23,6^{o}C. In 2000, temperature above 20^{o}C was observed for 25 days, with the maximum reaching 21,4^{o}C.In order to reproduce thermal conditions of the Vistula Lagoon, the average temperature from measuring points was adopted and that is presented in Fig. 2.30.

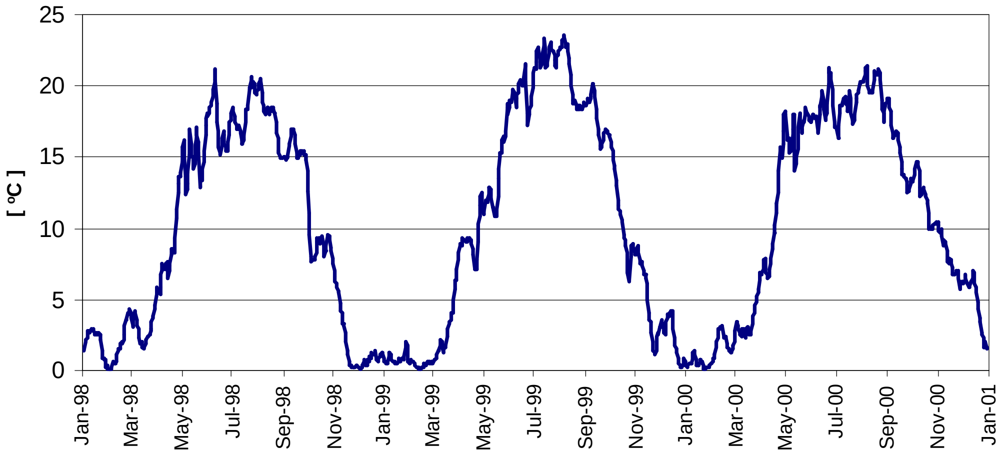


Fig. 2.30. The average temperature from measuring points used in the model.

Ice conditions

Information on ice condition in the Vistula Lagoon was gathered at two observation points – in Krynica Morska (Polish part of the lagoon) and Krasnoflotskoye (Russian part of the lagoon). In December 1997, the solid ice cover was observed for 10 days, whereas on the turn of January and February for 11 days. The longest period with the solid ice cover amounting to 58 days was noted from 20 November 1998 till the beginning of January 1999, and then from 10 February 1999 till the beginning of March 1999. Winter 1999/2000 was warmer than the preceding one, as the overall number with solid ice cover amounted to 23 days, i.e. from the end of December 1999 till February 2000. In winter 2000/2001 no ice cover was observed. Data on ice conditions are presented in Table 2.14.

Table 2.14. Time period of ice condition used in the model.

Year	Floating ice (time period)	Solid ice (time period)
1998	11.02 - 20.02	30.01 - 09.02 20.11 - 31.12
1999	14.01 - 16.01 29.01 - 30.01 02.02 - 09.02 03.03 - 06.03 29.12 - 31.12	01.01 - 05.01 10.02 - 02.03 25.12 - 31.12
2000	15.01 - 20.01	01.01 - 05.01 23.01 - 02.02

Light conditions

The light conditions in the Vistula Lagoon were established based on measurements carried out in Gdynia, located ca. 70 km west of the lagoon. The average illumination dose was ranged between 1,4-2,1 [MJ m^{-2} d^{-1}] (winter months December-January) and 15-21 [MJ m^{-2} d^{-1}] (spring and summer months May-July). In the model calculations, daily values of irradiation were adopted (PAR - Photosynthetically Active Radiation). Additionally, for winter conditions and at presence of solid ice cover in the Vistula Lagoon, the daily dose of irradiation was

limited to 10% of the measured value, and to 50% in the case of floating ice. Reproduction of light conditions (PAR) adopted in the model, is presented in Fig. 2.31.

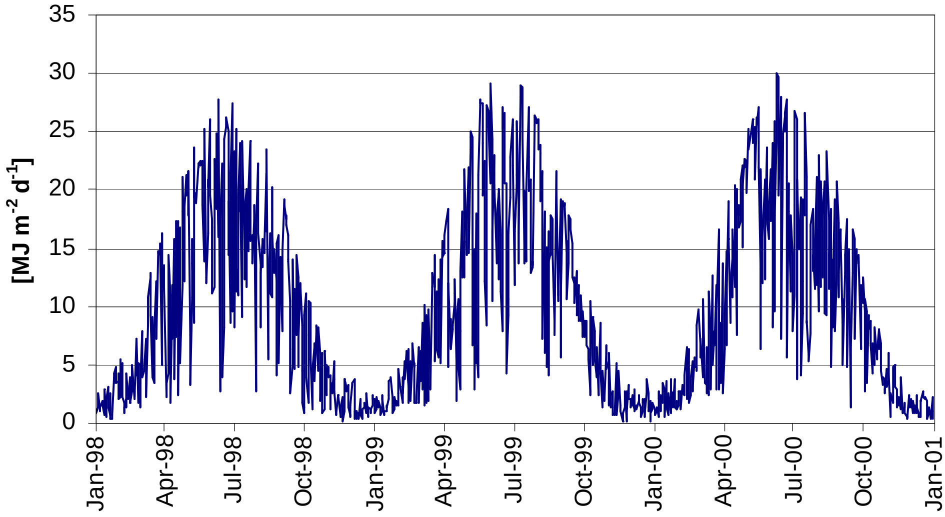


Fig. 2.31. Daily light measurements used in the model (measurements done in Gdynia by IMWM).

Wind conditions

Wind conditions for the period 1998-2000 were elaborated based on measurements collected in Baltiysk, with the frequency of four measurements daily. The average daily value was adopted in the model. In the considered period, there predominated winds with speed 2-8 [m s^{-1}] (50-80% of time within a month). In the winter season, the frequency and the strength of stormy winds increases, and at the same time the number of days with windless conditions (0-2 [ms^{-1}]) decreases to a few percent. For winter conditions and at the presence of solid ice cover, zero value for wind was adopted, whereas 50% of the value at floating ice. Reproduction of wind conditions is presented in Fig. 2.32.

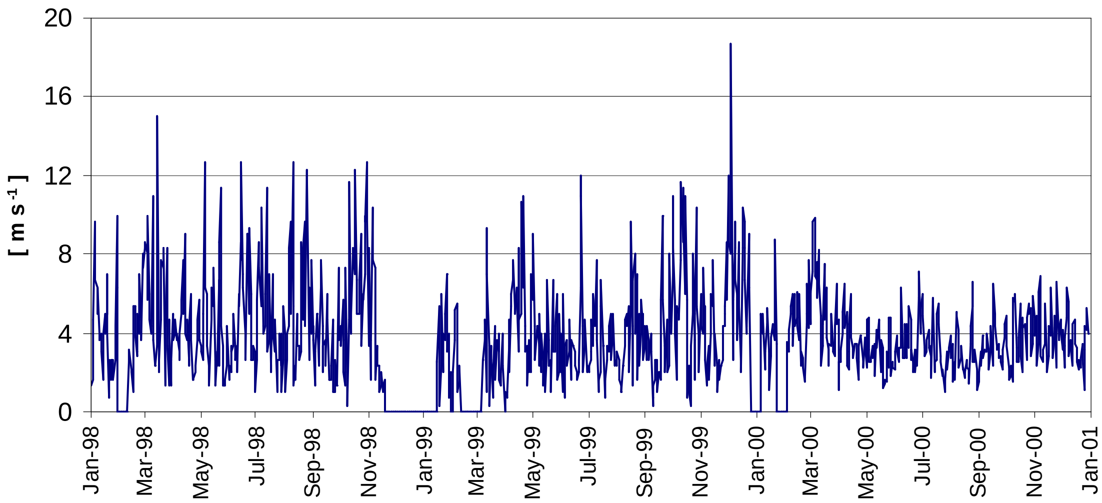


Fig. 2.32. Reproduction of wind conditions used in the model.

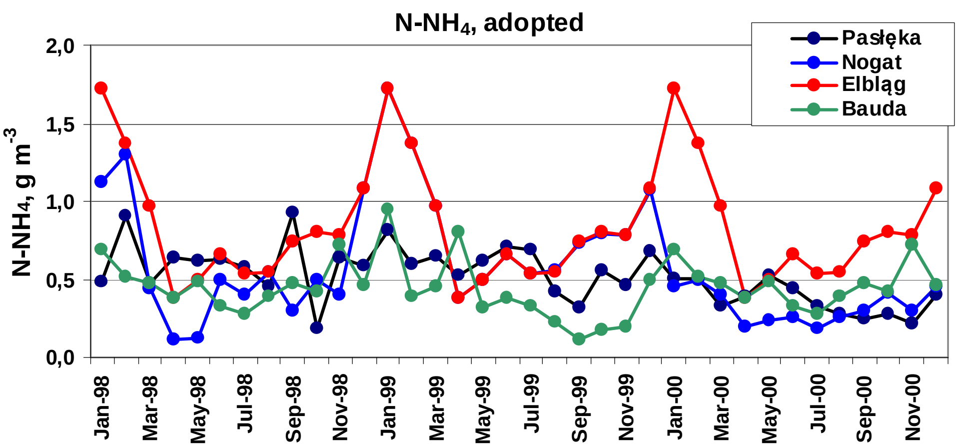
Rivers – water inflow to Vistula Lagoon

In the water quality model (Delft3D-WAQ) the average monthly water flows in rivers were adopted. Data were elaborated based on values used in the hydrodynamic model. The detailed information on water flows in Polish and Russian rivers are presented in Section 2.2.

Rivers – concentration of ammonium

Measurements of ammonium concentrations in the Polish rivers took place in the Nogat (in 1998 and 2000) and the Bauda (in 1999) rivers. Ammonium concentrations in the Pasłęka were approximated based on proportions between N-NH_4 and N-Kjeld determined for the years 1990-1995, when both parameters were measured. In that period the average value for N-NH_4 was equal to 39% of N-Kjeld, and such a proportion was adopted for the years 1998-2000. The values for the remaining years were approximated based on measurements carried out in 1989-1998.

In the Russian rivers, measurements of ammonium were carried out in the Pregolya, Mamonovka and Nelma rivers. The gaps in data were filled up by interpolation. Lacking data for the Prokhladnaya were replaced by respective concentrations in the Mamonovka. In the majority of cases, ammonium concentrations did not exceed 1 [gm^{-3}]. Higher concentrations were noted in the Elbląg, Nogat and Pregolya rivers. Ammonium concentrations used in the model are presented in Fig. 2.33.



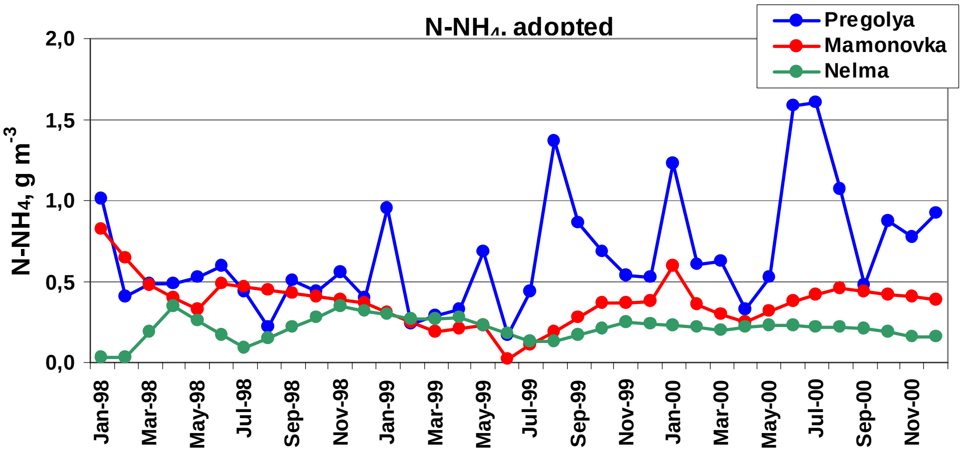
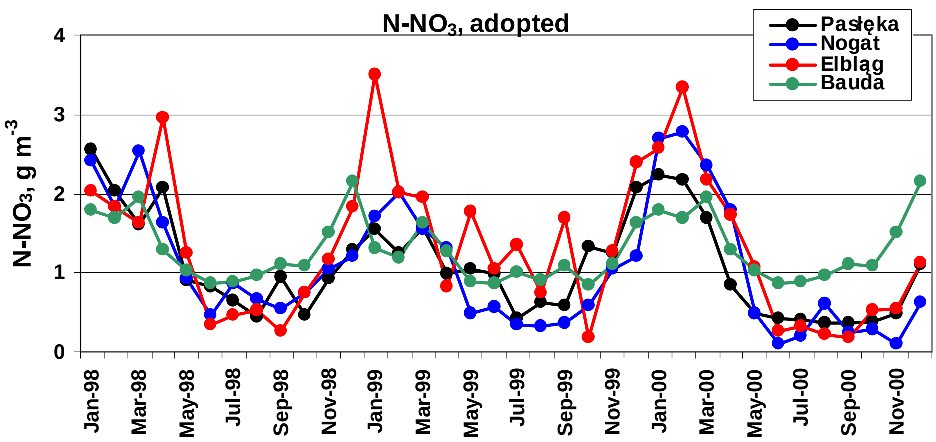


Fig. 2.33. N-NH_4 concentrations in rivers entering the Vistula Lagoon used in the model (based on data from KCGMS and IMWM). For the Prokhladnaya River the same values as for the Mamonovka River were adopted.

<u>Rivers – concentration of nitrates and nitrites</u>

In the Polish rivers, concentrations of nitrates and nitrites for the years 1998-2000 were measured in the Pasłęka and Elbląg. The missing data for the year 1999 for the Bauda and Nogat rivers were adopted in a similar way as in the case of ammonium. In the case of Nogat, model calculations were based on monthly concentrations from the years 1989-1998, whereas in the case of the Bauda river, monthly concentrations from 1994-1997 were adopted. In 1998 and 2000, concentrations of N-NO_x in Polish rives had very similar seasonal pattern with maximum values on the level of 2-3 [gm^{-3}] in winter season, and below 1 [gm^{-3}] in summer time.

As the data for the Pregolya and the remaining Russian rivers were lacking, concentrations measured by Aleksandrov and Dmitrieva 2003 were used. Additionally, the winter values for the Pregolya were adopted from the Polish rivers. For the remaining Russian rivers, concentrations from the Pasłęka River were adopted. Data adopted for calculations are presented in Fig. 2.34.



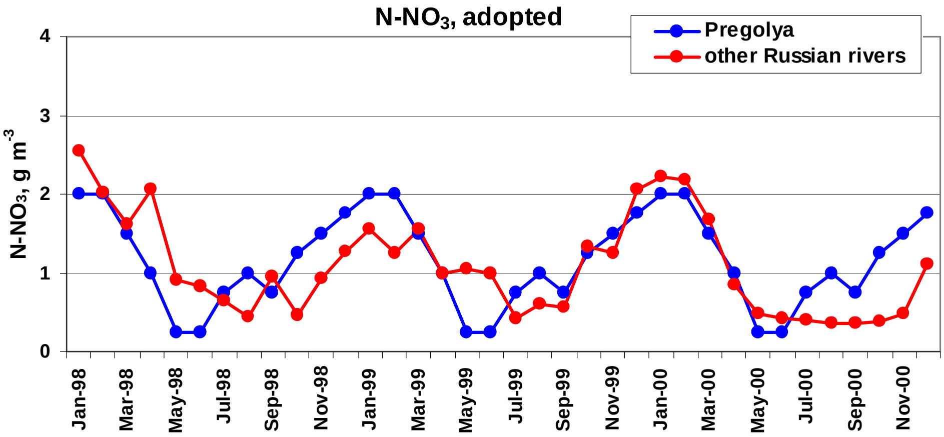
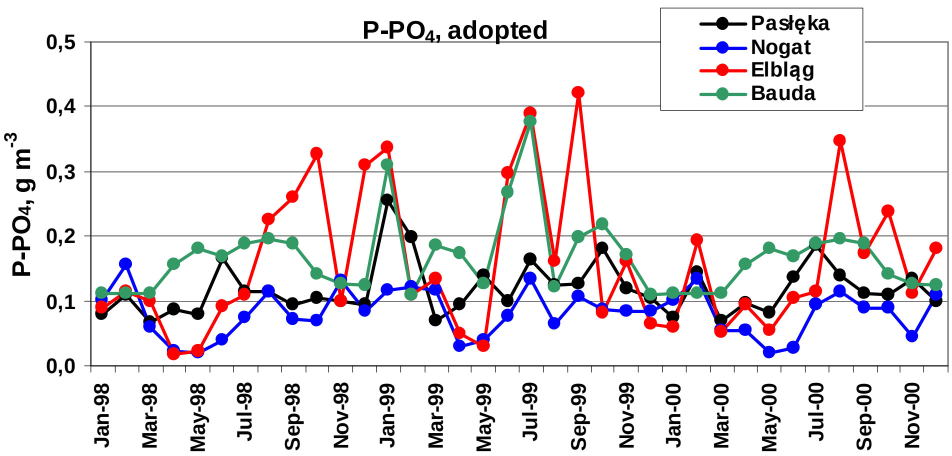


Fig. 2.34. Concentrations of nitrates and nitrites in Polish and Russian rivers entering the Vistula Lagoon used in the model.

Rivers – concentration of phosphates

In some Polish rivers concentrations of phosphates were measured, whereas the lacking data were adopted in a similar way as in the case of ammonium and nitrate concentrations. Minimal concentrations were noted in spring, and those were followed by an increase to reach the maximum values in summer and autumn. Due to the influence of the city of Elbląg, maximum concentrations were noted in the Elbląg River.

As to the Russian rivers, all available data on phosphate concentrations were questionable. Therefore, for the period 1998-2000 mean monthly values for the vegetative season from the 2001-2002 years (Aleksandrov and Dmitrieva, 2003) were adopted in the Pregolya River. The winter concentrations in this river were adopted from Polish rivers, and the accepted average value of P-PO_4 was equal to 0.1 [gm^{-3}]. In the remaining Russian rivers, concentrations of P-PO_4 were the same as in the Pasłęka River. Data adopted for calculations are presented in Fig. 2.35.



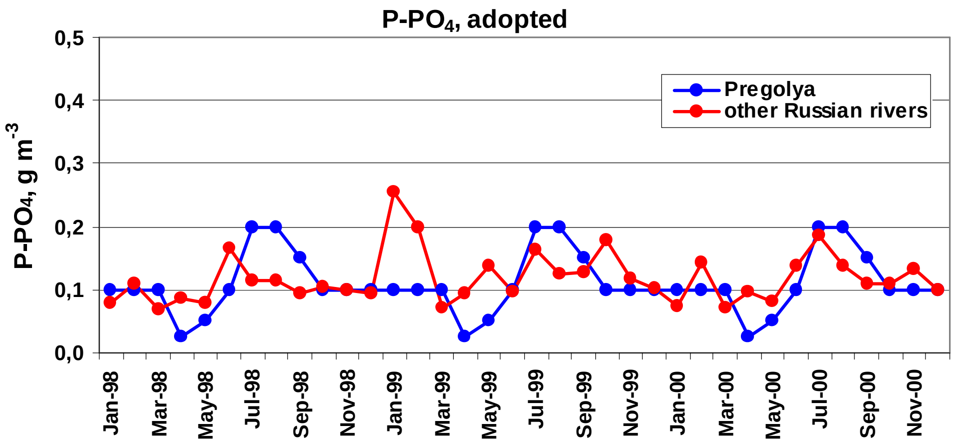
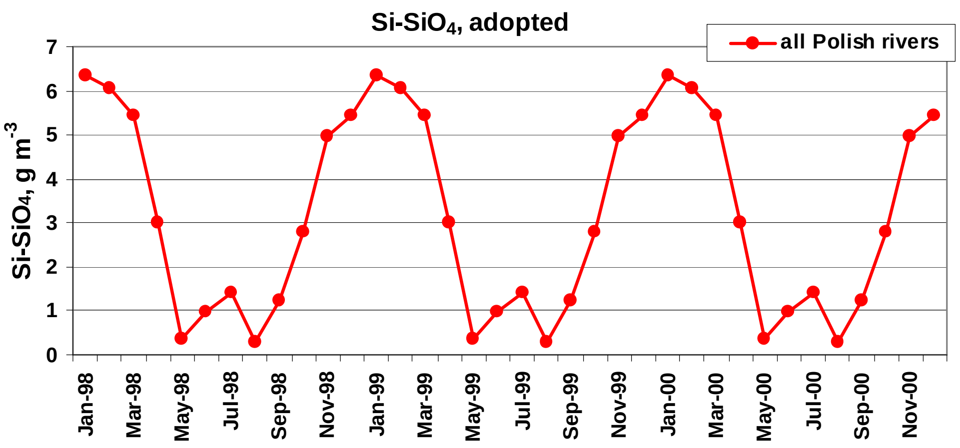


Fig. 2.35. Concentrations of phosphate in Polish and Russian rivers entering the Vistula Lagoon used in the model.

Rivers – concentration of silicates

Silicate data in the Polish rivers were not available, therefore, the seasonal pattern of silicate concentrations was calculated on the base of data collected in 2002-2004 in the Vistula and Oder Rivers by M. Pastuszak (NMFRI, Gdynia) and published in Humborg et al. (2006).They observed maximum values of concentration in winter season and minimum in spring and summer. For all the Polish rivers the same mean monthly values were used. For the Russian rivers the existing data were used for the Pregolya, Mamonovka and Nelma rivers; for the Prokhladnaya river the same values as for the Mamonovka were adopted. Data adopted for calculations are presented in Fig. 2.36.



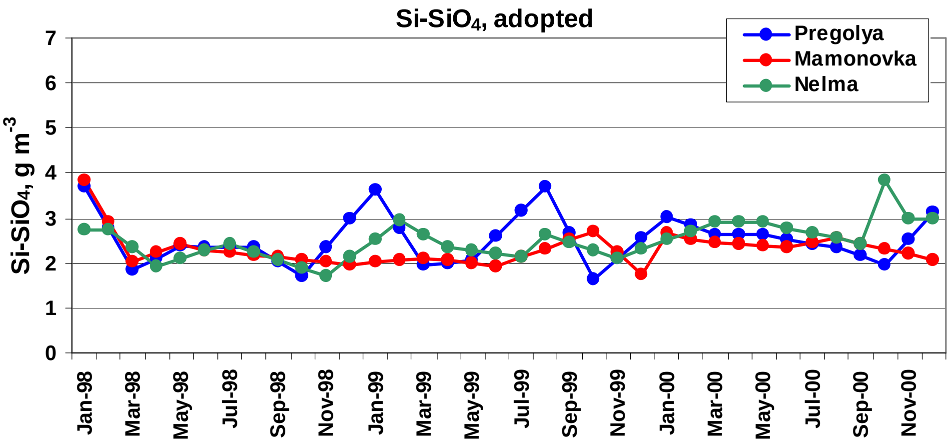


Fig. 2.36. Concentrations of silicates in Polish and Russian rivers entering the Vistula Lagoon used in the model.

Rivers – organic carbon

Organic carbon was not measured in the Polish and Russian rivers. Calculations of this parameter for the Polish rivers were done on the basis of COD-Mn relationship using the conversion factor calculated on the basis of data from the Oder River (data from 1993-2006; Zasoby Wodne Kraju, 1993-2003 and Biuletyn PSHM, 2004-2006):

Corg = COD-Mn × 1.1902 + 1,3632 (n=302, R^2 = 0.575)

As the variation of yearly values was very small, the same values were used for the Polish rivers. Data adopted for calculations are presented in Fig. 2.37.

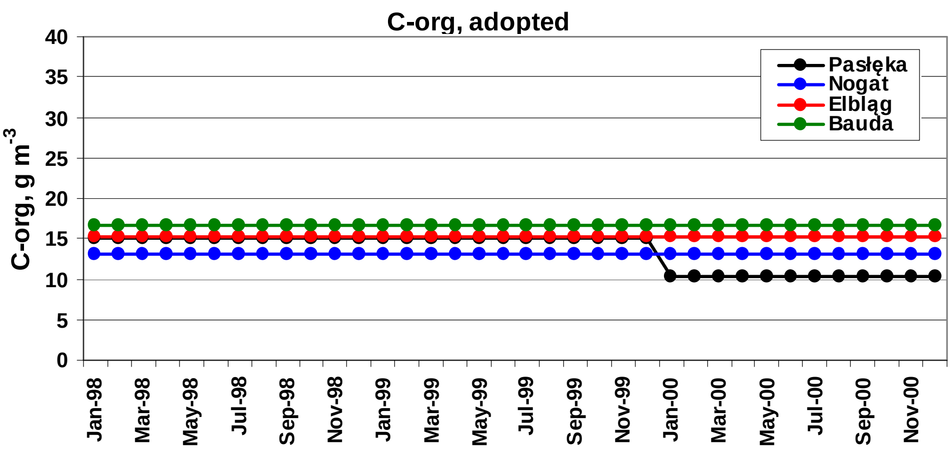


Fig. 2.37. Organic carbon in Polish rivers entering the Vistula Lagoon used in the model.

Approximations of organic carbon in the Russian rivers were done by comparing BOD5 in the Polish and Russian rivers. Only the Pregolya River had nearly twice as high BOD5 values as the remaining rivers in which BOD5 was on the level of 2-5 [gO_2m^{-3}]. The same values of organic carbon were used for the Mamonovka and Prokhladnaya rivers. Data adopted for calculations are presented in Fig. 2.38.

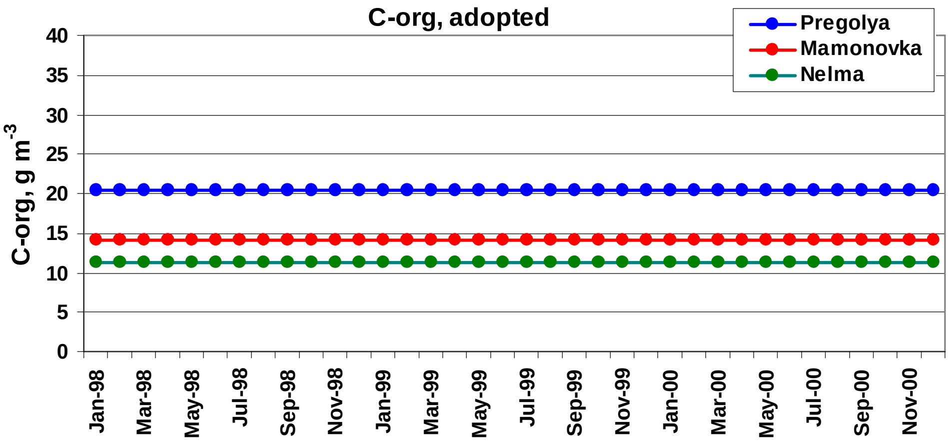


Fig. 2.38. Organic carbon in Russian rivers entering the Vistula Lagoon used in the model.

According to Wetzel (2001), the ratio of dissolved organic carbon (DOC) to particulate carbon (DetC) in rivers amounts to about 3:1, whereas in eutrophic lakes it is about 6:1. For the Polish and Russian rivers the ratio between DOC and DetC was assumed to be 4:1.

$$DetC = (Corg - Cphyt) \times 0.2$$

$$DOC = (Corg - Cphyt) \times 0.8$$

Carbon content in phytoplankton (Cphyt) was calculated from chlorophyll-a concentrations (40:1 [g/g]).

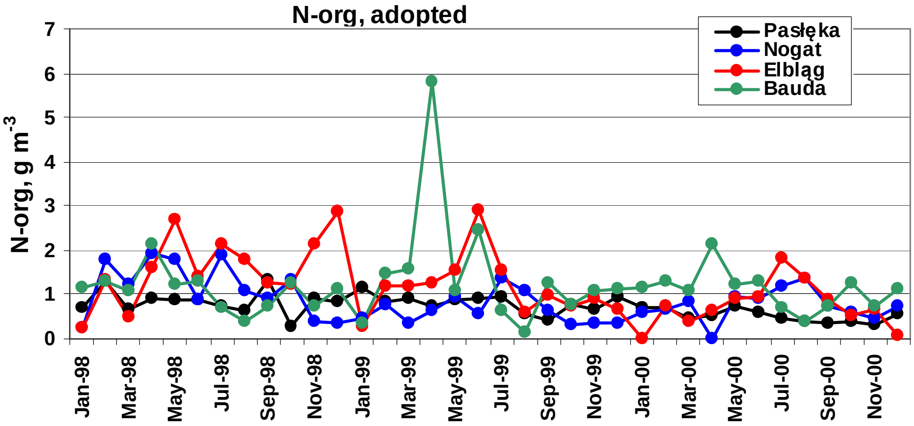
Rivers – organic nitrogen

Concentrations of organic nitrogen for the Polish rivers were estimated on the basis of N-Kjeld and $N\text{-}NH_4$:

$$Norg = N\text{-}Kjeld - N\text{-}NH_4$$

In the Russian rivers the concentrations of organic nitrogen were estimated based on data found in the literature. According to Wetzel (2001), the ratio of carbon to nitrogen oscillates around 12 in autochthonous organic matter, and reaches 45-50 in allochthonous organic matter. Organic carbon to organic nitrogen ratio was estimated as 15 for the Mamonovka, Nelma and

Prokhladnaya rivers, and that was close to the value determined for the Polish rivers (in Polish rivers C to N ratio falls into the range 13.2-18.5 in 1998-2000). Data adopted for calculations are presented in Fig. 2.39.



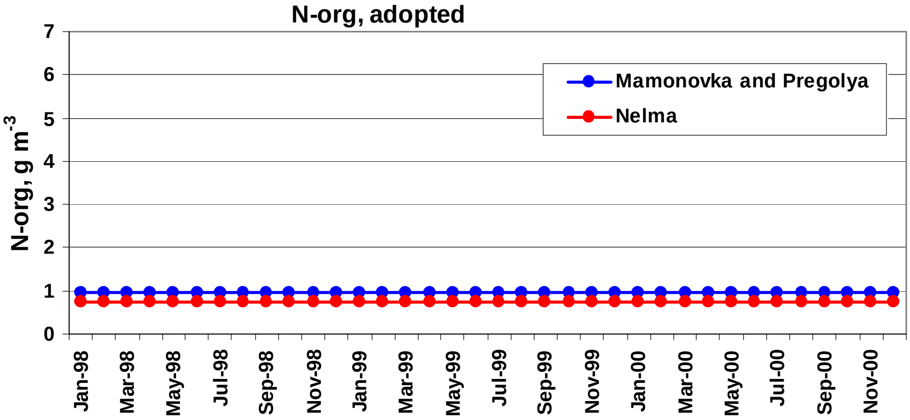


Fig. 2.39. Concentrations of organic nitrogen in Polish and Russian rivers entering the Vistula Lagoon used in the model. The same values were used for the Mamonovka, Pregolya and Prokhladnaya rivers.

Dissolved organic nitrogen (DON) and particulate organic nitrogen (DetN) were calculated in the same way as organic carbon:

$$DetN = (Norg - Nphyt) \times 0.2$$

$$DON = (Norg - Nphyt) \times 0.8$$

Using Redfield stochiometric ratios of elements in phytoplankton, the organic nitrogen was estimated based on carbon content.

Rivers – organic and absorbed phosphorus

Because there are not data on the proportion between non-living organic phosphorus and adsorbed phosphorus, a division of phosphorus into phosphorus in detritus (DetP), dissolved organic phosphorus (DOP), and phosphorus adsorbed onto inorganic matter (AAP) was done in the following way:

DetP = (Ptot - P-PO_4 - Pphyt) / 3

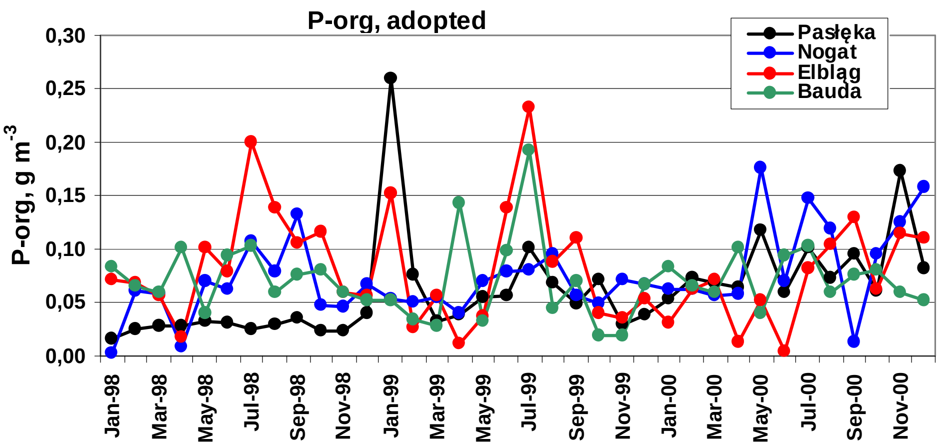
DOP = (Ptot - P-PO_4 - Pphyt) / 3

AAP = (Ptot - P-PO_4 - Pphyt) / 3

In the Polish rivers gaps in the data were filled like in the case of P-PO_4. Also organic phosphorus in phytoplankton was calculated using Redfield stochiometric ratios of elements in algae.

In the Russian rivers phosphorus in detritus (DetP) was estimated on the basis of DetC and carbon to phosphorus ratio, based on results from Wetzel (2001). In particulate organic matter in rivers and shallow lakes the ratios are as follows: C:P < 135 and N:P < 12 [g/g]. Therefore, for detritus in smaller Russian rivers, a ratio of carbon to phosphorus = 80 was adopted.

Similarly to Polish rivers, dissolved organic phosphorus was assumed to equal phosphorus in detritus (DOP = DetP) in the Mamonovka, Nelma and Prokhladnaya rivers. Data adopted for calculations are presented in Fig. 2.40.



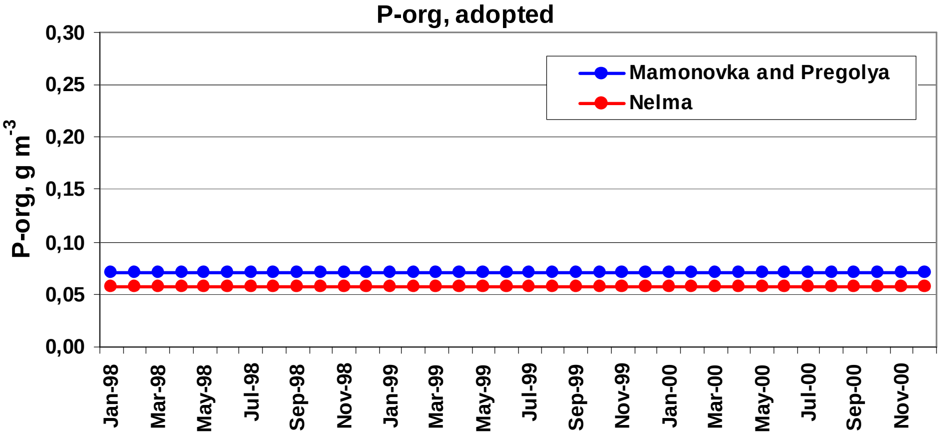


Fig. 2.40. Concentrations of organic phosphorus (Porg=Phyt) in Polish and Russian rivers entering the Vistula Lagoon used in the model. The same values were used for the Mamonovka, Pregolya and Prokhladnaya rivers.

As the measurements for phosphorus adsorbed onto inorganic matter (AAP) were lacking in the Russian rivers, the data for the Polish Pasłęka River were adopted. Data adopted for calculations are presented in Fig. 2.41.

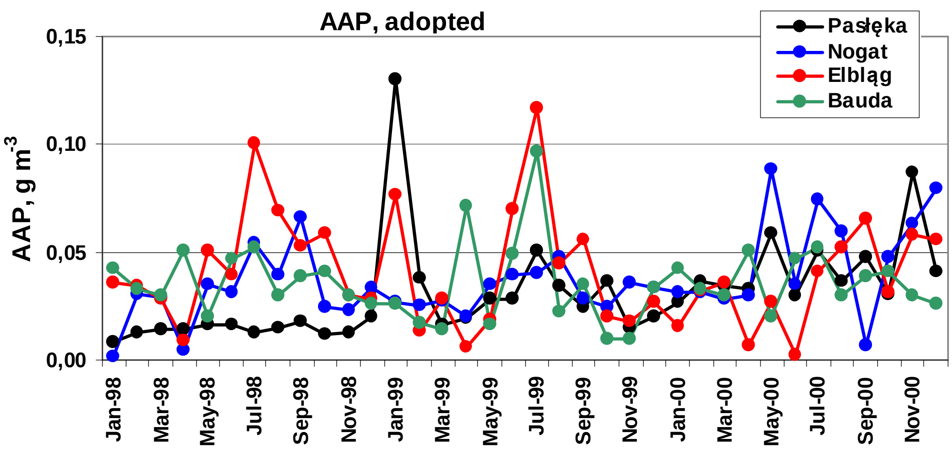


Fig. 2.41. Concentrations of phosphorus adsorbed onto inorganic matter (AAP) in Polish rivers entering the Vistula Lagoon used in the model. The same data were applied in all Russian rivers as in the Pasłęka River.

Rivers – organic silicon

Organic silicon in rivers was divided into two parts: particulate (DetSi) and dissolved (DOSi) on the basis of measurements carried by M. Pastuszak (NMFRI, Gdynia) in the Vistula and Oder rivers and published in Humborg el al. (2006). Monthly means for the years 2003-2004 were adopted according to following ratios:

DetSi : DOSi = 7:1

DetSi = 7/8 Si-org

DOSi = 1/8 Si-org

For decomposing diatoms the same ratio is suggested by the authors of the Delft3D-WAQ manual (Delft Hydraulics, 2001). In the Polish and Russian rivers the same mean monthly values of DetSi and DOSi were applied. Data adopted for calculations are presented in Fig. 2.42.

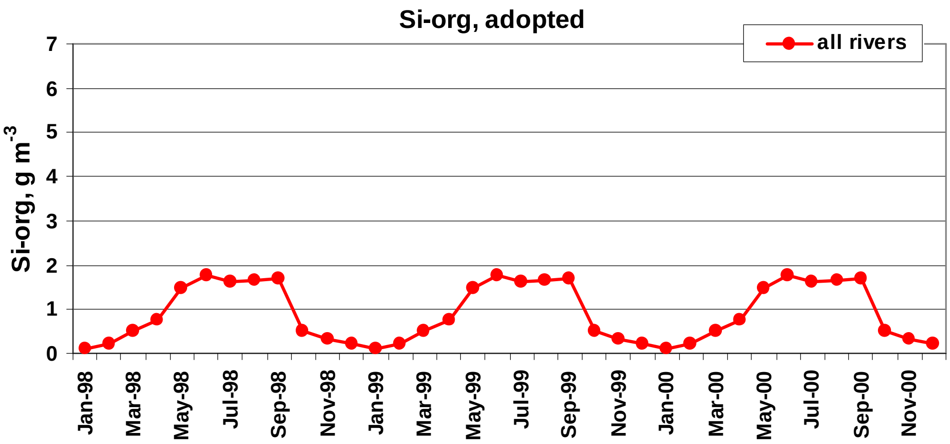


Fig. 2.42. Concentrations of organic silicon for all rivers entering the Vistula Lagoon used in the model.

<u>Rivers – chlorophyll-a</u>

For the Elbląg and Nogat rivers all data from the years 1996-2001 were averaged to monthly values and these results were used to fill gaps in data for the 1998-2000 period. For the Bauda River (due to lack of available data) monthly chlorophyll-a concentrations from the Pasłęka River were used (time period 1996-2001).

In the Russian rivers data for chlorophyll-a concentrations for 1998-2000 were not available, therefore for the Mamonovka, Nelma, and Prokhladnaya rivers the same values as in the Pasłęka River were adopted. For the vegetative season in the Pregolya River, chlorophyll-a concentration on the level of 18 [mg Chl-a m^{-3}] was accepted and that value followed the outcome of measurements carried out in 2001-2002 by Aleksandrov and Dmitrieva (2003). For the remaining months, chlorophyll *a* concentration on the level of 2 [mg Chl-a m^{-3}] was used. Data adopted for calculations are presented in Fig. 2.43.

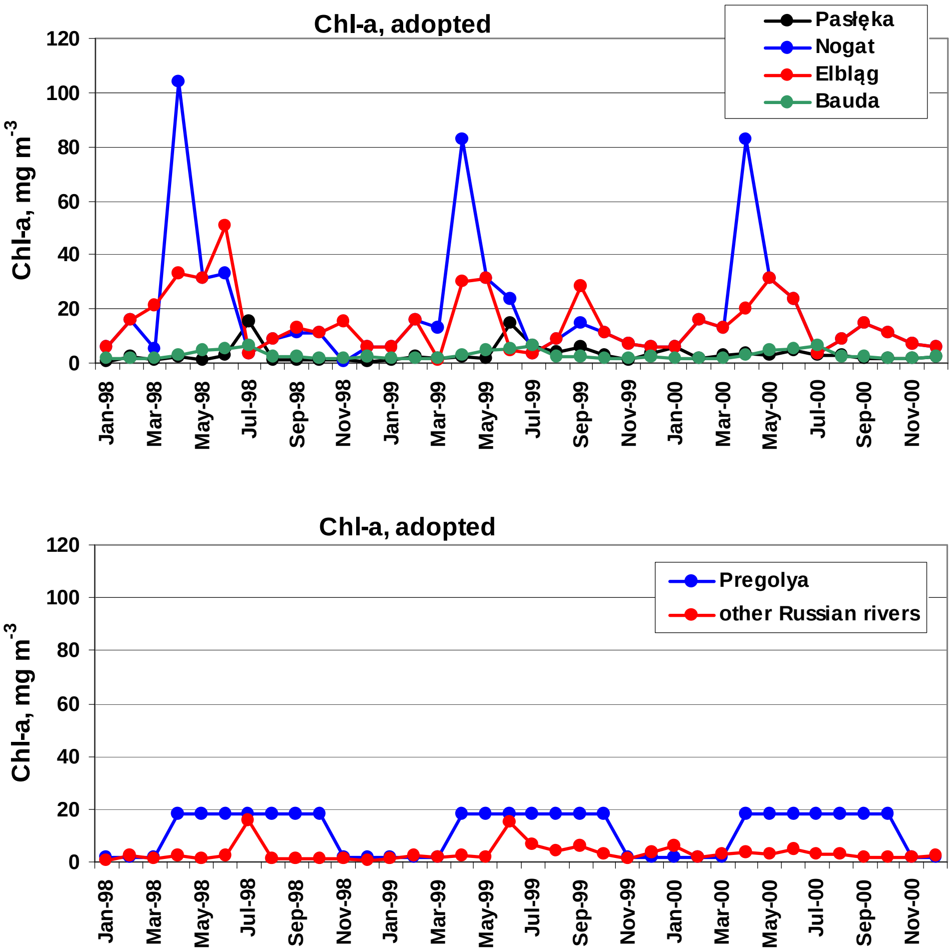
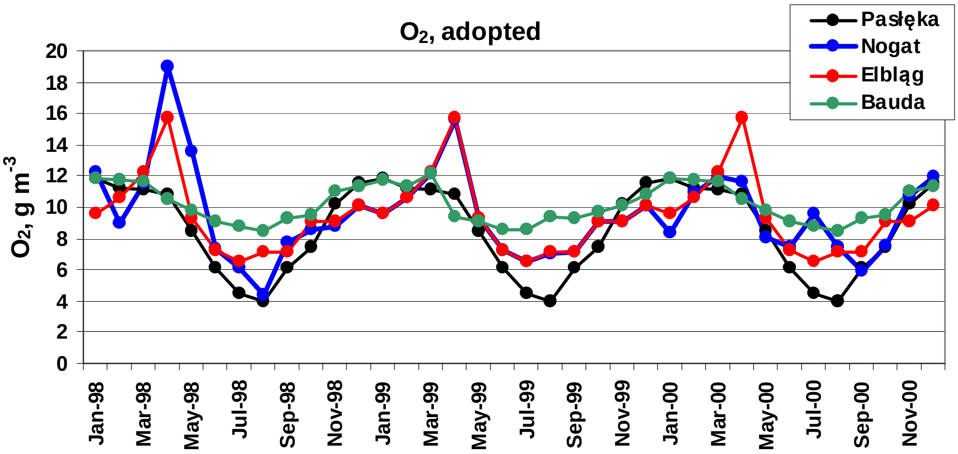


Fig. 2.43. Concentrations of chlorophyll-a for Polish and Russian rivers entering the Vistula Lagoon used in the model.

Rivers – oxygen

In all Polish and Russian rivers seasonal pattern of oxygen concentrations were observed, however, there are some gaps in data for the period 1998-2000. The pattern of measurements goes as follows: in the Nogat River - field measurements available from 1998 and 2000; in the Bauda River – the missing data for 1998 and 2000 were calculated as mean monthly concentrations from 1988-1997; in the Pasłęka River - mean monthly concentrations from the period 1985-1995 were used in the model; in the Elbląg River - mean monthly concentrations from 1989-1998 period were used, and in 1999 those were supplemented with numbers obtained for the Nogat River.

In the Russian rivers (the Mamonovka and Nelma) missing monthly values were calculated by interpolation. The data for the Mamonovka were used for the Prokhladnaya River. Minimum values of oxygen content were observed in summer and maximum in winter. Data adopted for calculations are presented in Fig. 2.44.



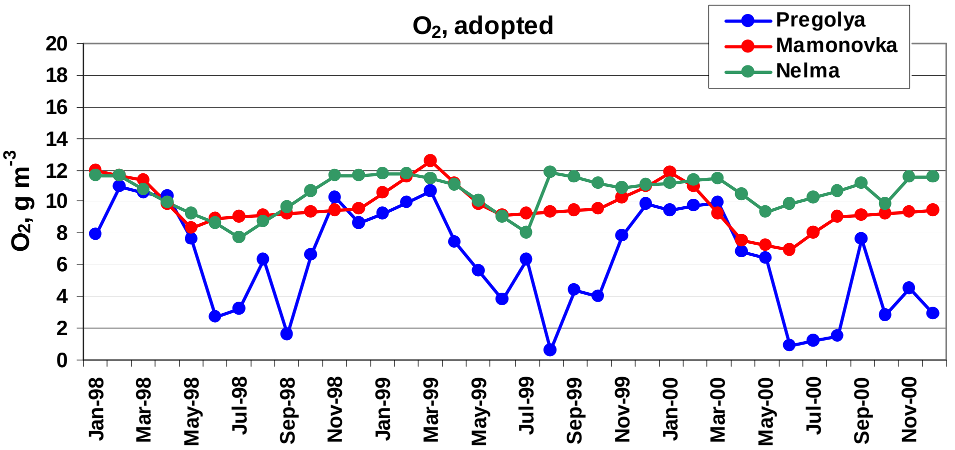


Fig. 2.44. Concentrations of oxygen for Polish and Russian rivers entering the Vistula Lagoon used in the model. The same values were used for the Mamonovka and Prokhladnaya rivers.

Rivers – inorganic matter

Concentrations of suspended inorganic matter (IM) used in the model were calculated as a difference between total suspended matter (TSM) and a sum of carbon in detritus (dry form) and carbon in phytoplankton (dry form) multiplied by 2.5, which is a ratio DetC/ Cphyt:

$$IM = TSM - (DetC + Cphyt) \times 2.5$$

Total suspended matter concentrations (TSM) were measured only in the Nogat River in 1998 and 2000, and in the Bauda River in 1999 and 1998-2000. For the Pasłęka River (as in the case of oxygen concentrations) the mean monthly concentrations of TSM were adopted from the 1986-1995 period. Similarly to oxygen concentrations, total suspended matter was determined for the Elbląg and Bauda rivers.

Due to lack of measurements of total suspended matter in the Russian rivers, values from Pasłęka River were applied. Data adopted for calculations are presented in Fig. 2.45.

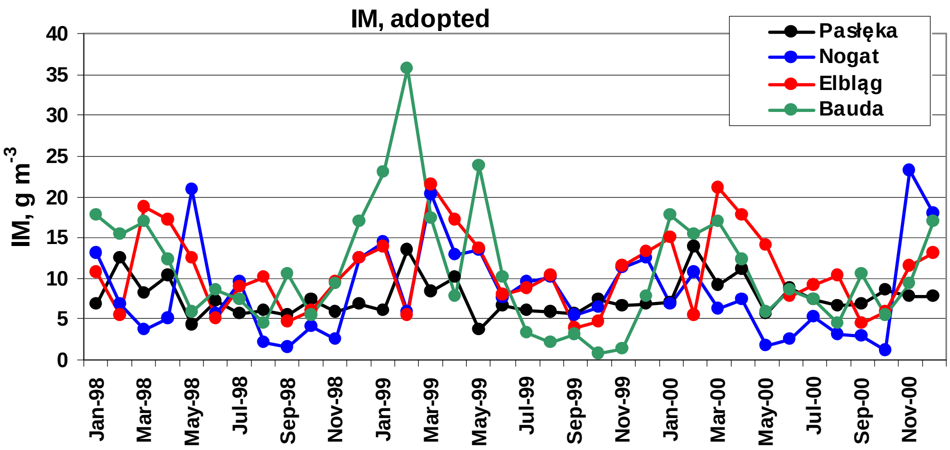


Fig. 2.45. Concentrations of inorganic matter (IM) for Polish and Russian rivers entering the Vistula Lagoon used in the model. The same values were used for Mamonovka and Prokhladnaya rivers.

Nutrients inflow to the Vistula Lagoon from the Baltic Sea

Water inflows from the Gulf of Gdańsk have a great impact on the water budget of the Vistula Lagoon. For the calculation of nutrient loads transported from marine into the lagoon waters, nutrient concentrations from the 0-20m layer in the northern part of the Gulf of Gdańsk were used. Data on N-NH_4, N-NO_x, N-tot, P-PO_4, P-tot, Si-SiO_4, O_2 and Chl-a concentrations were assessed from the Baltic Environmental Database (http://nest.su.se/bed/). Due to poor coverage of measurements, for the years 1998-2000 only monthly means were calculated.

Due to limited data on organic fractions of nutrients, only annual mean concentrations of these parameters could be estimated on the basis of works by Bradtke et al. (2005), Burska et al. (2005), Pęcherzewski and Ławacz (1975), Pempkowiak et al. (1984), Delft Hydraulics (2001).

Because in the hydrodynamic model salinity of 6 PSU was adopted for the seawater incoming from the Gulf of Gdańsk through the Baltiysk Strait, it was assumed that such water was composed of one part of the lagoon water (salinity 3PSU) and three parts of open sea water (salinity 7 PSU - typical for surface water of the Gulf of Gdańsk). Therefore, concentrations of all nutrients in water incoming through the Baltiysk Strait were calculated according to the following equation:

$$Cx = 0.25 \times C\text{-lagoon} + 0.75 \times C\text{-sea}$$

where:

Cx – nutrient concentration entering the lagoon,

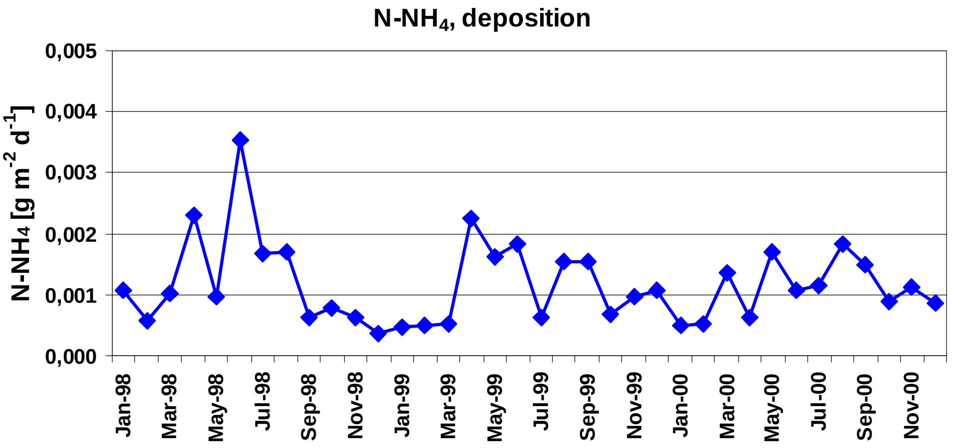
C-lagoon – nutrient concentration in the lagoon water,

C-sea – nutrient concentration in the Gulf of Gdańsk.

Nutrients – atmospheric deposition

Atmospheric depositions of nutrients were carried out in Gdynia and Łeba (the open Baltic Sea coast). These sampling stations were located about 100 km and 250 km away from the Vistula Lagoon. Data from both locations did not show evident seasonal trend in variation of ammonium and nitrogen deposition. Also no clear difference in concentrations measured in Łeba and Gdynia were observed. Therefore, atmospheric deposition of inorganic nitrogen to the Vistula Lagoon was evaluated on the basis of data from the station in Gdynia (located closer to the Lagoon than Łeba). Wet and dry deposition (total deposition) of N-NO_3 and N-NH_4 were taken into account in the model calculations. Data adopted for calculations are presented in Fig. 2.46.

According to HELCOM (2005), phosphorus atmospheric deposition to the Baltic Sea is low, amounting to 1-5% of riverine inputs in the year 2000. Therefore, this parameter was omitted in the model.



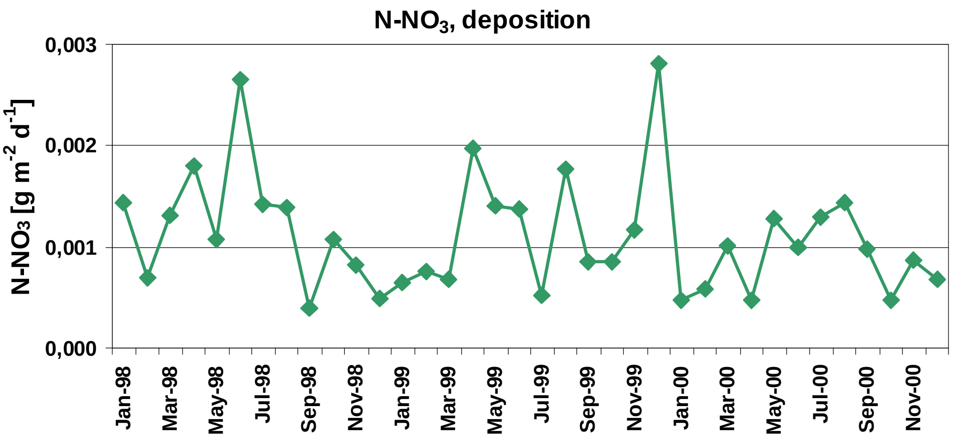


Fig. 2.46. Deposition of total (dry and wet) inorganic nitrogen measured in Gdynia used in the model (data based on the data by IMWM).

Sediments

Nutrient content in the bottom sediment of the Polish part of the Vistula Lagoon was studied in 1994 by Uścinowicz and Zachowicz (1996), and the sediment surface (2cm depth) samples were collected at ca. 100 sites. In the Russian part of the lagoon, nutrients in the 0-10cm layer of the sediment were measured at ca. 20 sampling sites located mainly in the north-eastern part of the lagoon (the Kaliningrad and Primorskaya Bays: Emelyanov, 2002). Nutrient content in the sediment was given as percentage of sediment dry mass. Mean C:N:P ratio in the surface layer of sediment in the Polish part equalled 19:2.3:1 and in the Russian part equalled 24:5:1 (data based on Uścinowicz and Zachowicz, 1996 and Emelyanov, 2002).

Estimations of carbon, nitrogen and phosphorus were based on concentrations in clayey silts (typically found in the Polish part of the Vistula Lagoon), and silts (common in the Russian part). The following concentrations of carbon, nitrogen, and phosphorus: 160 [gC m^{-2}], 26 [gN m^{-2}], 8 [gP m^{-2}] were used as spatially uniform starting values in the model. Division of phosphorus pool into organic phosphorus in the sediment (DetPSed) and adsorbed phosphorus in the sediment (AAPSed) was set arbitrary at 1:1 ratio. As the data on biogenic silicon concentrations in the sediment of the Vistula Lagoon were unavailable, the data from other coastal lagoon (Szczecin Lagoon) were used (Pastuszak et al., 2008). According to these authors, the average content of biologically originated SiO_2 in the 2cm layer equals 128 [gSi m^{-2}]. In the model a value of 125 [gSi m^{-2}] was used as a starting concentration.

In the water quality model the sediment layer (contents of the nutrients) is described below:

Organic carbon, carbon in the detritus (DetCSed) = 160 [gC m^{-2}],

Organic nitrogen, nitrogen in the detritus (DetNSed) = 26 [gN m^{-2}],

Organic phosphorus, phosphorus in the detritus (DetPSed) = 4 [gP m^{-2}],

Adsorbed inorganic phosphorus in the sediment (AAPSed) = 4 [gP m^{-2}],

Organic silicon, silicon in the detritus (DetSiSed) = 125 [gSi m^{-2}],

Inorganic matter in the sediment (IMSed) = 12500 [g m^{-2}].

Results

For the model calibration, data from 11 measuring points were used. These points correspond to eight model “cells” and were used for comparison of the model calculations with field data. On the Polish side, seven measuring points corresponded to four model (WAQ) “cells”, and on the Russian side four measuring points corresponded to four model (WAQ) “cells”. The selected stations had the most complete data sets and were located along the Vistula Lagoon, forming a longitudinal transect (Fig. 2.47).

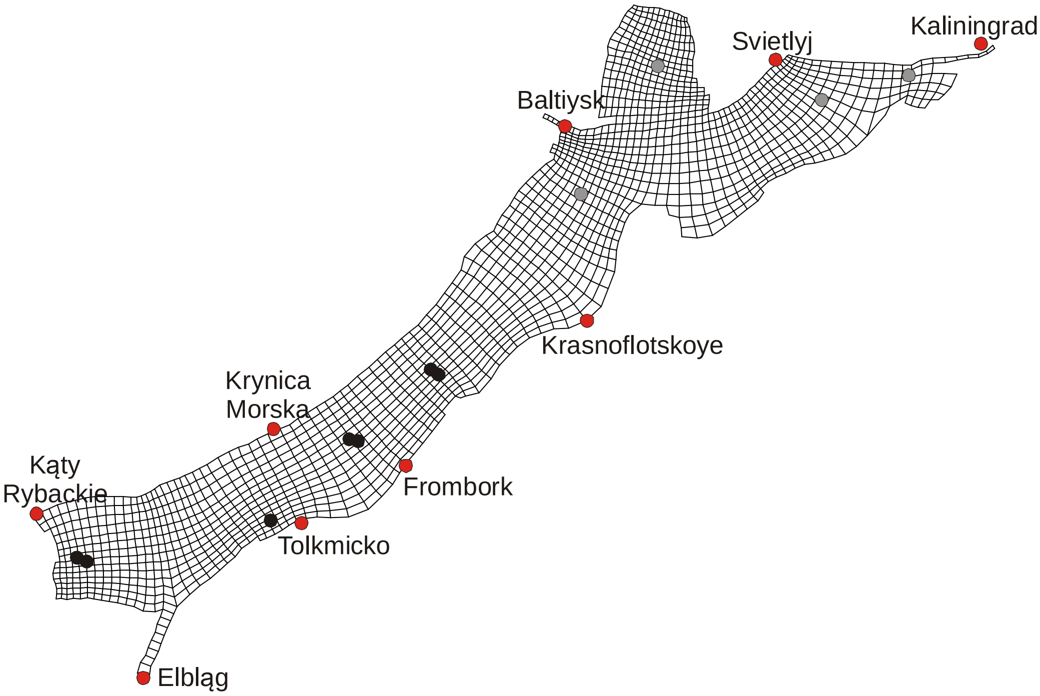


Fig. 2.47. Location of points used for model calibration (black and grey points).

In order to statistically compare the empirical data and the model calculation outcome, two mathematical measures were used: average deviation (AD) and deviation of average value (DAV). These are defined by the following formulae:

$$AD = \frac{1}{n}\sum_{i=1}^{n}\frac{\sqrt{(x_m - x_e)^2}}{x_e} \times 100\%$$

where:

x_e – measured (empirical) value,

x_m – modelled value for the same dates as measurement;

n – number of measurements compared during simulation period.

$$DAV = (x_m - x_e) / x_e \times 100\%$$

where:

x_e – average of measured (empirical) values,

x_m – average of modelled values for the same dates as measurements.

For all the parameters and all the locations, the average values of AD and DAV were used as final indicators of the model fit.

Comparison of data simulated by the water quality model and measured data showed that the best fit was obtained for parameters described by low variability in time (e.g. oxygen), also for parameters where field data were available only at one part of the lagoon, either the Polish part or the Russian part of the lagoon (mean value of average deviation < 30% and mean value of deviation of average values < 20% - absolute values; $N\text{-}NH_4$, $Si\text{-}SiO_4$, Ntot, Corg, oxygen). The range of calibration is given in Table 2.15.

Table 2.15. The range of average deviation (AD) and deviation of average values (DAV) obtained in the model calibration.

Average deviation, data 1998-2000

	N-NH4	N-NO3	P-PO4	Si-SiO4	Ntot	Ptot	Corg	OXY	Chl-a	Susp. Matter	Secchi depth	average value
Max	34,4	49,1	64,3	39,2	28,4	45,2	14,2	43,2	401,1	70,6	57,9	**77,1**
Min	0,0	23,8	20,1	13,9	23,3	20,2	9,9	6,7	34,9	42,7	7,6	**18,5**
Mean	9,3	33,1	45,3	26,2	26,2	32,6	11,9	14,5	73,3	55,2	29,8	**32,5**

Deviation of average values, data 1998-2000

	N-NH4	N-NO3	P-PO4	Si-SiO4	Ntot	Ptot	Corg	OXY	Chl-a	Susp. Matter	Secchi depth	average value
Max	2,5	24,9	17,9	-9,9	-7,4	28,8	-3,1	17,9	44,5	5,7	26,3	**17,2**
Min	-51,1	-39,2	-47,6	-30,3	-30,4	-25,1	-10,8	-10,3	-36,4	-7,9	-44,0	**30,3**
Mean	-15,9	-5,2	-21,0	-18,4	-16,4	-7,6	-8,0	-0,4	-6,8	-0,1	-4,2	**9,4**

For the data available from both parts of lagoon, the differences of average deviation were much higher, up to 65% for phosphate (P-PO4) or even several hundred percent for chlorophyll-*a* (Chl-*a*; Table 2.15). This situation could suggest a little bit different functioning of the Polish and Russian parts of the lagoon, and that was not accounted for in the model. Also the sets of available data might contribute to an increase of differences between model simulation and field data (data origin from different institutions which were using different methodologies).

Significant differences between the overall field data and the model simulations outcome of phosphate concentrations ($P\text{-}PO_4$) resulted rather from different functioning of the ecosystem in the Polish and Russian parts of the lagoon, but not only from a disturbance at one single station.

Measurements data suggest that seasonal patterns of phosphate concentration in the Polish and the Russian parts of the lagoon were similar. Also, loads discharged to the lagoon by rivers (with the monthly resolution) might generate differences between field and modelled data (especially for parameters with high variability). The data presented in the graphs (Figs 2.48 and 2.49) are from two locations; the first - (MIR-5) which is typical for the central part of the Vistula Lagoon, close to the Polish-Russian border, and the second - (AN-1) which is under riverine water influence as it is situated close to the mouth of the Pregolya River.

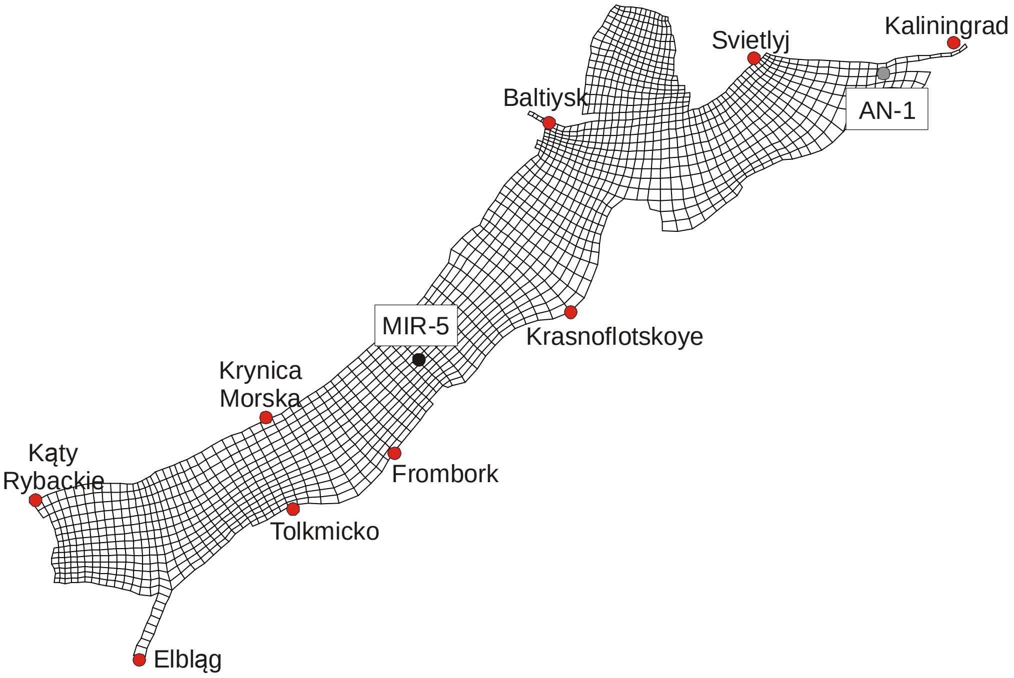


Fig. 2.48. Location of observation points.

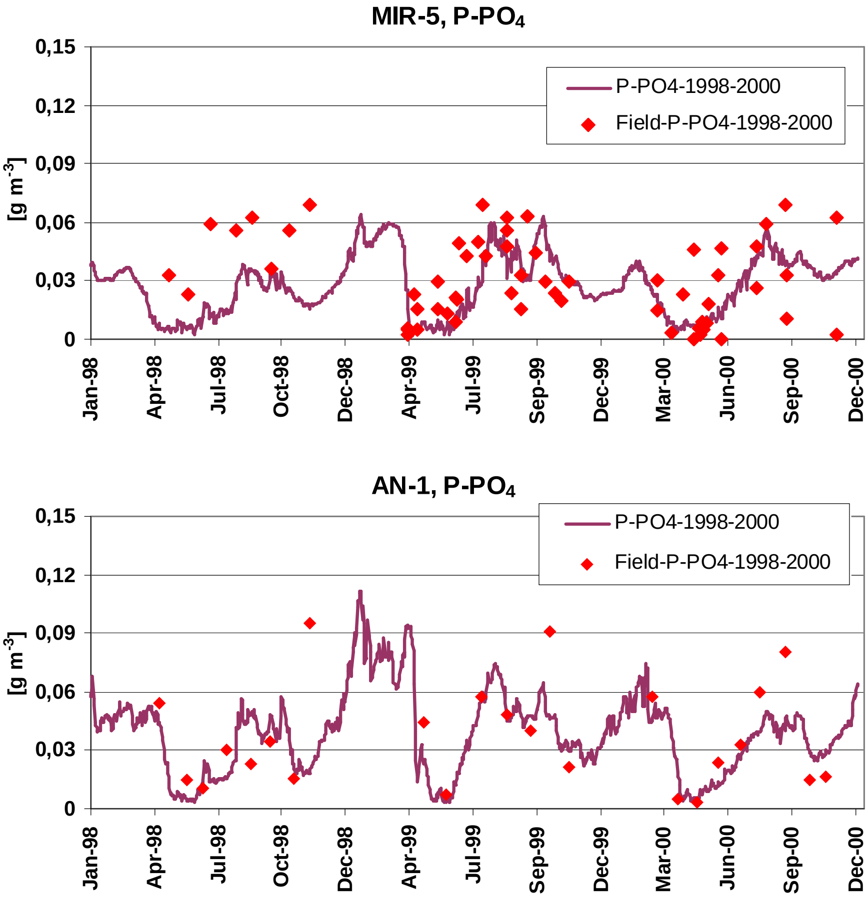


Fig. 2.49. Variability of phosphate concentrations, measured/field data and values simulated by the model.

Nitrate concentrations are a good example of data characterized by low variability and quite nice fit measurement data and model simulations. From May to October nitrate concentrations were low, whereas between the end of October and March they showed high values, reaching 1-2 [gN m^{-3}]. The model simulates a peak of nitrate concentration a little bit lower than the measurement data. Starting from April, i.e. the beginning of vegetative season, nitrate concentrations are steadily dropping to reach the minimum in summer (Fig. 2.50).

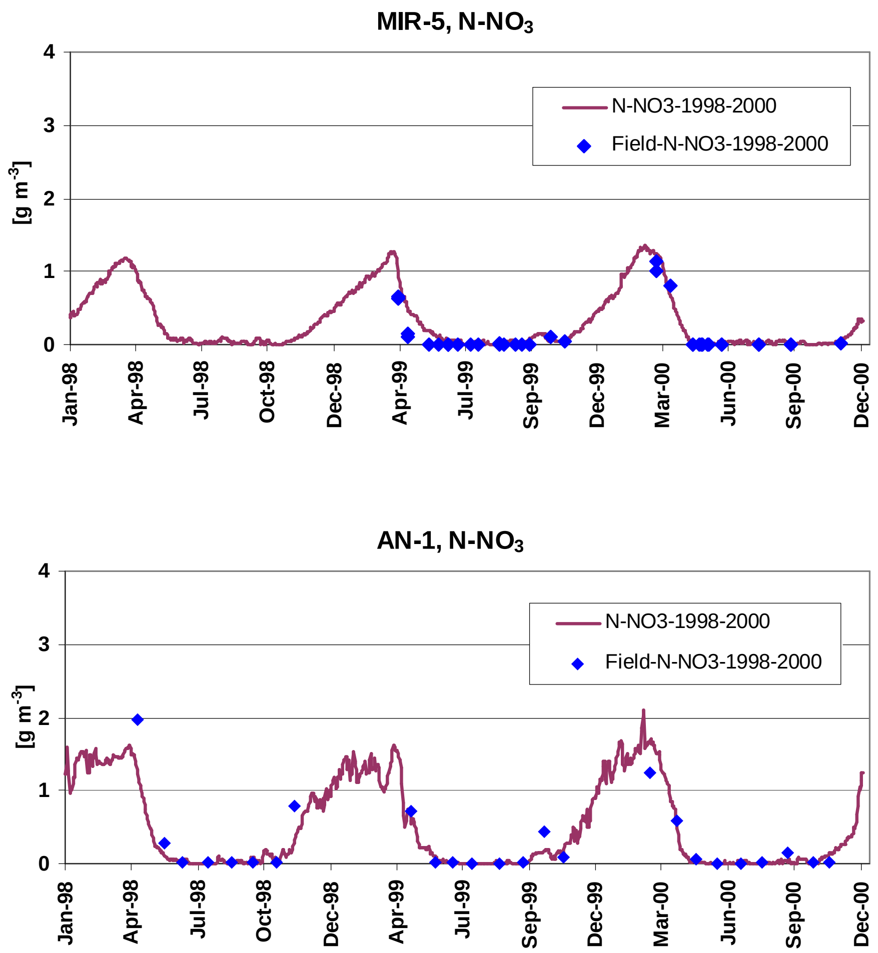
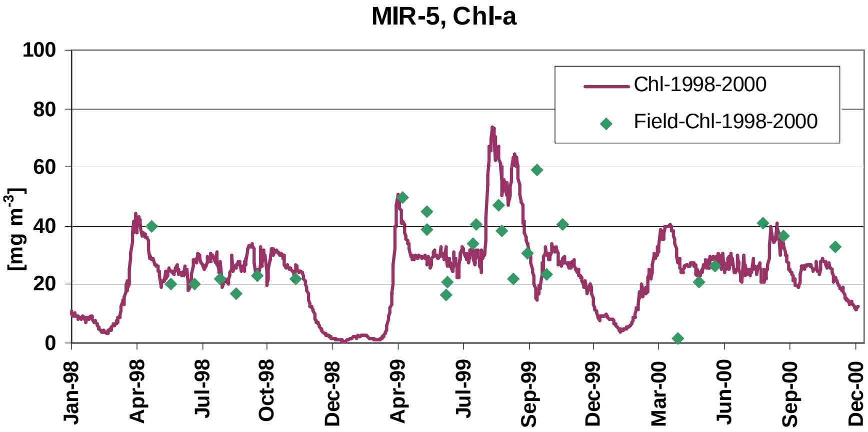


Fig. 2.50. Variability of nitrate concentrations, measured/field data and values simulated by the model.

The largest differences between the model results and the field data were exhibited by chlorophyll-*a* concentrations. Very low chlorophyll-a concentrations, observed at the Polish south-western part of the Vistula Lagoon, can be the main reason for this discrepancy to occur. This can be explained by the presence of dense zebra mussel beds (*Dreissena polymorpha*, Ezhova et al., 2005). Zebra mussels are very effective filtrators, and they are able to filter the whole water column within a few days (Wolnomiejski and Woźniczka, 2003, 2007). The model did not take into account this peculiarity.

During the vegetation season, chlorophyll-a concentrations changed from a few to over 60 [g m^{-3}] in the central part of the Vistula Lagoon and the vicinity of the Pregolya River mouth (Fig. 2.51). In spring 1998 and 2000, a moderate peak of chlorophyll-a concentration was observed

(in April). Then the concentrations dropped (May and June) and increased again in summer time. In general, high concentrations of chlorophyll-a were noted in 1999. This situation was probably linked to the development of nitrogen fixing cyanobacteria and water temperature in the Vistula Lagoon (the highest mean value of temperature in summer compared with values found in 1998 and 2000).



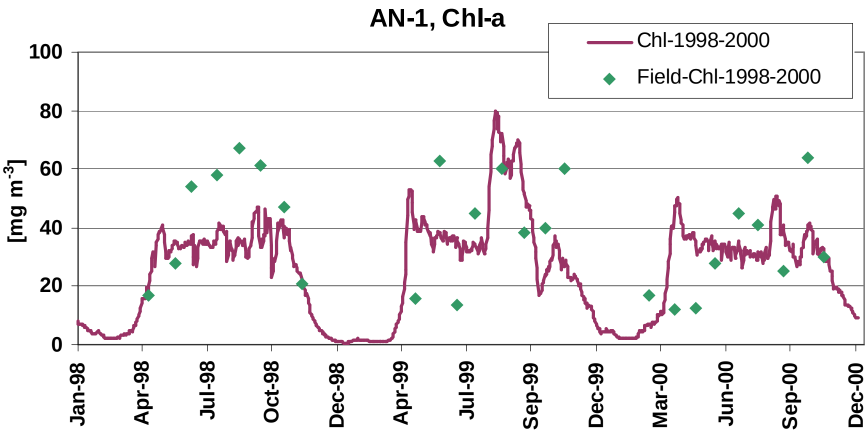


Fig. 2.51. Variability of chlorophyll-a concentrations, measured/field data and values simulated by the model.

For all the parameters, mean deviations of average values were lower than 20%, and in most cases lower than 8% (Table 2.15). It seems that in the majority of cases the model generated values a little bit lower than the field data (Table 2.15).

2.3.2 Validation methodology and results

Below the data used to validate water quality model and results obtained are described in detail.

Water temperature conditions

The daily measurements of water temperature in the Vistula Lagoon were used for the validation procedure. For the model calculations, a data set from the harbour of Tolkmicko was adopted. In 2009 summer season, water temperature above 20^{o}C was observed during 24 days. In contrast, in 1999 and 2000, water temperature above 20^{o}C was observed for 58 days and 25 days, respectively. Thermal conditions in the Vistula Lagoon in 2009 are presented in Fig. 2.52.

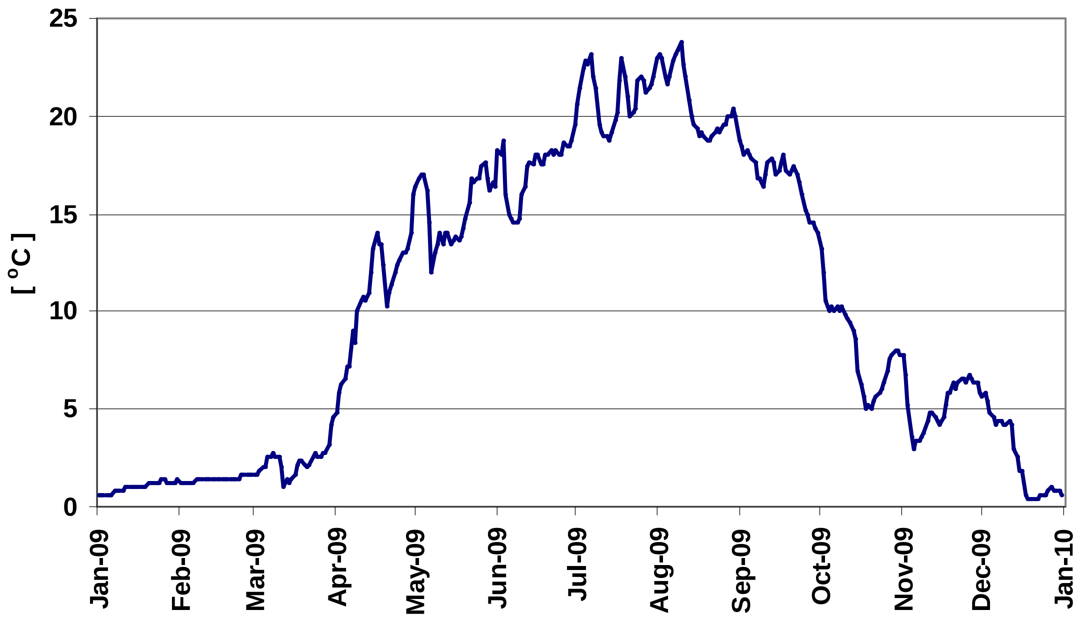


Fig. 2.52. Water temperature used in the model (validation procedure).

Light conditions

As in the calibration procedure, the light conditions in the Vistula Lagoon were established based on measurements carried out in Gdynia located ca. 70 km west of the lagoon. In the validation procedure daily values of irradiation were adopted (PAR - Photosynthetically Active Radiation). Reproduction of light conditions (PAR) adopted in the model, is presented in Fig. 2.53.

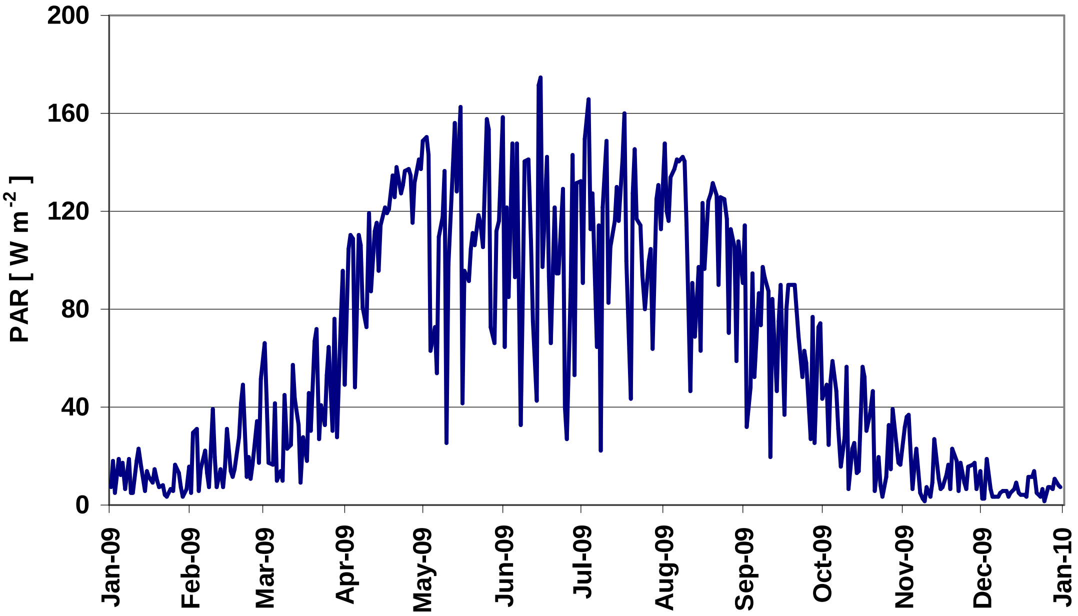


Fig. 2.53. Light conditions used in the model (validation procedure).

Wind conditions

For the year 2009, values of wind speed with daily frequency were adopted. The detailed information on wind speed in 2009 is presented in the hydrodynamic part of the report in Sections 2.1 and 2.2

Rivers – water inflow to Vistula Lagoon

In the water quality model (Delft3D-WAQ) the average monthly water flows in rivers were adopted. Data were elaborated based on values used in the hydrodynamic model. The detailed information on water flows in the Polish and Russian rivers is presented in Sections 2.1 and 2.2.

Rivers – concentration of ammonium

In Polish rivers, data concerning ammonium concentration in 2009 were taken as monthly values from the monitoring program conducted by the regional administration (IEP). Data adopted for calculations covering 2009 are presented in Fig. 2.54.

As to the Russian rivers, lacking data for 2009 made us adopt numbers from the years 1998-2000. The selection of a particular year from the period 1998-2000 was made by comparing the average annual riverine outflow in that year with the water outflow in 2009. The comparison gave the following outcome: in case of the Pregolya River, data from the year 1998 were adopted, whereas in case of the Mamonovka, Nelma and Prokhladnaya rivers, data from the year 2000 were adopted.

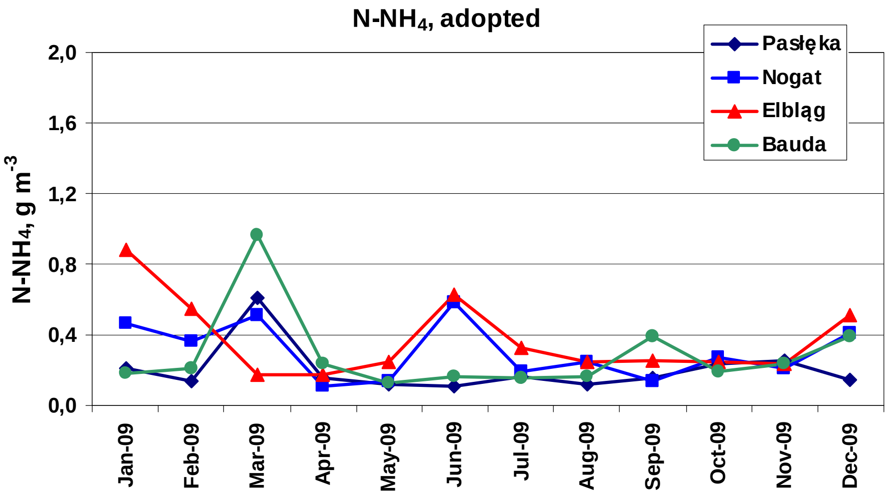


Fig. 2.54. Ammonium concentrations in Polish rivers entering the Vistula Lagoon used in the model for the year 2009.

Rivers – concentration of nitrates and nitrites

In the Polish and Russian rivers the same procedure was applied for preparation data for 2009 year as for ammonium. For the Polish rivers data adopted for the year 2009, the results of calculations are presented in Fig. 2.55.

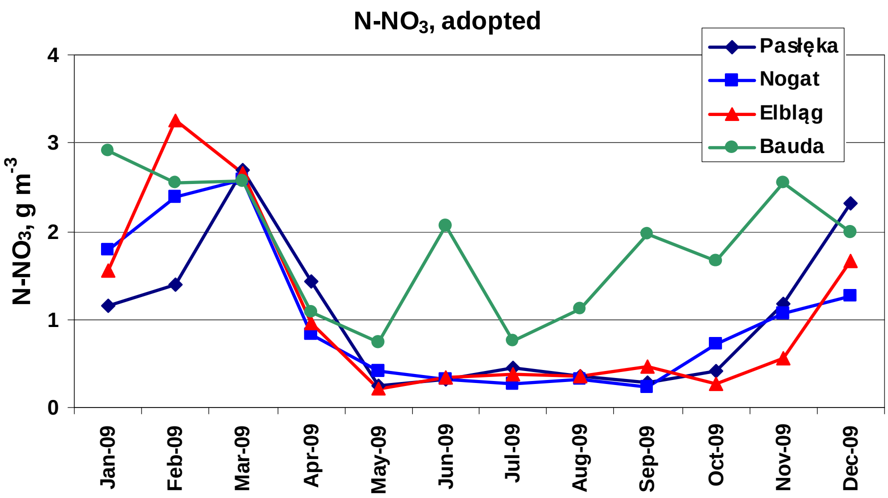


Fig. 2.55. Concentrations of nitrates in Polish rivers entering the Vistula Lagoon used in the model for 2009.

Rivers – concentration of phosphates

Data for 2009 in the Polish and Russian rivers were prepared in the same way as for ammonium. The Polish data are presented in Fig. 2.56 (the Russian data are presented in the calibration procedure).

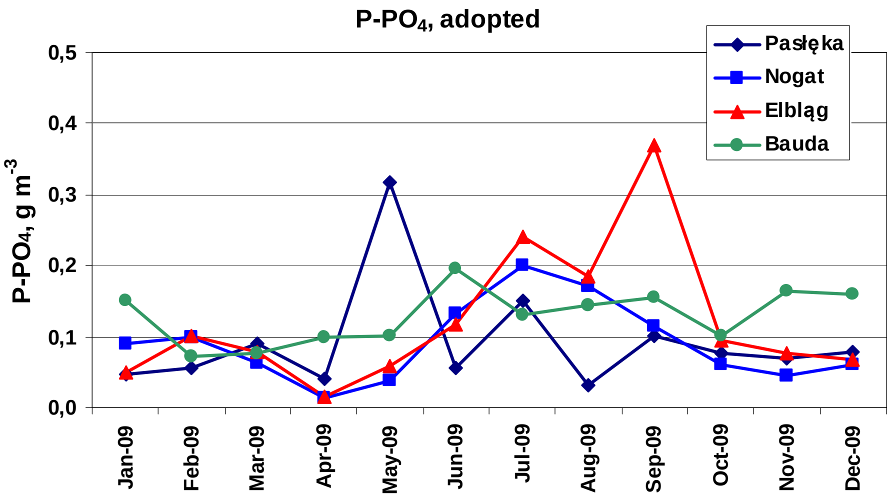


Fig. 2.56. Concentrations of phosphates in Polish rivers entering the Vistula Lagoon used in the model for 2009.

Rivers – concentration of silicates

In the Polish rivers, concentrations of silicates were based on available 2009 measurements. Missing data for this year (monthly values) were supplemented by adopting the average value calculated for the period 2007-2010. Data adopted in the Polish rivers for 2009 are presented in Fig. 2.57. As to the Russian rivers, the same procedure of data preparation was adopted as in the case of ammonium.

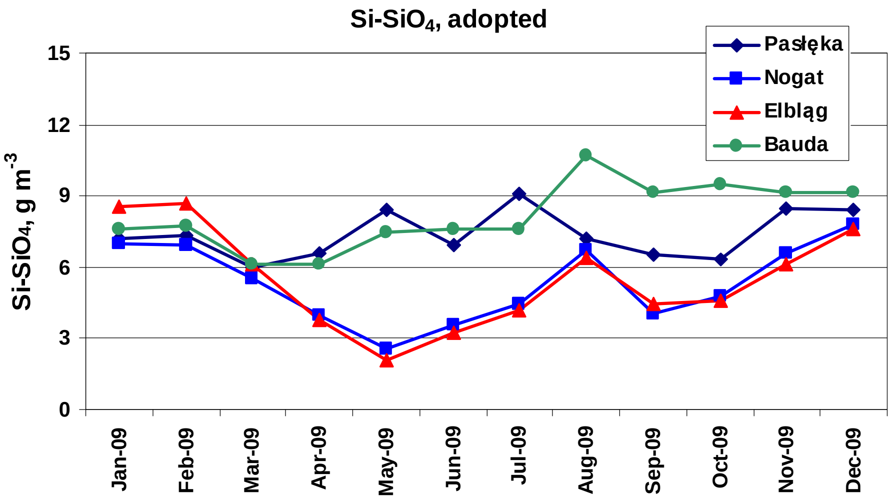


Fig. 2.57. Concentrations of silicates in Polish rivers entering the Vistula Lagoon used in the model for 2009.

Rivers – organic carbon

Data on organic carbon in 2009 in the Polish and Russian rivers were prepared in the same way as in the case of silicates. Polish data, adopted for 2009, are presented in Fig. 2.58.

As to the Russian rivers, the same procedure as in the case of ammonium and silicates was applied. Data for 2009 were adopted from years 1998-2000, and the annual riverine water outflows provided key information. The selection goes as follows: the Pregolya River - data from 1998 were adopted; the Mamonovka, Nelma and Prokhladnaya rivers - data from 2000 year were adopted.

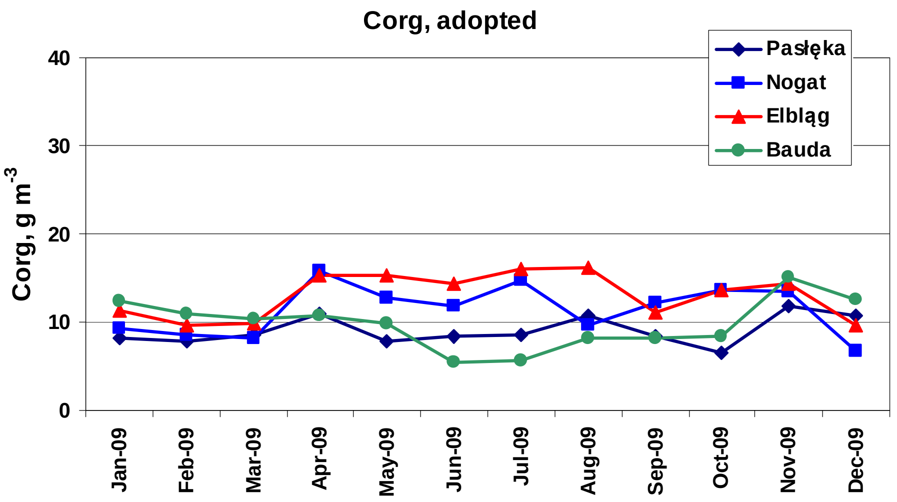


Fig. 2.58. Organic carbon in Polish rivers entering the Vistula Lagoon used in the model for 2009.

Rivers – organic nitrogen

As in the case of organic carbon in the Polish rivers, concentrations of organic nitrogen were based on 2009 measurements. The missing data for this year (monthly values) were supplemented by calculating the average values from the period 2007-2010. Data adopted in the Polish rivers for 2009 year calculations are presented in Fig. 2.59. For the Russian rivers, the same procedure as in the case ammonium was applied.

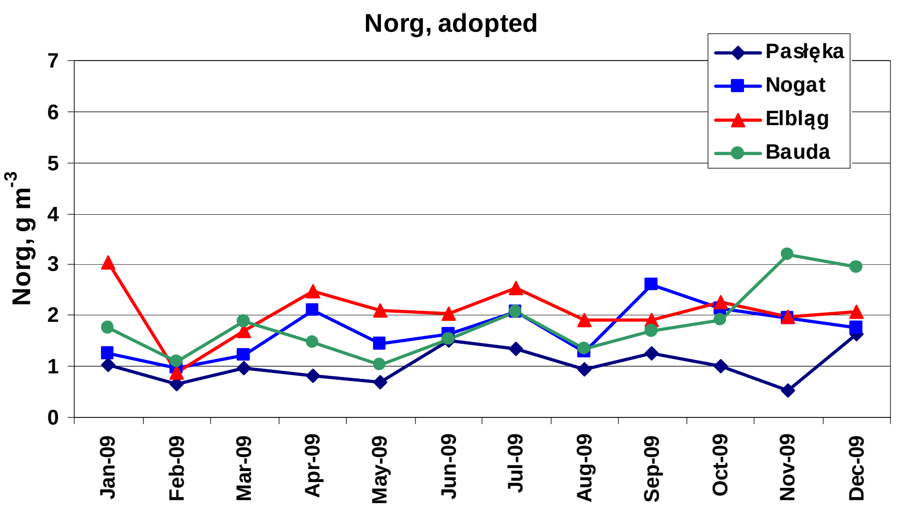


Fig. 2.59. Concentrations of organic nitrogen in Polish rivers entering the Vistula Lagoon used in the model for 2009.

Rivers – organic and absorbed phosphorus

For the year 2009, data preparation was carried out in a similar way to the calibration procedure. If there was a lack of data, monthly average values were calculated from respective values available for the years 2007-2010. Data adopted in the Polish rivers for 2009 modelling calculations are presented in Fig. 2.60.

As to the Russian rivers, the same procedure as in the ammonium and silicates was applied. Data for 2009 were adopted from years 1998-2000. Based on the annual riverine outflows, the selection goes as follows: the Pregolya River data from the year 1998 were adopted; the Mamonovka, Nelma and Prokhladnaya rivers data from the year 2000 were adopted.

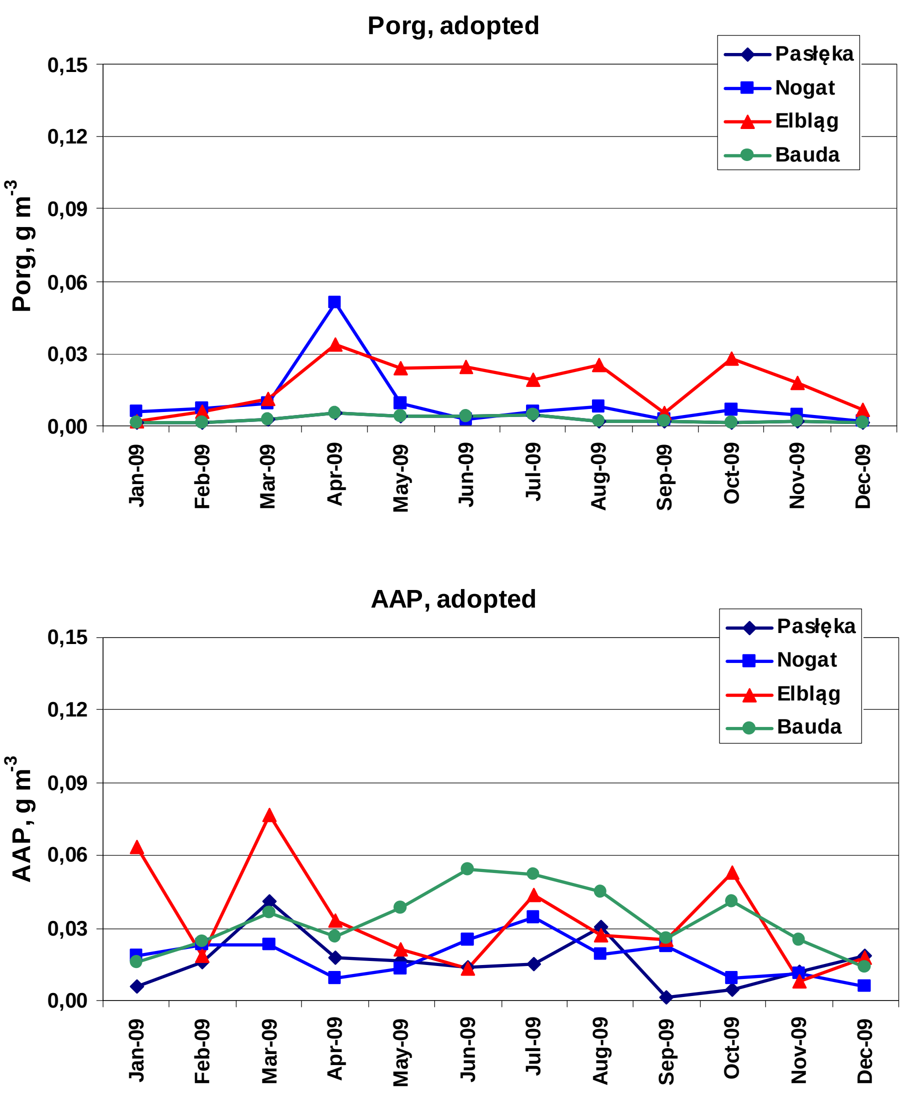


Fig. 2.60. Concentrations of organic and adsorbed phosphorus in Polish rivers entering the Vistula Lagoon used in the model for the 2009.

Rivers – organic silicon

Organic silicon in rivers was divided into two parts: particulate amorphous forms, which are referred to as biogenic silica (BSi) and dissolved (DSi) on the basis of measurements carried by M. Pastuszak (NMFRI, Gdynia) in the Vistula and Oder rivers and published in Humborg el al. (2006). For all the Polish and Russian rivers, the same data and assumptions as in the calibration procedure were used (see the calibration procedure).

Rivers – chlorophyll-a

As in the case of organic nitrogen in the Polish rivers, concentrations of organic nitrogen were based on 2009 measurements. Missing data for this year (monthly values) were supplemented by respective average values calculated from the data for the period 2007-2010. For the Elbląg River, data from Pasłęka River were applied. Data adopted in the Polish rivers for 2009 calculations are presented in Fig. 2.61.

For the Russian rivers, the same procedure as for ammonium was applied. Data for the year 2009 were adopted from the period 1998-2000. On the basis of the annual riverine outflows, the selection goes as follows: the Pregolya River data from 1998 were adopted; the Mamonovka, Nelma and Prokhladnaya rivers data from the year 2000 were adopted.

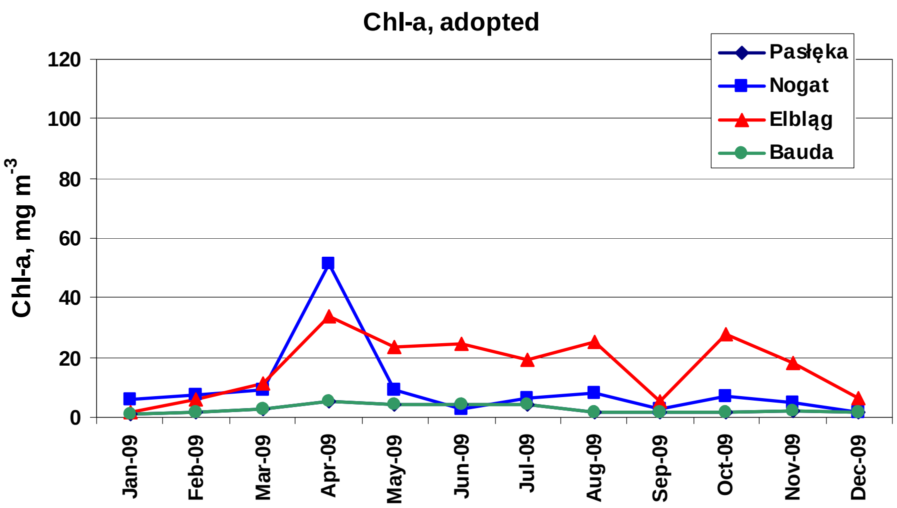


Fig. 2.61. Concentrations of chlorophyll-a for Polish rivers entering the Vistula Lagoon used in the model for 2009. For the Elbląg River, data from the Pasłęka River were applied.

Rivers – oxygen

Oxygen concentrations were based on field measurements of 2009. Missing data for this year (monthly values) were supplemented by average values calculated for the period 2007-2010, and the procedure was the same as in the case of chlorophyll-a concentrations. Data adopted in the Polish rivers for 2009 calculations are presented in Fig. 2.62.

For the Russian rivers, the same procedure as in the calibration was applied. Data for 2009 were adopted from the years 1998-2000. On the basis of annual riverine outflows, the selection

goes as follows: the Pregolya River data from 1998 were adopted; the Mamonovka, Nelma and Prokhladnaya rivers data from the year 2000 were adopted.

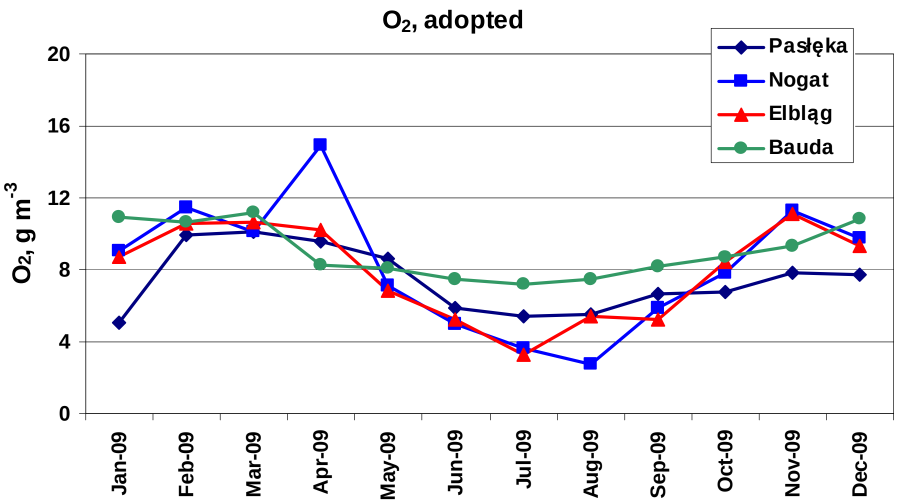


Fig. 2.62. Concentrations of oxygen for Polish rivers entering the Vistula Lagoon used in the model for 2009.

<u>Rivers – inorganic matter</u>

In all the Polish rivers, the annual patterns of inorganic matter concentrations were calculated on the basis of field measurements from 2009. Missing data for this year (monthly values) were supplemented by average values calculated based on the data from 2007-2010. All the remaining assumptions were used in the same way as in the calibration procedure. Data adopted in the Polish rivers for 2009 calculations are presented in Fig. 2.63.

In the Russian rivers, annual patterns of inorganic matter concentrations were based on data for the period 1998-2000, and the procedure was the same as in the case of oxygen concentrations.

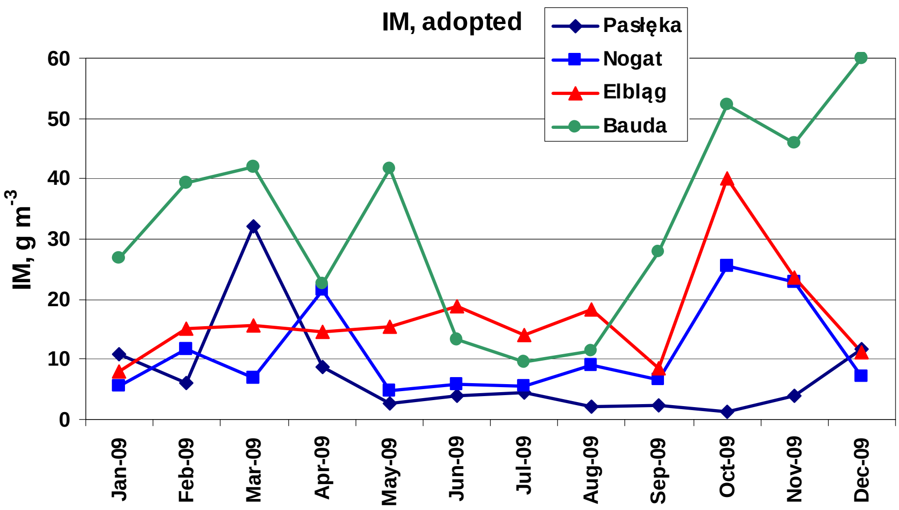


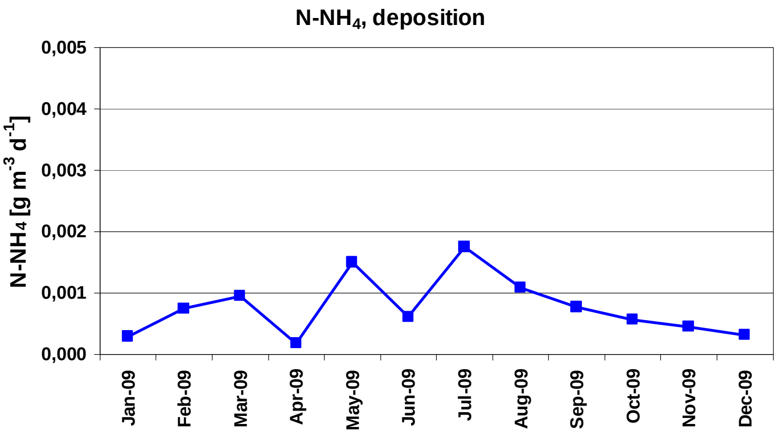
Fig. 2.63. Concentrations of inorganic matter (IM) for Polish rivers entering the Vistula Lagoon used in the model for 2009.

Nutrients inflow to the Vistula Lagoon from the Baltic Sea

Comparisons of levels of phosphates, nitrates, silicates and chlorophyll-a did not generate significant differences between mean monthly values from the 1998-2000 period and those from 2009. Therefore, the same data for nutrient inflow to the Vistula Lagoon from the Baltic Sea as for the calibration procedure were used. This assumption allowed keeping fixed balance between inorganic and organic fractions/forms of nutrients (for details see the data for calibration).

Nutrients – atmospheric deposition

There were available data concerning atmospheric deposition for 2009. Field measurements were carried out in Łeba (the open Baltic Sea coast). This sampling station is located about 250 km away from vicinity of Vistula Lagoon. Wet and dry depositions (total deposition) of N-NO_3 and N-NH_4 were taken into account in the model calculations. Data adopted for the calculations for 2009 are presented in Fig. 2.64. All the remaining assumptions for 2009 year were the same as in the calibration procedure.



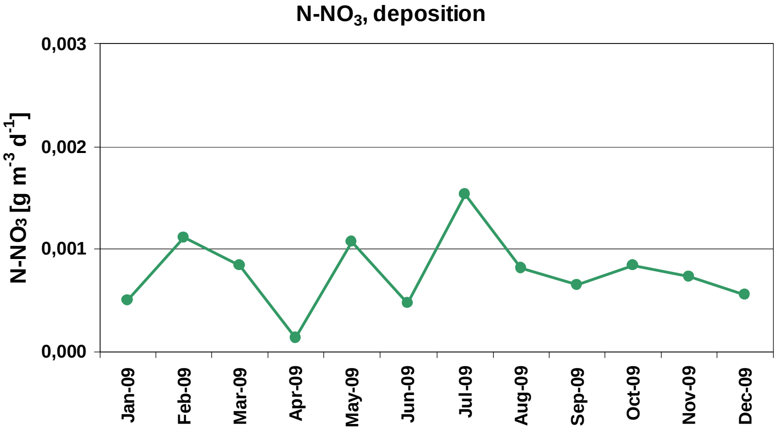


Fig. 2.64. Deposition of total (dry and wet) inorganic nitrogen measured in Łeba and used in the model for 2009 (data based on the data by IMWM).

Sediments

Because of the lack of specific data of nutrient content in bottom sediments of the Vistula Lagoon for 2009, the data were adopted in the same way as for the calibration procedure. For details, see the sediments in calibration procedure.

Validation results

Ten measuring points were used for the validation procedure for 2009. These points corresponded to seven model "cells" and were used for comparison of the model calculations with the field data. On the Polish side, seven measuring points corresponded to four model (WAQ) "cells", whereas on the Russian side, three measuring points corresponded to three model (WAQ) "cells". Similarly to the calibration procedure, the selected stations were located along the Vistula Lagoon and they formed a longitudinal transect (Fig. 2.65).

Similarly to the calibration procedure, two mathematical measures were used (average deviation (AD) and deviation of average values (DAV)). The data presented in the graph (Fig. 2.51) are from two locations, as in the calibration procedure. The first - (MIR-5) is typical for the central part of the Vistula Lagoon, close to the Polish-Russian border, and the second - (AN-1) remains under a river influence as it is located close to the mouth of the Pregolya River.

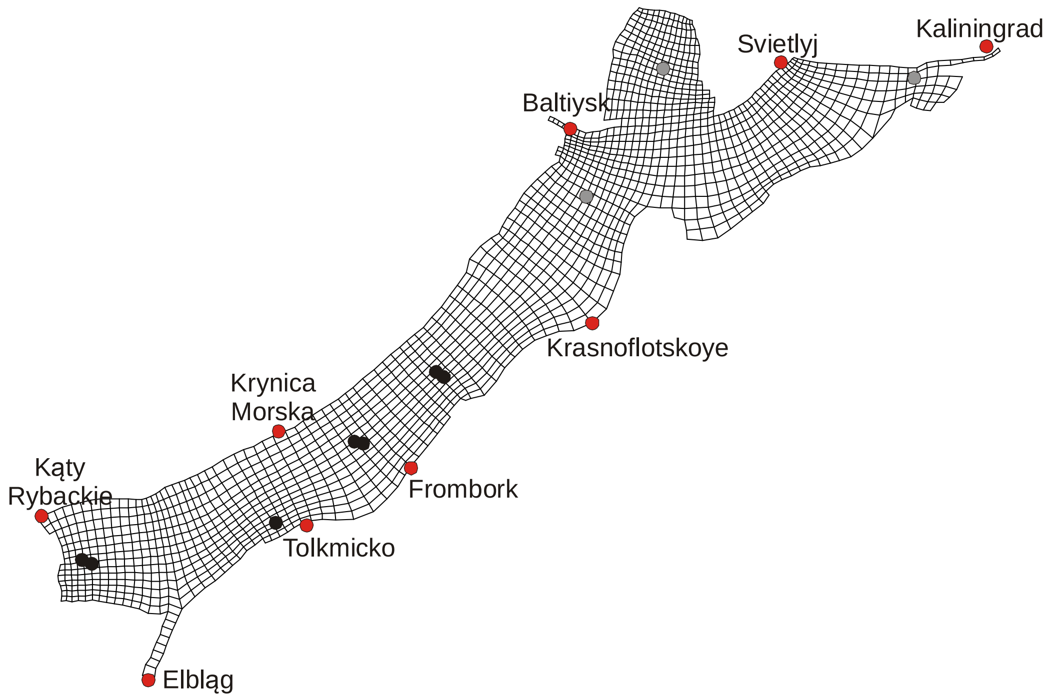


Fig. 2.65. Location of points used for model validation (black and grey points).

Average deviations (AD) between the calibration and validation procedure showed values which stayed at similar levels. Maximum differences of average values (between the calibration and validation) came to not more than 15% (the average deviation for all estimated parameters). The maximum difference of deviation of the average values (DAV; for mean

values) was reached about 5% between the calibration and validation procedure (Tables 2.15 and 2.16).

Table 2.16. The range of average deviation (AD) and deviation of average values (DAV) obtained in the model validation.

Average deviation, data 2009

	N-NH4	N-NO3	P-PO4	Si-SiO4	Ntot	Ptot	Corg	OXY	Chl-a	Susp. Matter	Secchi depth	average value
Max	38,3	35,4	67,3	29,6	32,0	41,8	19,1	42,3	255,1	49,6	77,5	**62,6**
Min	0,0	24,1	18,3	17,7	23,8	24,4	15,0	8,2	33,6	34,8	18,7	**19,9**
Mean	10,5	37,0	52,2	25,5	28,5	32,6	16,6	15,4	64,5	39,9	35,8	**32,6**

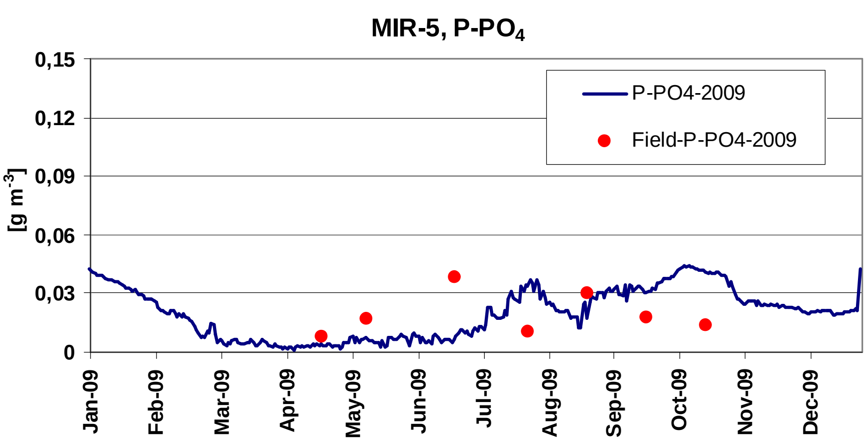
Deviation of average values, data 2009

	N-NH4	N-NO3	P-PO4	Si-SiO4	Ntot	Ptot	Corg	OXY	Chl-a	Susp. Matter	Secchi depth	average value
Max	0,0	26,5	20,3	25,8	-4,1	13,6	-9,4	14,0	15,7	-13,1	55,0	**18,0**
Min	-50,7	-56,0	-53,5	8,2	-31,0	-32,6	-15,2	-11,0	-37,2	-30,5	-25,6	**32,0**
Mean	-17,2	-18,0	-24,5	17,2	-15,4	-14,9	-13,1	-2,2	-10,6	-20,0	8,6	**14,7**

Similarly to the calibration, in the validation procedures better fits were observed for parameters characterized by low variability in time (e.g. oxygen, organic carbon). Comparable deviations (for the calibration and validation) of average deviations (AD) were seen in the case of ammonium, phosphates, total nitrogen, and total phosphorus. Better fits between the field data and the model simulation were achieved for chlorophyll-a concentrations (see compared values of calibration and validation; Tables 2.15 and 2.16).

Measurement data showed that seasonal patterns of phosphate concentration in the Polish and Russian parts of the lagoon were similar. The available data on phosphate concentrations point to the fact that in 2009 phosphate concentrations were similar in both parts of the lagoon, or slightly higher in the Russian part (Fig. 2.66).

Both, the model simulations and the measurement data of phosphates, indicate that this parameter could be recognized as a limiting factor for phytoplankton growth (very low concentrations of phosphates during the spring season).



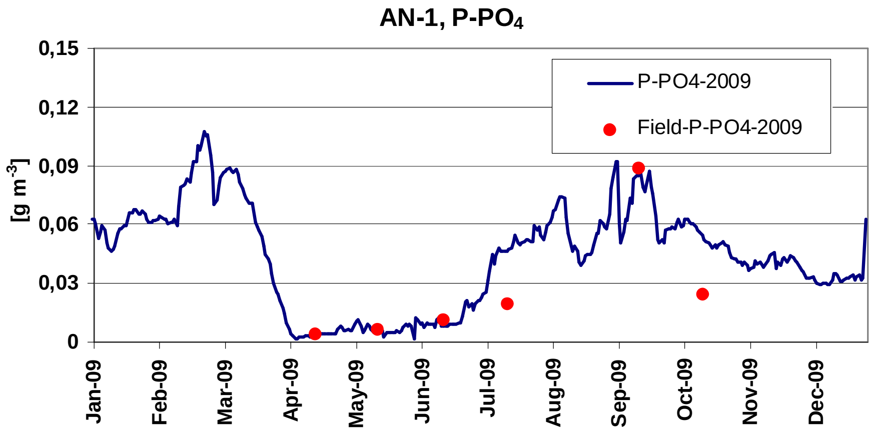


Fig. 2.66. Variability of phosphate concentrations, measured/field data and values simulated by the model (validation procedure).

Similarly to the calibration procedure, nitrate concentrations are characterized by low variability and quite a good fit between the measurement data and the model simulations. Starting from the turn of April and May, nitrates steadily decline to reach the minimum concentrations in the period of May to October. So, in late spring and throughout the entire vegetative period, nitrogen can become a limiting nutrient phytoplankton for the growth. Model simulates nitrate concentrations a bit lower than the measurement data (Fig. 2.67).

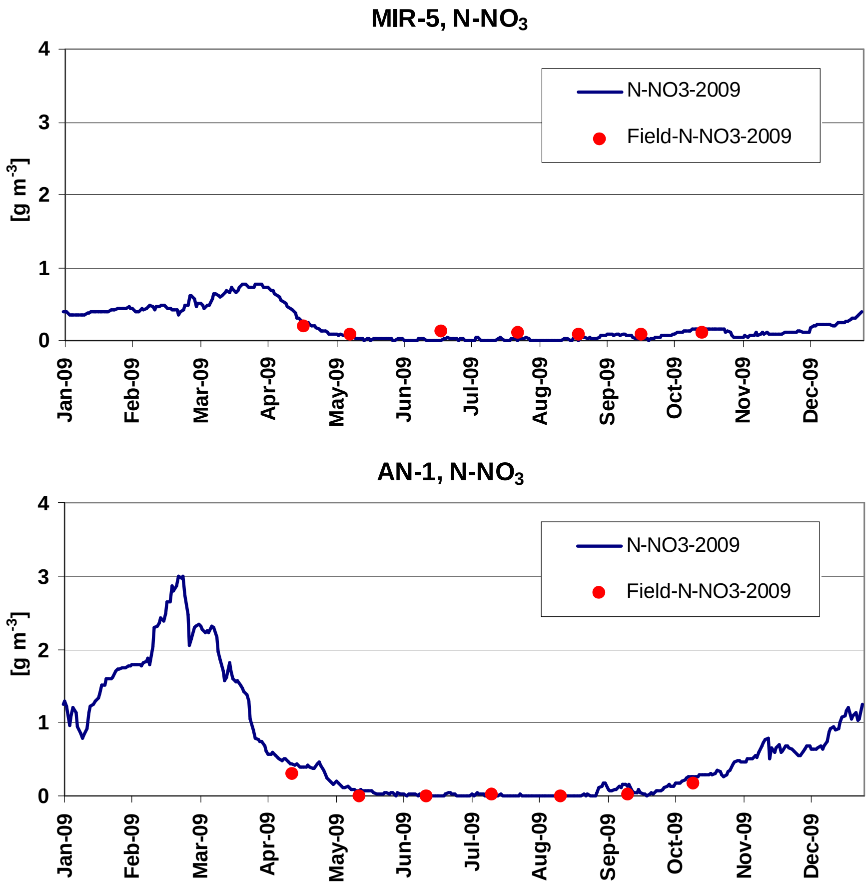


Fig. 2.67. Variability of nitrate concentrations, measured/field data and values simulated by the model (validation procedure).

Also in the validation procedure for chlorophyll-*a* concentrations, the largest differences were observed between the model results and the field data. The main reason of this discrepancy was described in the calibration procedure. In the validation procedure, the discrepancy between the field data and the model simulation result was by about 40% lower than in the calibration procedure (Tables 2.15 and 2.16).

Chlorophyll-a concentrations, during vegetative season, changed from a few to over 70 [g m^{-3}] in the central part of the Vistula Lagoon and in the vicinity of the Pregolya River mouth (Fig. 2.68). In spring 2009, chlorophyll-*a* concentrations showed moderate values (below 40 [g m^{-3}] (the model simulations and measurements). Then, in summer time, concentrations increased to over 40 [g m^{-3}] (in the measurements and model simulations).

The model results and field measurements allowed to state that during vegetative season there was a change of limiting nutrient from phosphorus (which plays a key role during early spring time) to nitrogen (which plays a key role during late spring and summer time; Fig. 2.68).

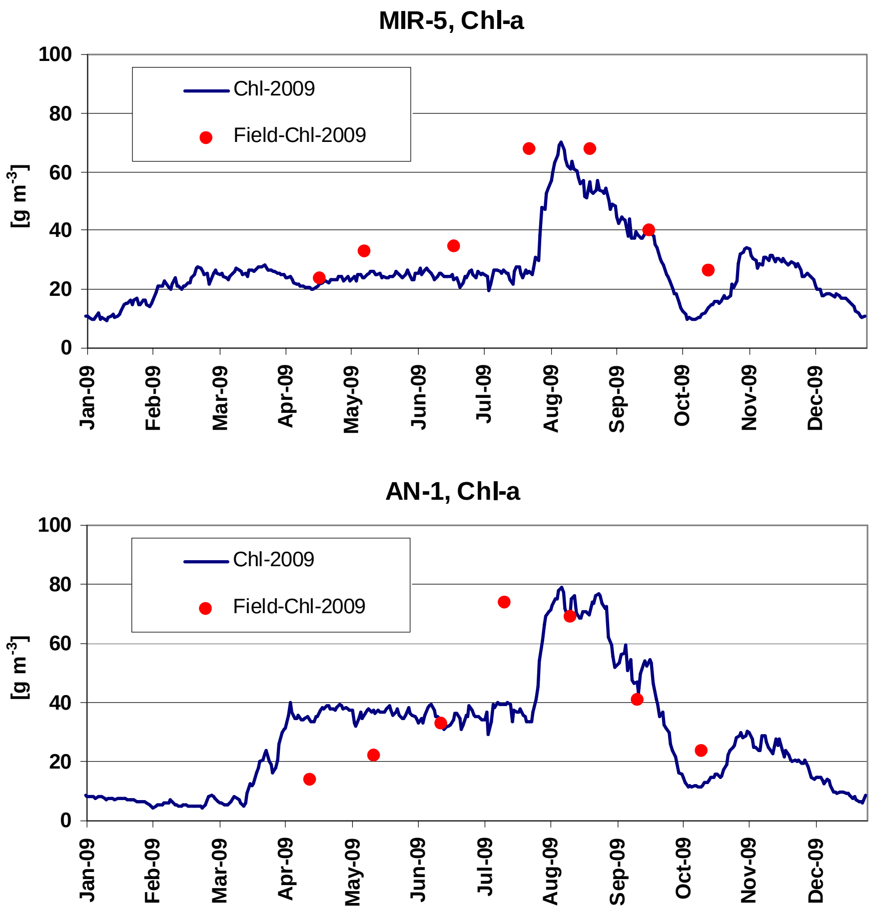


Fig. 2.68. Variability of chlorophyll-*a* concentrations, measured/field data and values simulated by the model (validation procedure).

3. MIKE modelling suite

3.1 Data overview and analysis

3.1.1 Climate data (atmospheric forcing)

The following data regarding the atmospheric forcing were used for the lagoon simulations.

Period 01.01.1998-29.12.2000. MIKE 21 regular mesh (200 x 200 m) simulations. Calibration of the model set-up for the Vistula Lagoon. Wind (magnitude and direction) is uniform for the whole computational domain. Wind data is for the station in Baltiysk (measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring). Wind data were imported from an archive of the MANTRA-East project.

Period 29.09–11.10.2012. MIKE 21 flexible mesh simulations. Calibration of the model set-up for the Vistula Lagoon and downstream area for the Pregolya River. Wind (magnitude and direction) is uniform for the whole computational domain. Wind data is for the station in Baltiysk (measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring). Wind data were collected during a national project RFBR 12-05-31248 (supervisor - D. Domnin).

Period 13.08-15.09.2013. Verification of the flexible mesh model set-up for the Vistula Lagoon and downstream area for the Pregolya River. Wind (magnitude and direction) is uniform for the whole computational domain. Wind data is for the station in Baltiysk (measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring). Wind data were collected during a national project RFBR 12-05-31248 (supervisor - D. Domnin).

Exact date for the verification is 04.09.2013, when direct salinity measurements were made in the Kaliningrad city segment of the Pregolya River.

3.1.2 Hydrological data

Period 01.01.1998-29.12.2000. MIKE 21 regular mesh (200 x 200 m) simulations. Calibration of the model set-up for the Vistula Lagoon. Time variations of the discharge of 7 rivers – Pregolya, Mamonovka, Nelma, Bauda, Elblag, Nogat, Pasleka. Water level and salinity variations at the open boundary (Baltiysk) – are results of measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring. Data was imported from an archive of the MANTRA-East project.

Period 29.09-11.10.2012. MIKE 21 flexible mesh simulations. Calibration of the model set-up for the Vistula Lagoon and downstream area for the Pregolya River. Time variations of the discharge of only Pregolya River was used. This discharge as well as water level and salinity variations at the open boundary (Baltiysk) were obtained during a national project RFBR 12-05-31248 (supervisor - D. Domnin). Data of salinity measurements in the Pregolya River for three days (06-08.10.2012).

Period 13.08-15.09.2013. Verification of the flexible mesh model set-up for the Vistula Lagoon and downstream area for the Pregolya River. Time variations of the discharge of only Pregolya River were used. This discharge as well as water level and salinity variations at the open boundary (Baltiysk) were obtained during a national project RFBR 12-05-31248 (supervisor -

D. Domnin). Exact data for verification is 04.09.2013, when direct salinity measurements were made in the Kaliningrad city segment of the Pregolya River.

3.2 Hydrodynamic model calibration and validation

3.2.1 Calibration methodology and results

The MIKE 21 regular grid model for the Vistula Lagoon (Fig. 3.1) was calibrated during the MANTRA-East Project and re-calibrated during the LAGOON project.

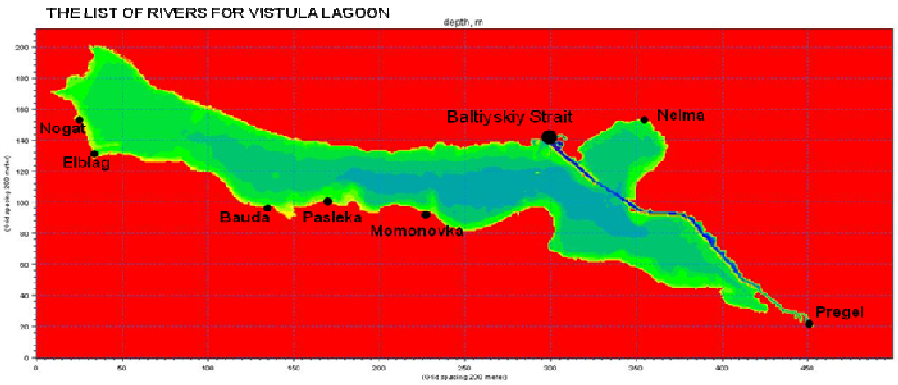


Fig. 3.1. Regular mesh (200 x 200 m) model set-up for the Vistula Lagoon, including existing navigational canal, and 7 rivers.

MIKE 21 regular grid, mesh size is of 200 x 200 m. Existing navigation canal is included. Calibration period was 01.01.1998-29.12.2000. Wind (magnitude and direction) is uniform for the whole computational domain. Wind and atmosphere temperature data were for the station in Baltiysk (measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring). Time variations of the discharge of 7 rivers - Pregolya, Mamonovka, Nelma, Bauda, Elblag, Nogat, Pasleka. Water level and salinity variations at the open boundary (Baltiysk). All boundary data – are results of measurements of the Kaliningrad Centre for Hydrometeorology and Environmental Monitoring. All data was imported from an archive of the MANTRA-East project.

40 simulations were made with different values of calibration parameters (wind and bottom friction coefficients and eddy viscosity and dispersion coefficients).

The set of calibration simulations was divided into two sub-sets:

- calibration on the basis of data for water level variations at 4 coastal points: Krynica and Tolkmicko (Poland), Krasnoflotskoe and Kaliningrad (Russia), Fig. 3.2.

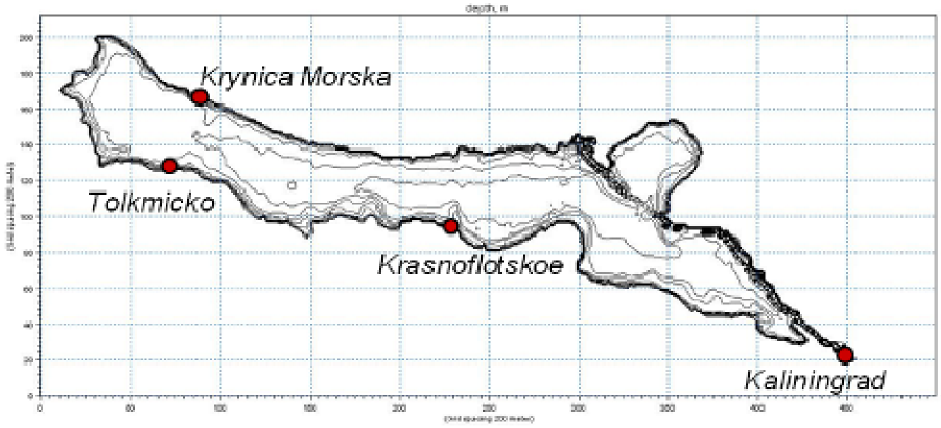


Fig. 3.2. Coastal points of water level measurements used for re-calibration of the MIKE 21 model (regular grid mode, 200 x 200 m) in the LAGOON project.

These sub-series gave information for the calibration against wind and bottom friction coefficients;

- calibration on the basis of data for salinity and temperature variations at 11 monitoring stations within the lagoon area (7 stations on the Russian side and 4 stations on the Polish side of the Vistula Lagoon), Fig. 3.3.

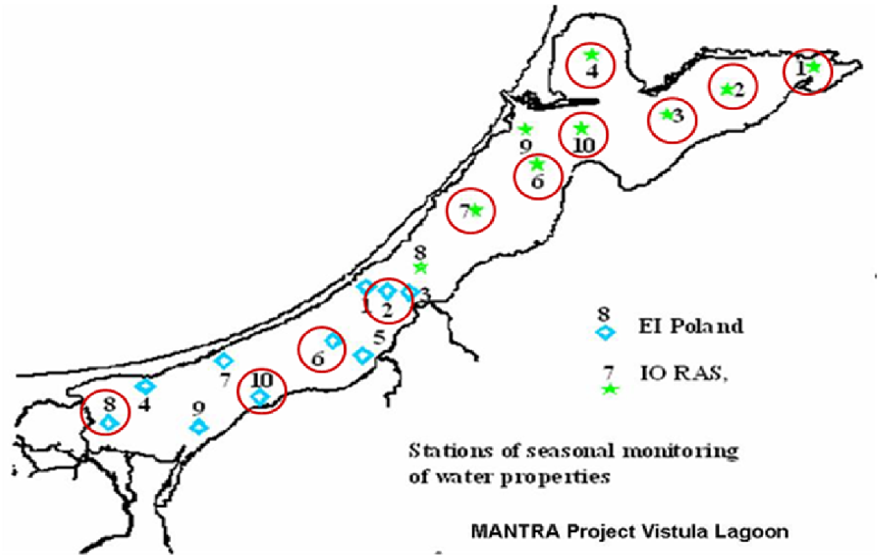


Fig. 3.3. Monitoring points (4 on the Polish side and 7 on the Russian one) of salinity and temperature measurements used for re-calibration of the MIKE 21 model (regular grid mode, 200 x 200 m) in the LAGOON project.

These sub-series gave information for calibration against eddy viscosity and dispersion coefficients.

Calibration against wind and bottom friction coefficients. Time period 09.04 – 20.11.1998, model “warming” from 01.01.1998. Time step is 25 sec. Values of wind friction and bed resistance coefficients (both are dimensionless) are listed in Table 3.1.

Table 3.1. Values of wind friction and bed resistance coefficients (both are dimensionless) used for calibration.

Wind friction coefficient	Bed resistance
0.0001	5
0.0026	**32**
0.0017	40
0.0013	50
	70

Examples of time sets (modelled and measured) for water level variations in Kaliningrad are presented at Fig. 3.4.

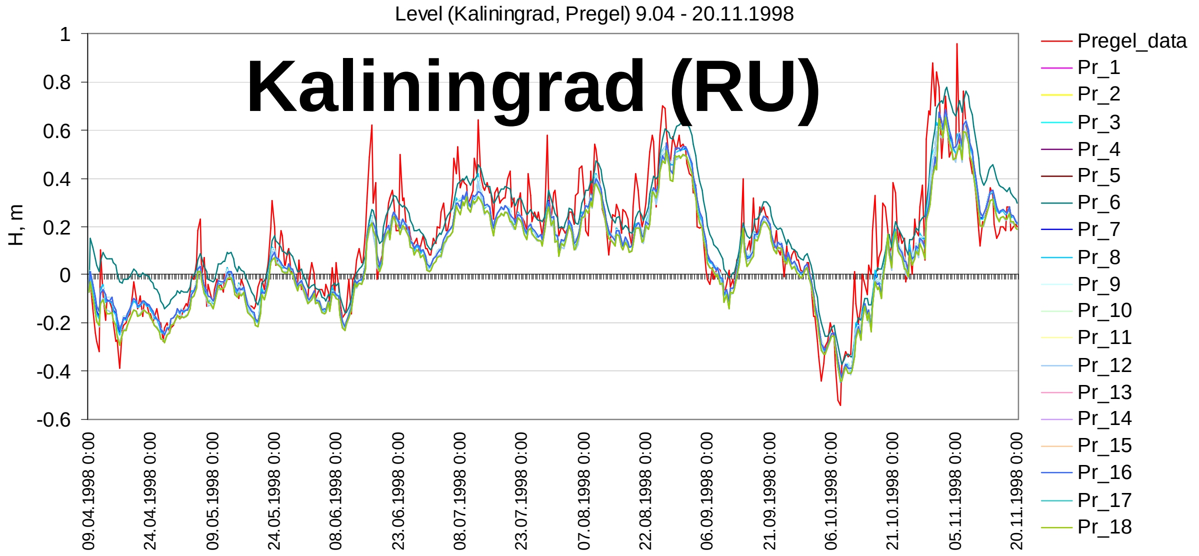


Fig. 3.4. Time sets of modelled (for different calibration parameters) and observed water level variations at the point Kaliningrad (see Figure 3.2) for the period of 09.04 – 20.11.1998.

The same results were obtained for Krynica and Tolkmicko (Poland), and Krasnoflotskoe (Russia). For each modelled time series its standard deviation as well as the correlation coefficient between it and the measured time series at this particular coastal point were calculated. Taylor diagram technique was used to visualise the relations between statistics of each modelled series (characterized by standard deviation and correlation coefficient) and measured data series (observed standard deviation, correlation coefficient equal to 1). An example of such a diagram for Kaliningrad is presented in Fig. 3.5, the same diagram was

obtained for Krynica and Tolkmicko (Poland), and Krasnoflotskoe (Russia). A minimum value of the root mean square difference between the observed and each modelled time series for all four coastal points was achieved for the wind friction coefficient equal to 0.0017**,** and the bed resistance coefficient equal to 32**.** These values were selected and used further during the calibration against the eddy viscosity and dispersion coefficients.

a) b)

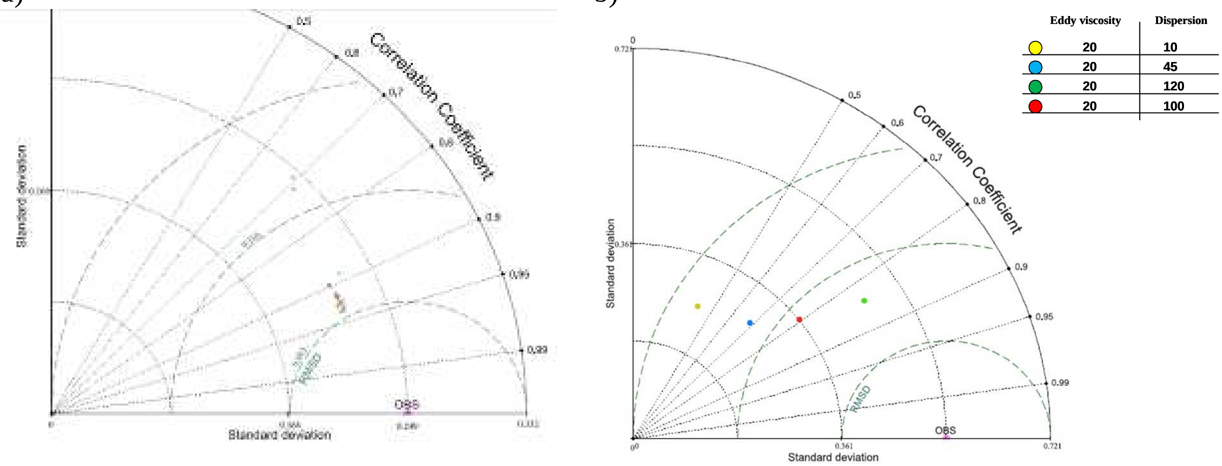


Fig. 3.5. Examples of Taylor diagrams for calibration modelled time sets (a) for water level variations at the Kaliningrad and (b) for salinity variations at the point R7, both for the period of 09.04 – 20.11.1998. Each colour point is referred to one simulated time series. The distance between each colour point and the point ‘OBS’ (‘OBS’ means observation time series) illustrates the root mean square difference between these two time sets. The closer are a colour point (referred to simulation time series) and “OBS” point, the better this simulated series fits to observation results.

Calibration against eddy viscosity and dispersion coefficients. Time period 09.04 – 20.11.1998, model “warming” from 01.01.1998. Time step is 25 sec. Values of eddy viscosity and dispersion coefficients are listed in Table 3.2.

Table 3.2. Values of eddy viscosity and dispersion coefficients used for calibration.

Eddy viscosity coefficient (m^2/sec)	Dispersion coefficient (m^2/sec)
0	10
10	20
20	30
50	45
200	70
800	80
	100
	120
	150
	170

Modelling time sets for salinity at each monitoring point (see Fig. 3.3) were obtained. For each modelled time series, its standard deviation as well as the correlation coefficient between it and the measured time series at this particular monitoring point were calculated. Taylor diagram technique was used to visualise the relations between statistics of each modelled series (characterized by standard deviation and correlation coefficient) and the measured data series (observed standard deviation, correlation coefficient equal to 1) at this particular monitoring point. An example of such a diagram for monitoring point R7 at the Russian side of the Vistula Lagoon is presented in Fig. 3.6.

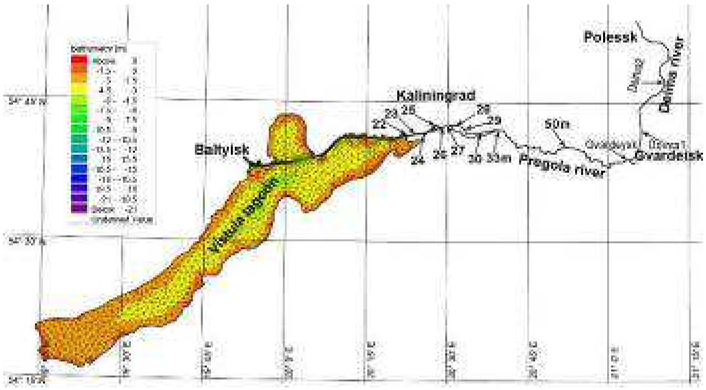


Fig. 3.6. Combined computational domain for the Vistula Lagoon and downstream area of the Pregolya. River including the Deyma River branch, flexible mesh, triangular elements (mesh size is of 50-100 m in the river stream and of 1 – 1.5 km in the lagoon area), rivers (except Pregolya) are not included.

A minimum value of the root mean square difference between the observed and each modelled time series for all 11 monitoring points within the Vistula Lagoon was achieved for the eddy viscosity coefficient equal to 10 and 20 (m^2/sec), and the dispersion coefficient equal to 100 and 120 m^2/sec. These values were selected for further simulations.

The same parameters of the wind friction and bed resistance coefficients as well as the viscosity characteristics were used for the MIKE 21 Flexible Mesh model for the Vistula Lagoon.

Calibration of ***MIKE 21 Flexible Mesh model set-up for the combined domain – the Vistula Lagoon and downstream area of the Pregolya River,*** including the Deyma River branch, (Fig. 3.6) was made on the basis of data of real measurements of salinity in the Pregolya River during the period of 06-08.10.2012, collected during a national project RFBR 12-05-31248 (supervisor - D. Domnin).

There were two events of high wind (gusts were up to 25 m/sec) during the period of 29.09 – 11.10.2012. Measurements were made at the segment of the Pregolya River corresponding to the Kaliningrad centre (stations numbers of 24-30) on 6th, 7th and 8th of October 2012 at noon or evening (Fig. 3.7).

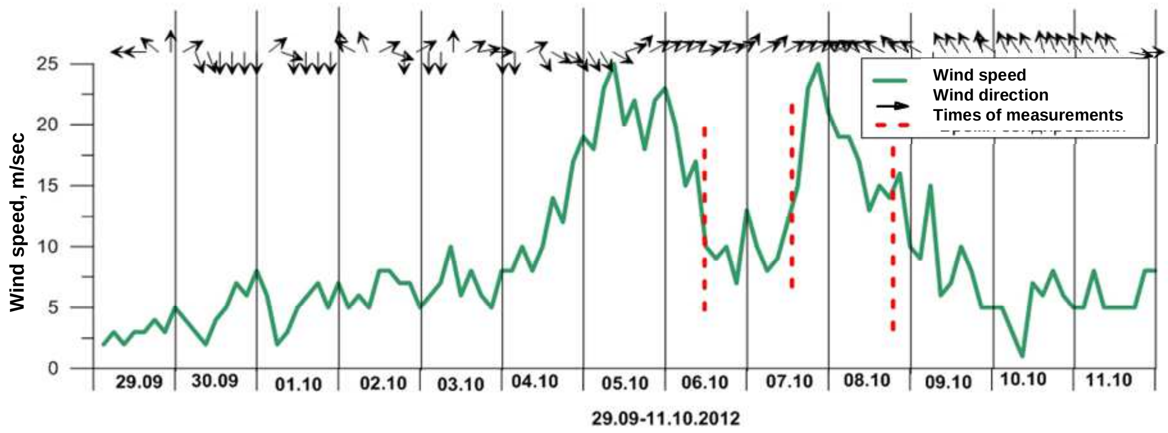


Fig. 3.7. Wind speed (gusts) and wind direction during calibration period (data from the Baltiysk Station). Red dashed lines correspond to times of field measurements in the Pregolya River (Kaliningrad city segment).

Boundary conditions on water level variations at the boundaries of the computational domain: Baltiysk (sea-lagoon boundary), Gvardeysk (upstream of the Pregolya River), Polessk (Deyma Branch mouth at the Curonian Lagoon) for the period of 29.09 – 11.10.2012 are presented in Fig. 3.8.

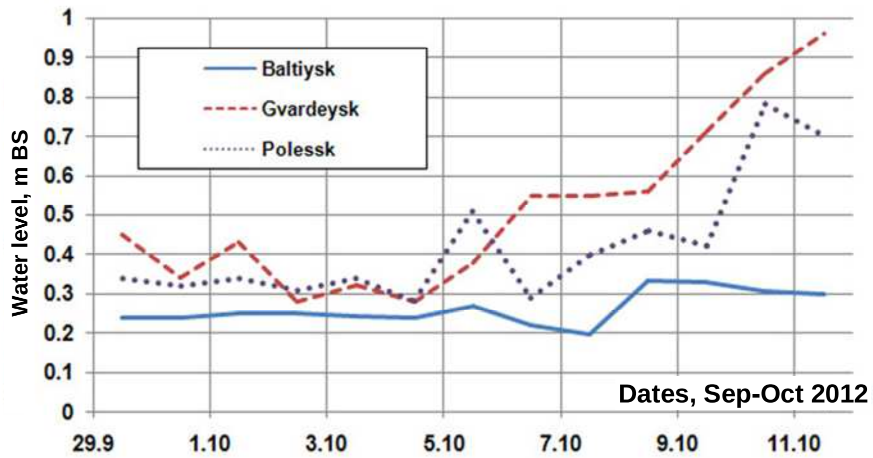


Fig. 3.8. Water level variations at the boundaries of the computational domain: Baltiysk (sea-lagoon boundary), Gvardeysk (upstream of the Pregolya River), Polessk (Deyma Branch mouth at the Curonian Lagoon) for the period of 29.09 – 11.10.2012.

Comparisons of simulation results with measured values are presented in Figs 3.9 and 3.10 for different sets of the calibration parameters – the bed resistance and eddy viscosity coefficients, respectively.

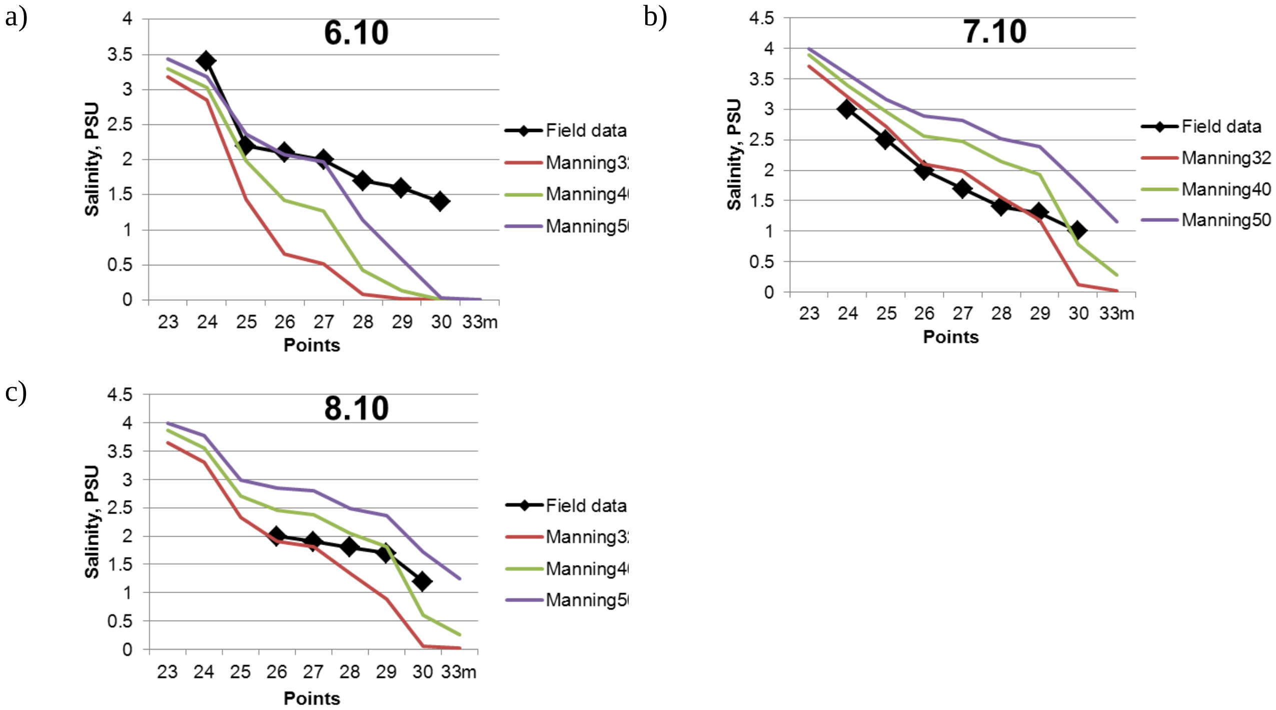


Fig. 3.9. Salinity distribution along the Pregolya River (Kaliningrad city segment) on 06, 07, 08.10.2012 during a strong western wind event. Measured data (11:00 – 13:00 local time) and simulated results for different bed resistance (different value of the Manning coefficient).

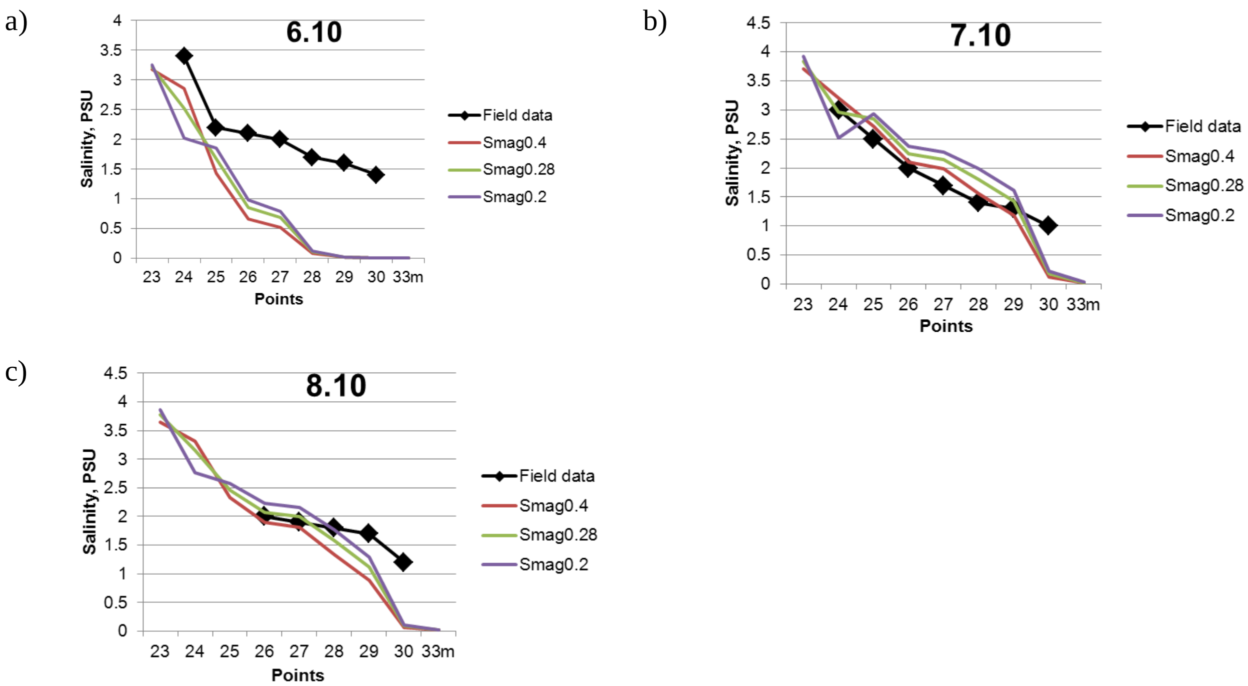


Fig. 3.10. Salinity distribution along the Pregolya River (Kaliningrad city segment) on 06, 07, 08.10.2012 during a strong western wind event. Measured data (11:00 – 13:00 local time) and simulated results for different values of the eddy viscosity coefficient (in a Smagorinsky approach).

After a quantitative analysis of differences between modelling and measurements results for three days and at each station (Tables 3.3 and 3.4) the following calibration parameters were selected: the Manning number equal to 40, a coefficient in the Smagorinsky formulation equal to 0.28.

Table 3.3. Root mean square deviations between modelled and measurements series for different values of the Manning number in a bed resistance formulation.

	6.10.12	7.10.12	8.10.12	Mean for 06-08.10.12
Manning32	1.32	0.38	0.66	0.79
Manning40	1.27	0.41	0.57	0.75
Manning50	1.29	0.52	0.55	0.79

Table 3.4. Root mean square deviations between modelled and measurements series for different values of the eddy viscosity coefficient.

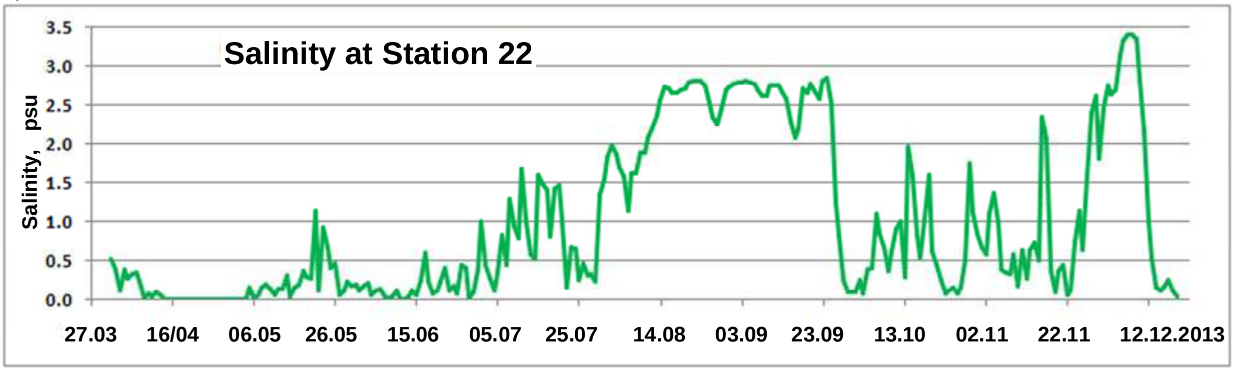
	6.10.12	7.10.12	8.10.12	Mean for 06-08.10.12
Smag 0.4	1.32	0.38	0.66	0.79
Smag 0.28	0.99	0.57	0.42	0.66
Smag 0.2	0.69	0.92	0.73	0.78

3.2.2 Validation methodology and results

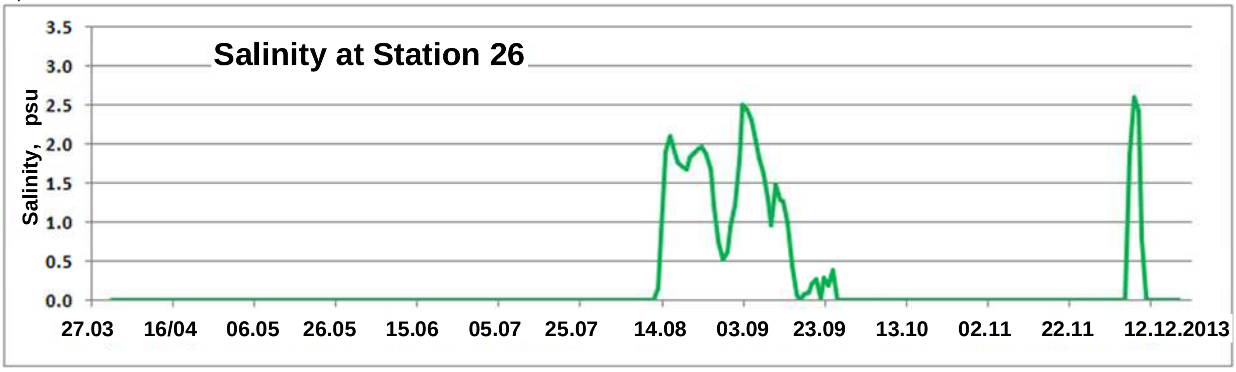
The validation of the MIKE21 flexible mesh model set-up was made for the event of 04.09.2013. Only two events of salt wedge intrusion upstream the Pregolya River were observed during 2013. The first time it was observed in the period of 13.08–15.09.2013, after an impulse of increasing western wind velocity (maximal wind speed was 12-18 m/sec, lowest speed was of 4-8 m/sec). The second time it was in a period starting on 24th of November 2013.

Using available data for the water level variations and Pregolya River discharge (a national project RFBR 12-05-31248, supervisor - D. Domnin) from March to December of 2013, the salinity variations were simulated for different points along the Pregolya River stream, corresponding to locations of monitoring stations (Fig. 3.6). Modelled salinity variations in time at the different points on the Pregolya River are presented in Fig. 3.11.

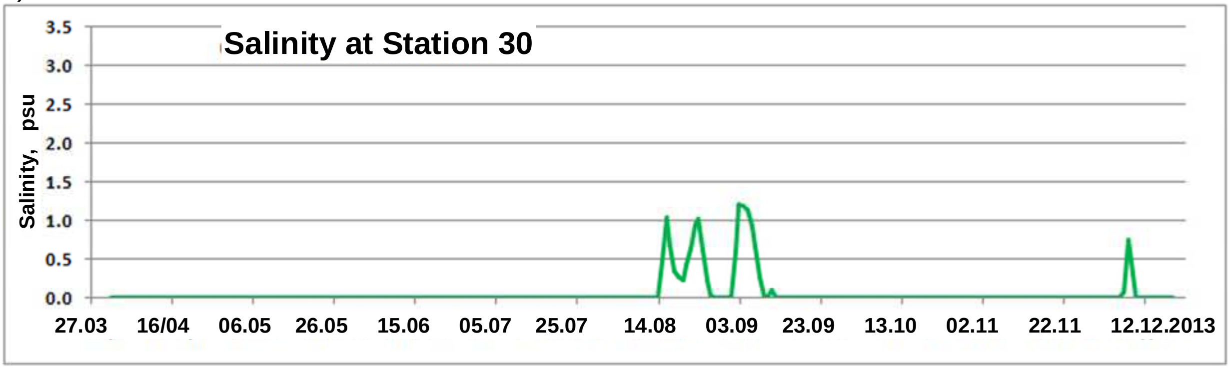
a)



b)



c)



d)

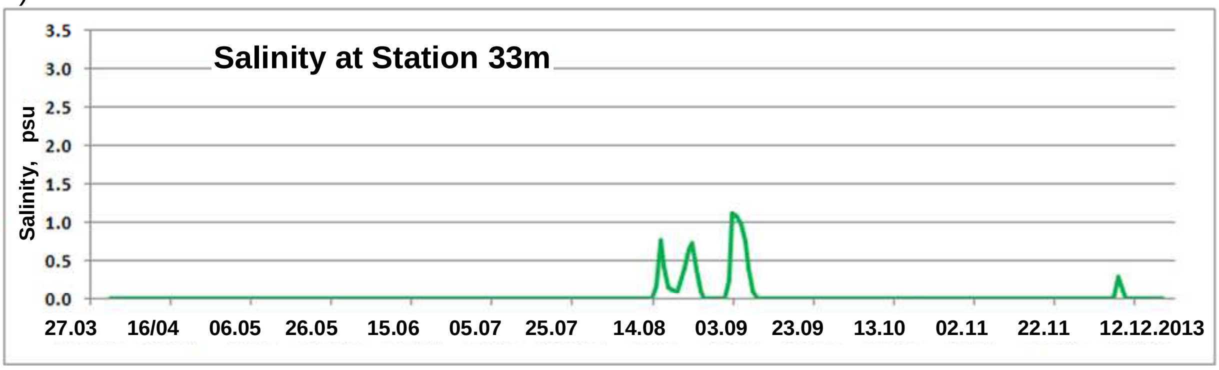


Fig. 3.11. Variations of salinity at different locations of the monitoring stations along the Pregolya River, stations 22, 26, 30, 33m, 27.03 – 12.12.2013.

Due to the lack of measured data, only one event was used for the validation, namely that of 13.08-15.09.2013. Direct measurements were done on 04.09.2013. Modelling results fit the measured characteristics quite well (Fig. 3.12). Therefore, we may consider the validation to be was fulfilled successfully.

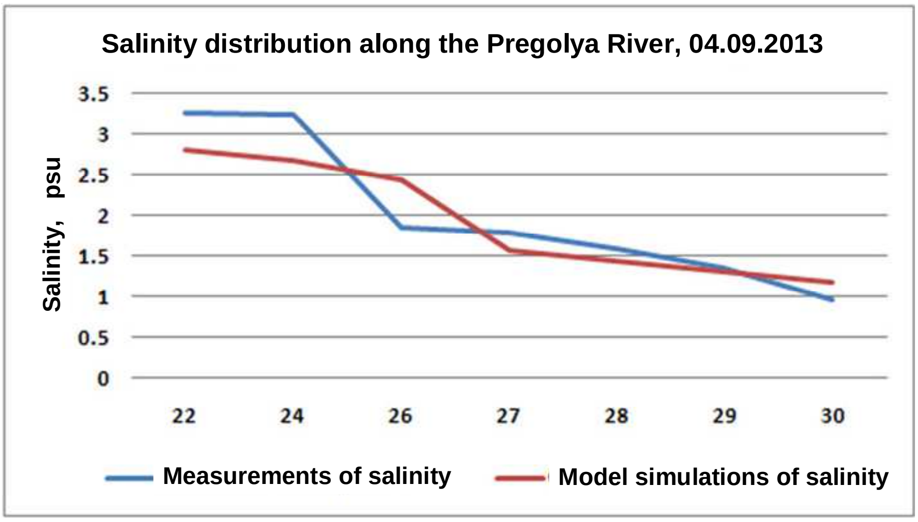


Fig. 3.12. Spatial distribution of salinity along the Pregolya River segment in the centre of the Kaliningrad City, 04.09.2013, stations 22-30.

4. Problems and recommendations

The calibration and validation of the hydrodynamic and the water quality models were carried out using available data sets from years 1998–2000 and 2009.

The basic problems encountered concern the quality and representation of initial and boundary conditions:

- data: data homogeneity – the data were collected at different times, with different time resolution and different methodology of measurements;
- initial conditions:
  - lack of in situ data to represent spatial distribution of analysed parameters (e.g. salinity, temperature);
- boundary conditions:
  - available *river discharge* data coming from in situ measurements was done with a different frequency for the calibration and verification periods;
  - *wind* conditions, due to limited in situ measurements, were introduced into the model as spatially uniform;
  - limited information on water exchange in the Baltiysk Strait;
- calibration/verification data:
- smaller database from 2009 than from years 1998-2000 for almost all parameters;

- salinity measurements mainly from CTD probes, hardly any long-term data in the lagoon available;
- no measurements to calibrate water currents.

The weakest point in the future simulations of climate scenarios and the anthropogenic influence on the system consisting of the Vistula Lagoon and the Pregolya River will be the estimation of the water level in the Pregolya River system (upstream points). The model set-up for the combined domain (Fig. 3.6) is very sensitive to water level differences at the lateral boundaries of this domain.

The problem is that the catchment SWIM model provides characteristics of the river discharge, but not of the water level. Therefore, some specific procedure has to be applied to complete the set-up by using the information about the water level at two open boundaries – in the Pregolya River (near the City of Gvardeysk) and at the Curonian Lagoon mouth of the Deyma Branch.

It is planned to test additionally the usage of the level-discharge curve for the upstream points of the Pregolya River.

Recommendations:

The Vistula Lagoon is a very dynamic water body. Hydrodynamic and water quality processes in the Polish and Russian parts are quite different due to natural characteristics of both parts. Modelling capabilities of the Vistula Lagoon go beyond the present data availability with respect to representation of initial and boundary conditions.

The collected hydrodynamic and water quality data base for the Vistula Lagoon is relatively extensive (e.g. chlorophyll-a, oxygen, nutrients in both Polish and Russian sides); however, the existing picture of nutrients supply from the Vistula Lagoon catchment remains incomplete. As an example, the lack of winter data or incomplete information on important parameters of river loads can be mentioned. Filling the existing gaps required assumptions and simplifications resulting in averaged picture of the Vistula Lagoon conditions, often lacking important details.

Appearing inconsistency in data for some parameters, manifested in a considerable difference in values, lead to their rejection.

All remarks mentioned above indicate the necessity of better coordination of research activities, carrying out intercalibration between laboratories involved in in-situ measurements, and further development of joint monitoring program for Polish and Russian parts.

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Glossary

AAP	Adsorbed inorganic phosphorus (in water column);
AAPSed	Adsorbed inorganic phosphorus in sediment;
AD	Average deviation;
AtlantNIRO	Atlantic Scientific Research Institute of Marine Fisheries and Oceanography in Kaliningrad;
BED	Baltic Environmental Database, website;
BOD_5	Biochemical oxygen demand;
C	Carbon;
Chl *a*	Chlorophyll *a*;
COD	Chemical oxygen demand;
COD_{Mn}	Chemical oxygen demand – potassium permanganate method;
C_{org}	Organic carbon;
C_{phyt}	Carbon in algae cells;
DAV	Deviation of average value;
Delft3D	modelling software for 3-dimensional modelling developed by Delft Hydraulics, website;
Delft3D FLOW	hydrodynamic module of the Delft3D;
Delft3D WAQ	water quality (biogeochemical) module of the Delft3D;
DetC	Detritus carbon (in water column);
DetCSed	Detritus carbon in sediment;
DetN	Detritus nitrogen (in water column);
DetNSed	Detritus nitrogen in sediment;
DetP	Detritus phosphorus (in water column);
DetPSed	Detritus phosphorus in sediment;
DetSi	Detritus silicon (in water column);
DetSiSed	Detritus silicon in sediment;
DOC	Dissolved organic carbon;
DON	Dissolved organic nitrogen;
DOP	Dissolved organic phosphorus;
DOSi	Dissolved organic silicon;
HD	Hydrodynamic;
IBW PAN	Institute of Hydro-Engineering, Polish Academy of Sciences in Gdańsk;

IEP	Inspectorate of Environmental Protection in Elbląg/Gdańsk/Olsztyn (WIOŚ);
IM	Particulate inorganic matter (in water column);
IMWM	Institute of Meteorology and Water Management – National Research Institute;
IMSed	Particulate inorganic matter in sediment;
KCGMS	Kaliningrad Centre for Hydrometeorology and Environmental Monitoring;
N	Nitrogen;
N-Kjeld	Kjeldhal nitrogen (sum of ammonium and organic nitrogen);
NMFRI	National Marine Fisheries Research Institute in Gdynia;
$N\text{-}NH_4$	Ammonium nitrogen;
$N\text{-}NO_2$	Nitrite nitrogen;
$N\text{-}NO_3$	Nitrate nitrogen;
$N\text{-}NO_x$	Sum of nitrite and nitrate nitrogen;
N_{org}	Organic nitrogen;
N_{phyt}	Nitrogen in algae cells;
N_{tot}	Total nitrogen;
O_2	Oxygen (dissolved in water);
P	Phosphorus;
PAR	Photosynthetically active radiation;
P_{org}	Organic phosphorus;
P_{phyt}	Phosphorus in algae cells;
$P\text{-}PO_4$	Phosphate phosphorus;
PSU	Practical salinity units;
P_{tot}	Total phosphorus;
R	Correlation coefficient (linear);
SD	Secchi disc visibility (Secchi depth);
Shirshov IO RAN	Shirshov Institute of Oceanology, Russian Academy of Sciences, Kaliningrad;
Si	Silicon;
Si_{org}	Organic silicon;
$Si\text{-}SiO_4$	Silicate silicon;
Temp	Temperature;
TSM	Total suspended matter;

Appendix 1

Table 2.1. Overview of river discharge data applied in the Vistula Lagoon model (KCGMS, Russia; IMWM – Institute of Meteorology and Water Management, Poland).

River discharge:	**1998-2000**		**2009**	
	frequency	data source	frequency	data source
sewage collector	estimated - constant		estimated - constant	
Nelma	1/5days	KCGMS	estimated	
Pregola	1/ 5 days	KCGMS	1/day	KCGMS
Prokhladnaya	estimated - time varying	KCGMS	estimated - time varying	
Mamonovka	1/5 Days	KCGMS	1/day	KCGMS
Pasłęka	1/10 Days	IMWM	1/day	IMWM
Bauda	1/month	IMWM	1/day	IMWM
Elbląg	1/month	IMWM	1/day	IMWM
Nogat	1/month	IMWM	1/day	IMWM

Table 2.2. Overview of water level measurements at coastal stations of the Vistula Lagoon in years 1998, 2000 and 2009.

water level gauge:	**frequency**			**data source**
	1998	**1999–2000**	**2009**	
Baltiysk	6 hours	6 hours	6 hours	KCGMS
Kaliningrad	6 hours	3 hours		KCGMS
Krasnoflotskye	6 hours	3 hours		KCGMS
Nowa Pasłeka	4 hours	4 hours	2 hours	IMWM
Tolkmicko	4 hours	4 hours	12 hours	IMWM
Nowe Batorowo	4 hours	4 hours		IMWM
Osłonka	4 hours	4 hours		IMWM
Krynica Morska	4 hours	4 hours	2 hours	IMWM

Table 2.3. Overview of water temperature measurements at coastal stations of the Vistula Lagoon in years 1998–2000 and 2009.

water temperature gauge:	1998–2000		2009	
	frequency	data source	frequency	data source
Tolkmicko	1/day	IMWM	1/day	IMWM
Baltiysk	6 hours	HYDROMET		
Krasnoflotskoe	6 hours	HYDROMET		

Table 2.4. Overview of salinity measurements at coastal stations of Vistula Lagoon in years 1998–2000 and 2009.

water salinity gauge:	1998–2000		2009	
	frequency	data source	frequency	data source
Tolkmicko	1/day	IMWM	1/day	IMWM
Baltiysk	1/day	KCGMS	1/day	KCGMS
Krasnoflotskoe	1/day	KCGMS		

Table 2.5. Dates of CTD measurements done by IMWM at verticals located in the Polish part of the Vistula Lagoon (see Fig. 2.4).

date	P1	P2	P3	P5	p6	p7/T5	p8	p9/T2	p10
1998-04-23	+	+	+	+	+	+	+	+	+
1998-05-20	+	+	+	+	+	+	+	+	+
1998-06-22	+	+	+	+	+	+	+	+	+
1998-07-28	+	+	+	+	+	+	+	+	+
1998-08-19	+	+	+	+	+	+	+	+	+
1998-09-16	+	+	+	+	+	+	+	+	+
1998-10-07	+	+	+	+	+	+	+	+	+
1998-11-09	+	+	+	+	+	+	+	+	+
1999-04-07		+	+	+	+	+	+	+	+
1999-04-23	+								
1999-05-12		+	+	+	+	+	+	+	+
1999-05-20	+								
1999-06-22	+								
1999-07-28	+								
1999-08-19	+	+	+	+	+	+	+	+	+
1999-09-08		+	+	+	+	+	+	+	+
1999-09-16	+					+	+	+	+
1999-10-11		+	+	+	+	+	+	+	+
1999-11-03		+	+	+	+	+	+	+	+
2000-04-26	+	+	+	+	+	+	+	+	+
2000-05-25	+	+	+	+	+	+	+	+	+
2000-06-15	+	+	+	+	+	+	+	+	+
2000-08-22	+	+	+	+	+	+	+	+	+
2000-09-19	+	+	+	+	+	+	+	+	+
2000-11-30	+	+	+	+	+	+	+	+	+
2009-04-20	+	+	+	+					
2009-04-21					+	+	+	+	+
2009-05-11	+	+	+	+					
2009-05-12					+	+	+	+	+
2009-06-22									
2009-06-23						+	+	+	+
2009-07-27	+	+	+	+	+				
2009-07-28						+	+	+	+
2009-08-24	+	+	+	+					
2009-08-25					+	+	+	+	+
2009-09-21	+	+	+	+					
2009-09-22					+	+	+	+	+
2009-10-19	+	+	+	+					
2009-10-20					+	+	+	+	+

Table 2.6. Dates of CTD measurements done by KCGMS at verticals located in the Russian part of the Vistula Lagoon (see Fig. 2.4).

date	V1	V2	V3	V4	V6	V7	V8	V9	V10
1998-04-17	+	+			+	+	+		+
1998-05-28	+	+	+	+	+	+	+	+	+
1998-06-19	+	+	+	+	+	+	+	+	+
1998-07-16	+	+	+	+	+	+	+	+	+
1998-08-10	+			+	+	+	+	+	+
1998-08-20	+	+	+	+	+	+	+	+	+
1998-09-19	+	+	+	+	+	+		+	+
1998-11-03	+	+	+	+	+	+	+	+	+
1999-05-27	+	+	+	+	+	+	+	+	+
1999-08-26	+	+	+	+	+	+	+	+	+
1999-10-11	+	+	+		+	+		+	+
2000-03-29	+	+	+	+	+	+	+	+	+
2000-04-29	+	+	+	+	+	+	+	+	+
2000-05-22	+	+	+	+	+	+	+	+	+
2000-06-02	+	+	+	+	+	+	+	+	+
2000-07-26	+	+	+	+	+	+		+	+
2000-08-18	+	+	+	+	+	+	+	+	+
2000-08-23							+	+	
2000-09-13	+	+	+	+	+	+		+	+
2000-10-17	+	+	+	+	+	+	+	+	+
2000-11-16	+	+	+	+	+	+	+	+	+
2000-12-13	+	+	+	+	+			+	+
2009-06-01	+	+	+		+			+	+
2009-07-29	+	+	+		+			+	+
2009-08-21	+	+	+		+			+	+
2009-08-29	+	+	+		+	+	+		+

Table 2.7. Dates of CTD measurements done by Atlant-NIRO at verticals located in Russian part of the Vistula Lagoon (see Fig. 2.4).

date	V1	V2	V3	V4	V6	V7	V9	V10
1998-04-09	+	+	+	+	+	+	+	+
1998-05-18	+	+	+	+	+	+	+	+
1998-06-10	+	+	+	+	+	+	+	+
1998-07-15	+	+	+	+	+	+	+	+
1998-08-17	+	+	+	+	+	+	+	+
1998-09-15	+	+	+	+	+	+	+	+
1998-10-19	+	+	+	+	+	+	+	+
1998-11-11	+	+	+	+	+	+	+	+
1999-04-21	+	+	+	+	+	+	+	+
1999-05-24	+	+	+	+	+	+	+	+
1999-06-17	+	+	+	+	+	+	+	+
1999-07-13	+	+	+	+	+	+	+	+
1999-08-19	+	+	+	+	+	+	+	+
1999-09-21	+	+	+	+	+	+	+	+
1999-10-20	+	+	+	+	+	+	+	+
1999-11-15	+	+	+	+	+	+	+	+

Table 2.8. Time resolution of the hydro-meteorological data for the 1998–2000.

Parameter	Station location	Time resolution	Data source
Water temperature	Krasnoflotskoye	daily	KCGMS (unpubl.)
	Baltiysk	daily	
	Kaliningrad	daily	
	Tolkmicko	daily	IMWM (unpubl.)
Ice cover	Krasnoflotskoye	daily	KCGMS (unpubl.)
	Krynica Morska	daily	Warunki środowiskowe (1999÷2001)
Wind direction and speed	Baltiysk	daily	KCGMS (unpubl.)
Irradiance	Gdynia	daily	IMWM (unpubl.)
Precipitation	Elbląg	monthly	Warunki środowiskowe (1999÷2001)

Table 2.9. The data sources and frequency of measurements of riverine, atmosphere, and the Gulf of Gdańsk loads.

Parameters	Station location	Time period	Time resolution	Data source
River water flow (Polish rivers)	Pasłęka	1998÷2000	monthly	IMWM (unpubl.)
	Bauda	1998÷2000	monthly	
	Elbląg, Nogat and Szkarpawa	1951÷1965	monthly	Łazarienko and Majewski, 1975
River water flow (Russian rivers)	Pregolya	1998÷2000	monthly	KCGMS (unpubl.)
	Nelma	1998÷2000	monthly	
	Mamonovka	1998÷2000	monthly	
	Prokhladnaya	1951÷1965	monthly	Łazarienko and Majewski, 1975
Concentrations O_2, COD_{Mn}, COD_{Cr}, BOD_5, N-NH_4, N-NO_2, N-NO_3, P-PO_4, N_{tot}, P_{tot}, TSM	Pasłęka	1988÷2000	monthly	IEP Gdańsk, IEP Olsztyn/ Elbląg (unpubl.)
	Bauda	1999	monthly	
	Nogat	1998 & 2000	monthly	
	Elbląg	1998÷2000	monthly	
Concentrations O_2, COD_{Cr}, BOD_5, N-NH_4, N-NO_2, N-NO_3, P-PO_4, Si-SiO_4	Pregolya	1998÷2000	monthly or every 2 month	KCGMS (unpubl.)
	Mamonovka	1998÷2000	every 2 month	
	Nelma	1998÷2000	every 2 month	
Concentrations N-NO_3, P-PO_4, Chl *a*	Pregolya	2000÷2002	monthly during vegetative season	Aleksandrov and Dmitrieva, 2003
Loads N_{tot}, P_{tot}, BOD_5	Kaliningrad sewage collector	2000÷2001	annual	Doklad o sostojanii, 2002
Atmospheric loads N-NH_4, N-NO_3	Gdynia	1998÷2000	monthly	IMWM (unpubl.)
	Łeba	1998÷2000	monthly	
Concentrations O_2, N-NH_4, N-NO_3, N-NO_2, P-PO_4, N_{tot}, P_{tot}, Si-SiO_4, Chl a	Gulf of Gdańsk	1993÷1998	monthly	BED, website

Table 2.10. The hydro-chemical data from the Vistula Lagoon used in the modelling.

Parameter	Stations and time period	Depth	Data source
Russian part			
Temp., salinity, O_2, BOD_5, N-NH_4, N-NO_3, N-NO_2, P-PO_4, N_{tot}, P_{tot}, Chl *a* , Secchi depth	9 stations, monthly April–November 1998÷2000	surface measurements	AtlantNIRO (unpubl.)
Temp., salinity, O_2, Secchi depth	3–9 stations, 3–10 times per year, 1998÷2000	surface and near bottom	Shirshov IO RAN (unpubl.)
Polish part			
Temp., salinity, chlorides, O_2, COD_{Mn}, COD_{Cr}, BOD_5, N-NH_4, N-NO_3, N-NO_2, P-PO_4, N_{tot}, N_{Kjeld}, P_{tot}, TSM, Chl *a* , Secchi depth	10 stations, monthly April–November, 1998÷2000	surface	IEP Olsztyn/ Elbląg (unpubl.)
Temp., salinity, N-NH_4, N-NO_3, N-NO_2, P-PO_4, Si-SiO_4, Chl *a* , Secchi depth	3–15 stations, every two weeks April–November 1998 and 1999, February–June 2000	Temp. and salinity every 0.25 m, other parameters - surface and 1.5 m depth	NMFRI (unpubl.)
N-NH_4, N-NO_3, N-NO_2, P-PO_4, N_{tot}, P_{tot}	4 stations, 4–6 measurements during vegetative period, 1999÷2000	surface and near bottom	IMWM (unpubl.)

Table 2.11. Time resolution of hydro-meteorological data for the year 2009.

Parameter	Station location	Time resolution	Data source
Water temperature	Tolkmicko	daily	IMWM (unpubl.)
Wind direction and speed	Baltiysk	daily	KCGMS (unpubl.)
Irradiance	Gdynia	daily	IMWM (unpubl.)

Table 2.12. Data on riverine, atmosphere, and the Gulf of Gdańsk loads and concentrations used for validation of the water quality model.

Parameters	Station location	Time period	Time resolution	Data source
River water flow (Polish rivers)	Pasłęka	2009	monthly	IMWM (unpubl.)
	Bauda	2009	monthly	
	Elbląg, Nogat and Szkarpawa	2009	monthly	IMWM (unpubl.)
River water flow (Russian rivers)	Pregolya	2009	monthly	KCGMS (unpubl.)
	Nelma	2009	monthly	
	Mamonovka	2009	monthly	
	Prokhladnaya	2009	monthly	Łazarienko and Majewski, 1975
Concentrations O_2, Corg, COD_{Mn}, COD_{Cr}, BOD_5, $N\text{-}NH_4$, $N\text{-}NO_2$, $N\text{-}NO_3$, $P\text{-}PO_4$, N_{tot}, P_{tot}, TSM	Pasłęka	2007-2010	monthly	IEP Gdańsk, IEP Olsztyn/ Elbląg (unpubl.)
	Bauda	2007-2010	monthly	
	Nogat	2007-2010	monthly	
	Elbląg	2007-2010	monthly	
Concentrations O_2, COD_{Cr}, BOD_5, $N\text{-}NH_4$, $N\text{-}NO_2$, $N\text{-}NO_3$, $P\text{-}PO_4$, $Si\text{-}SiO_4$	Pregolya	1998÷2000	monthly or every 2 month	KCGMS (unpubl.)
	Mamonovka	1998÷2000	every 2 month	KCGMS (unpubl.)
	Nelma	1998÷2000	every 2 month	
Concentrations $N\text{-}NO_3$, $P\text{-}PO_4$, Chl *a*	Pregolya	2000÷2002	monthly during vegetative season	Aleksandrov and Dmitrieva, 2003
Loads N_{tot}, P_{tot}, BOD_5	Kaliningrad sewage collector	2000÷2001	annual	Doklad o sostojanii, 2002
Atmospheric loads $N\text{-}NH_4$, $N\text{-}NO_3$	Łeba	2009	monthly	IMWM (unpubl.)
Concentrations O_2, $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$, $P\text{-}PO_4$, N_{tot}, P_{tot}, $Si\text{-}SiO_4$, Chl a	Gulf of Gdańsk	1993÷1998	monthly	BED, website

Table 2.13. The hydro-chemical data from the Vistula Lagoon used for validation of the model.

Parameter	Stations and time period	Depth	Data source
Russian part			
O_2, BOD_5, N-NO_3, P-PO_4, P_{tot}, Chl *a*	4 stations, monthly April–November 2007-2009	surface measurements	Aleksandrov and Smyslov, 2011
Polish part			
Temp., salinity, chlorides, O_2, COD_{Mn}, COD_{Cr}, BOD_5, N-NH_4, N-NO_3, N-NO_2, P-PO_4, N_{tot}, N_{Kjeld}, P_{tot}, TSM, Chl *a* , Secchi depth	9 stations, monthly April–November, 2007-2010	surface measurements	IEP Olsztyn/ Elbląg (unpubl.)

Chapter 2

The Ria de Aveiro Lagoon - Modelling results and recommendations

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1. Introduction

The Ria de Aveiro (Fig. 1.1) consists of four main channels which radiate from the mouth with several branches, islands and mudflats. The lagoon is mesotidal with an average tidal range of 2 m (tidal amplitude at the inlet ranges from 0.6 m in neap tides to 3.2 m in spring tides) (Dias *et al.*, 2000).

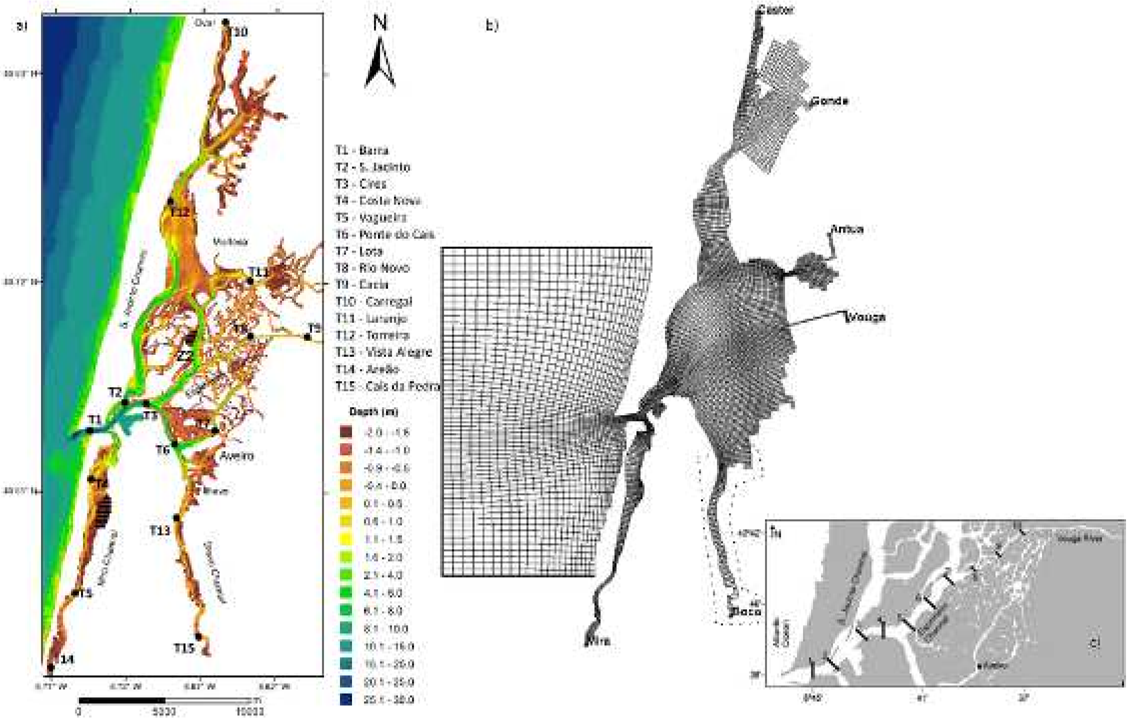


Fig. 1.1. (a) Study area, bathymetry and stations used in the calibration of the tide; (b) numerical grid, discharge locations and open boundary (thick line), area modified after calibration (dashed line); (c) stations used in the calibration of heat and salt according to Vaz and Dias (2008). Adapted from Lencart e Silva *et al*. (2013).

The total fluvial discharge into the lagoon during a tidal cycle is about 1.8×10^6 m^3, while the tidal prism is 137×10^6 m^3 for maximum spring tide, and 35×10^6 m^3 for minimum neap tide (Dias *et al.*, 2000). Due to the combined effects of the freshwater discharge and tidal propagation, the central area of the Ria de Aveiro exhibits a longitudinal salinity gradient from about 0 in the upper reaches of the Espinheiro channel to about 36 at the bar entrance (e.g. Vaz and Dias, 2008). The tide dominates as the main transport mechanism for the better part of the

hydrological cycle. However, due to the characteristics of part of the catchment draining into the lagoon, after strong rainfall events, the rivers can increase their flow by 2 orders of magnitude and the lagoon is flooded with freshwater, with estuarine circulation assuming a greater influence in the transport of dissolved and suspended substances, mainly at the head of the channels (Vaz *et al.*, 2012). The average depth of the lagoon relative to chart datum is about 1 m, except in the navigation channels where dredging operations are frequently carried out. Due to the shallowness and to the tidal wave amplitude, the intertidal area is a significant part of the total area being studied.

The model used for hydrodynamics and transport modelling, Delft3D-Flow, is a three-dimensional, finite difference hydrodynamic and transport model which simulates flow and transport resulting from tidal and meteorological forcing. In the present application, the hydrodynamic model solves the Navier-Stokes shallow water equations with hydrostatic, Boussinesq and f-plane approximations (Delft3D-FLOW, 2010; Lesser et al., 2004). Delft3D-Flow uses a horizontal Arakawa-C grid with control volumes, and for most applications an Alternating Direction Implicit (ADI) integration method. The Delft3D-Flow platform has been used previously in estuarine conditions under mesotidal forcing in, e.g., Tomales Bay, California (Harcourt-Baldwin and Diedericks, 2006).

A Cartesian, curvilinear orthogonal grid was designed to represent the main hydrodynamic features of the lagoon with the minimum number of calculation points. An offshore zone was set to allow for the dissipation of spurious open boundary effects before reaching the mouth of the lagoon. The original grid has 267 by 164 cells, calculating the solution at 9828 points. An open boundary at the shelf was defined for the segments represented in Fig. 1.1b. The curvilinear properties of the grid allow a ~30 m resolution in narrow tidal channels and a ~700 m resolution at the offshore open boundary. A 2-dimensional depth-averaged approximation was made, given that the Ria de Aveiro is mostly a vertically well-mixed system (Vaz and Dias, 2008). During the calibration process a 3-dimensional setup was tested. For more details please see LAGOONS (2012).

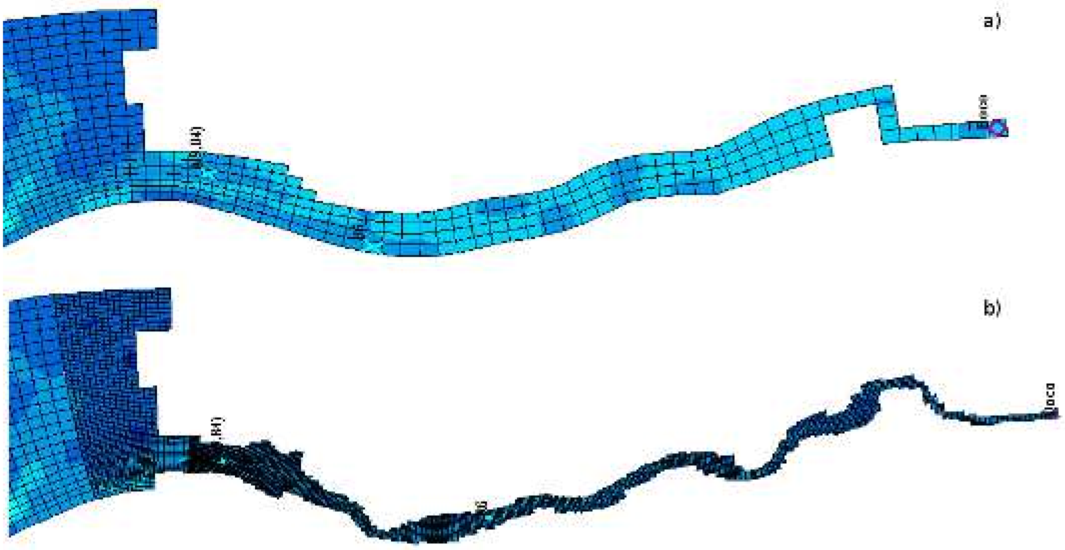


Fig. 1.2. Computational grid detail of the Ílhavo Channel: (a) original single domain (detail from Fig. 1.1b); (b) decomposed domain with corrected channel morphology.

During the calibration stage of the water quality model, significantly low values for river-borne variables prompt for a revaluation of the hydrodynamic grid and bathymetry. The original depth soundings for the Ílhavo Channel were found to be defective, and a new grid had to be drawn to allow the accurate representation of the valid bathymetric dataset. The fine resolution of the bathymetric data and the narrow morphology of the channel could be better represented with a domain decomposition strategy, where different resolutions coexist in 6 domains, exchanging information in two ways between the coarser and finer domains. Fig. 1.2 shows a detail of the redesigned area, comparing the original design presented in Fig. 1.1 and the final design (Fig. 1.2b). The resolution of the original grid is approximately ten times coarser than the new domain at its finest resolution.

All hydrodynamic runs start from a still, unperturbed water surface and constant salinity and temperature. From this cold start, the model is spun for 4 summer months (June to October). This initial time interval is always considered invalid in terms of results and only after the 1st of October are the results analysed.

Table 1.1. List of active processes in the Delf3D-WAQ water quality model.

Process Name	**Description**	**Process Name**	**Description**
Compos	Composition	S12TraDetN	Transport in S1-S2: detritus nitrogen
Sed_IM1	Sedimentation IM1	S12TraDetP	Transport in S1-S2: detritus phosphorus
S12TraIM1	Transport in S1-S2: IM1	SedNPOC2	Sedim. nutrients in POC2
Secchi	Secchi depth for visible-light (370-680nm)	S12TraOON	Transport in S1-S2: OON
TraSe2_IM1	Total of transport in sediment for IM1	S12TraOOP	Transport in S1-S2: OOP
NutUpt_Alg	Uptake of nutrients by growth of algae	S12TraDiat	Transport in S1-S2: Diatoms
Nitrif_NH4	Nitrification of ammonium	ResN_DiaS1	Resuspension nutrients in detritus
RearOXY	Reaeration of oxygen	Phy_dyn	Computation of phytoplankton – Dynamo
BMS1_DetC	Mineralisation detritus carbon in sediment S1	CalVS_IM1	Sedimentation velocity IM1 = f (Temp SS Sal)
BMS1_OOC	Mineralisation other organic C in sediment S1	CalTau	Calculation of bottom friction
GroMrt_Gre	Nett primary production and mortality green algae	DynDepth	dynamic calculation of the depth
PPrLim	Limitation (numerical) on primary production	S1_Comp	Composition sediment layer S1
CONSBL	Grazing module	Res_DM	Resuspension total bottom material (dry mass)
PosOXY	Positive oxygen concentration	Extinc_VLG	Extinction of visible-light (370-680nm) DLWQ-G
BMS1_DetN	Mineralisation detritus nitrogen in sediment S1	Emersion	handle emersion z layers
BMS1_OON	Mineralisation other organic N in sediment S1	AdvTra	Advective transport of solids in sediment
DecFast	Mineralization fast decomp. detritus POC1	SaturOXY	Saturation concentration oxygen
DecMedium	Mineralization medium decomp. detritus POC2	TotDepth	depth water column

DecSlow	Mineralization slow decomp. detritus POC3	DL_Green	Daylength function for green algae
DecRefr	Mineralization part. refractory detritus POC4	NLGreen	Nutrient limiation function for green algae
NutRel_Alg	Release (nutrients/detritus) by of mortality algae	Rad_Green	Light efficiency function green algae
NRAlg_S1	Nutrient release of algae in S1	TF_Green	Temperature functions for green algae
BMS1_DetP	Mineralisation detritus phosphorus in sediment S1	CalVS_POC2	Sedimentation velocity POC2 = f (Temp SS Sal)
BMS1_OOP	Mineralisation other organic P in sediment S1	CalVS_POC1	Sedimentation velocity POC1 = f (Temp SS Sal)
Sed_POC2	Sedimentation POC2 3d	S2_Comp	Composition sediment S2
S12TraOOC	Transport in S1-S2: OOC	ExtPhDVL	Extinction of visual light by algae (Dynamo)
Sed_POC1	Sedimentation POC1 3d	DMVolume	Volume of dry matter in a segment
S12TraDetC	Transport in S1-S2: detritus carbon	Daylength	Daylength calculation
SedNPOC1	Sedim. nutrients in POC1	CalcRad	Radiation at segment upper and lower boundaries

The model used for water quality modelling, Delft3D-WAQ (Deltares, 2013), solves the advection-diffusion-reaction equations to calculate the space and time variation of biogeochemical and water quality state variables and derived quantities. Table 1.1 shows the list of the processes implemented in this version of the WAQ model.

For the water quality model, spin-up interval of 12 months (October to October) starts from uniform ocean conditions in the water column and using a spatially varying distribution of inorganic and organic particulate matter. Exceptions to this are the quantities calculated by the hydrodynamic model (water levels, velocities, shear stress, salinity and temperature) which are read from the corresponding valid record of the hydrodynamic run.

All calibration and validation runs were forced at the catchment boundary using modelled water quantity and quality.runs were forced at the catchment boundary using modelled water quantity and quality.

2. Data overview and analysis

From among the three stations available, T1 (Fig. 1.1a) is the one which best represents the majority of the volume of the lagoon. Despite its exposure to oceanic conditions, the tidal excursion of the order of 10 km allows the majority of the volume to be advected pass T1 in a single tidal cycle. As for the stations T11 and T13, these two are placed deep inside the lagoon and subjected to strong influence of river-borne discharges.

2.1 Climate data

For the calibration interval between the years 2002 and 2004, time series of wind speed, air temperature and relative humidity from a local weather station (Fig. 1.1a) and radiation from the NCEP reanalysis (Kalnay et al., 1996) were prescribed for the atmospheric boundary.

Hourly weather for the local station for the full validation period of 1999-2001 was not available. Hence, all of the parameters used for the atmospheric data were taken from NCEP reanalysis.

Fig. 2.1 shows the distribution of the wind series for both the calibration and validation runs. From the comparison of the two, the more synoptic character of the NCEP data is evident, where a northerly predominance is present with strong storm winds from the SW. The calibration data reflects better the local wind directions and breeze system characteristic of the weather in the lagoon.

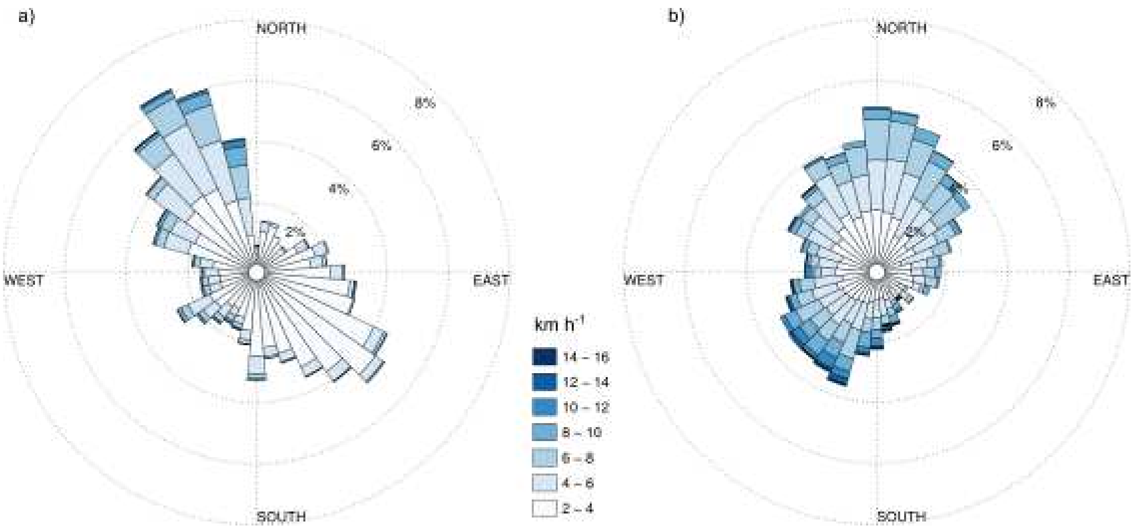


Fig. 2.1. Wind distribution for calibration (a) and validation (b) runs.

2.2 Hydrological data

The input of freshwater volume, temperature, dissolved oxygen and loads of NO_3, NH_4, PO_4 were taken from the SWIM model for both the final calibration and validation runs, due to the unavailability of useful measured data for the interfaces between the lagoon and the catchment. Figures 2.2 and 2.3 show the concentrations used as inputs calculated from flow and loads with a flow cut-off at values < 0.01 m^3s^{-1}. From the six entry points, the Vouga, Antuã and Mira Rivers transport more than 80% of the loads into the bay. Most of the sources have a load peak at the beginning of winter which tails off during the year despite some peaks in concentration due to very low flows. An exception to this is the Antuã River which has a much flatter load curve, with consistent rise in concentration during the year for both nitrogen and phosphorous loads.

For the tidal calibration a set of 15 tide gauge stations (Fig. 1.1a) were used, where time series of SSE were available for at least 30-days-long periods, measured from 2002 to 2004 (Araújo, 2005).

For the calibration of heat and salt, a dataset was needed which represented the full temperature and salinity gradients, with good spatial resolution and a temporal resolution capable of reproducing the annual cycle. The transect sampled by Vaz and Dias (2008) crosses the lagoon, spanning most of its conditions and receiving the outflow of all of the other channels, thus making a good proxy for the temperature and salinity conditions inside the lagoon and fulfilling the conditions needed for the calibration dataset. The observations were made at a set of 32 stations along 10 sections of the Espinheiro Channel (Fig. 1.1c). These observations were compared against the water temperature and salinity model predictions. In their work, this transect was sampled fortnightly from September 2003 to September 2004, from the inlet to the mouth of the Vouga, the main river discharging into the lagoon.

The validation set for salinity and temperature belongs to the same observation program, where water quality validation data was gathered (Cunha Duarte *et al.*, 2002). This dataset was collected at stations T1, T11 and T13 fortnightly between 04/12/2000 and 21/11/2001 at low water and high water. There are several problems connected with this dataset: (i) the spatial resolution is very coarse; (ii) the values were all gathered at or near slack water, and most frequently near neap tide when dynamic conditions were particularly weak; (iii) the data was collected only at the surface; and most importantly (iv) this hydrological year experienced the heaviest rainfall of the recent decades. The points (ii) to (iv) will lead to bias in the observations under strong freshwater flow, thus overestimating river-borne substances, due to the likelihood of sampling under stratified conditions only a small fraction of the water column.

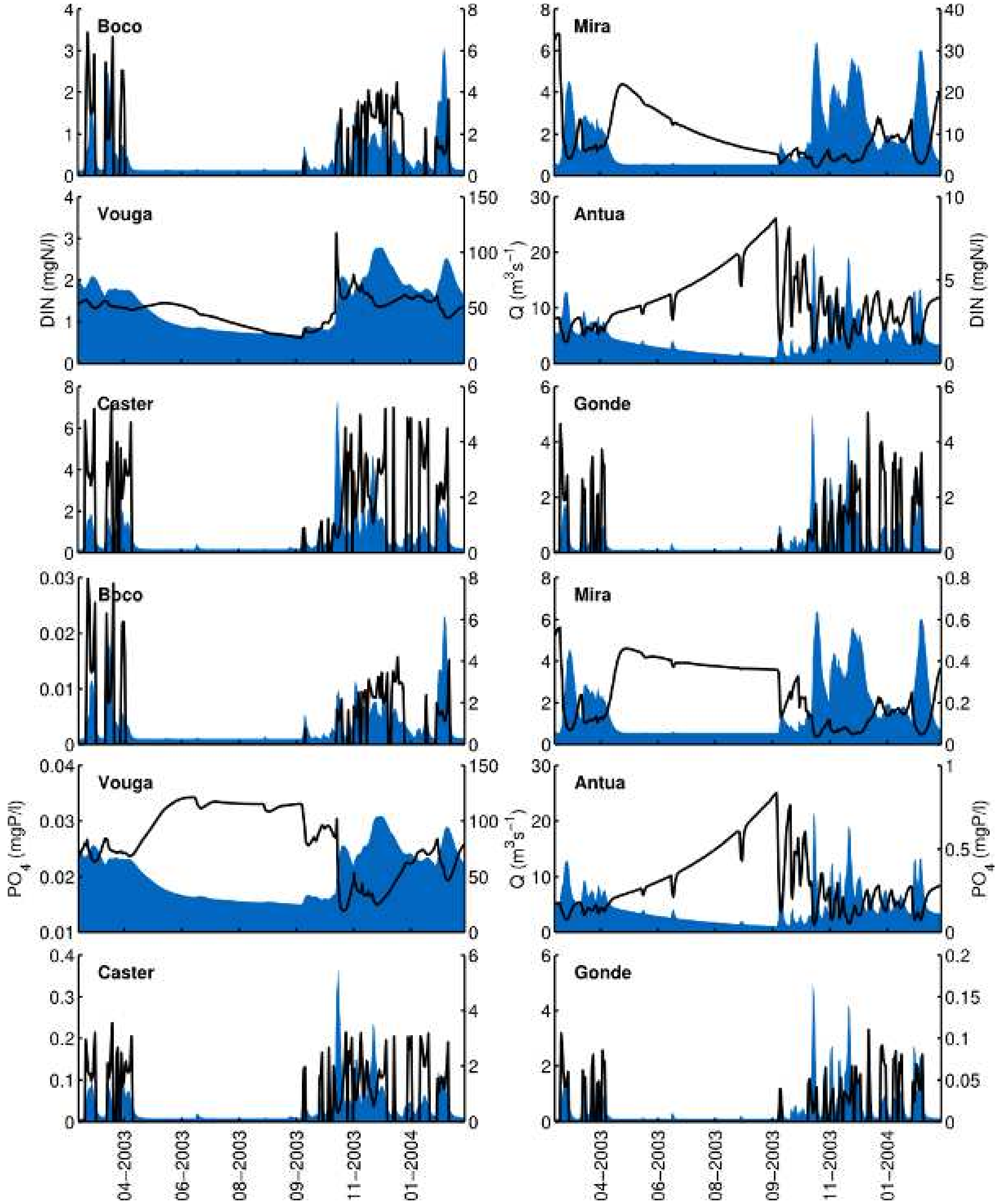


Fig. 2.2. Calibration run inputs from the SWIM model. Freshwater flows (blue area) and concentrations DIN and PO_4 (black line) for all of the entry points in the lagoon model used in the calibration run.

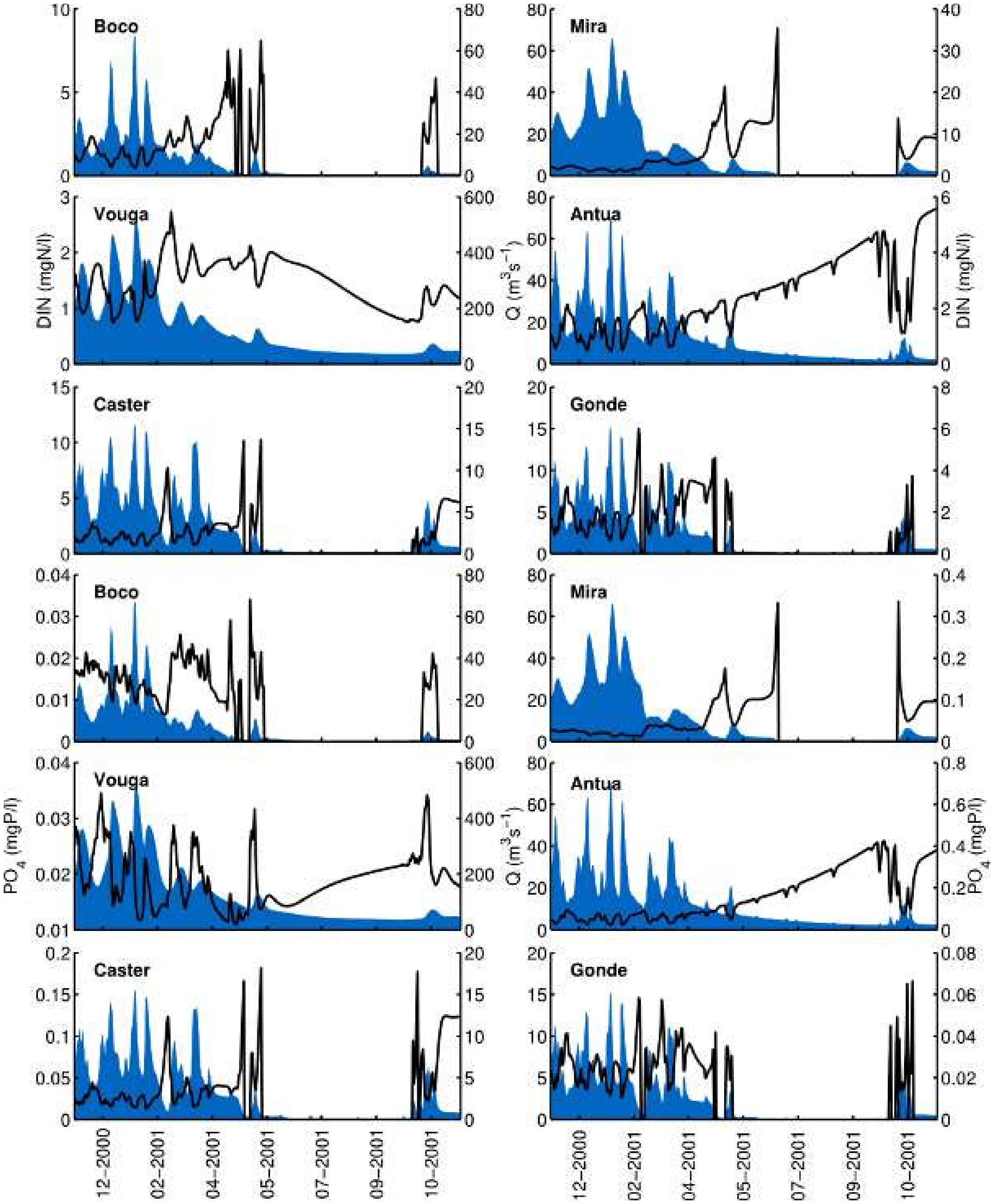


Fig. 2.3. Validation run inputs from the SWIM model. Freshwater flows (blue area) and concentrations DIN and PO_4 (black line) for all of the entry points in the lagoon model used in the validation run.

2.3 Ecological data

The dataset used to generate the initial sediment distribution was taken from the surveys in Rodrigues *et al.* (2011) in which the authors give an account of the relative fraction of fines, sand and coarse grain sediment.

The dataset used in the calibration of water quality parameters was gathered by Cunha Duarte *et al.* (2004). Due to the paramount importance of establishing the fitness of the annual cycle, from the dataset only the stations with monthly or better resolution were used. The stations T1, T11 and T13 were sampled monthly during low and high tide at the surface. The calibration parameters consistently sampled were NH_4, NO_3, PO_4, chlorophyll a, and Total Suspended Solids (TSS) between 07/03/2003 and 17/02/2004. For the validation dataset, the same parameters, with the exception of TSS, were sampled fortnightly for the dates between 04/12/2000 and 21/11/2001 (Cunha Duarte *et al.*, 2002).

Similarly to the salinity and temperature validation dataset, the water quality calibration and validation datasets present the same shortcomings. In both the calibration and the validation dataset, NH_4 and PO_4 were under the detection limit for the measurements at T1, with exception of 2 points. These were 0.007 mgNl-1 for NH4 and 0.0077 mgPl-1 for PO4 for the calibration dataset. For the validation dataset the detection limits were 0.0280 mgNl-1 for NH4 and 0.0155 mgPl-1 for PO4 (Cunha Duarte et al. 2002; 2004).

3. Hydrodynamic model calibration and validation

3.1 Calibration methodology and results

The calibration of the hydrodynamic model was performed in two steps: (i) the adjustment of the parameters governing the response to tidal and wind forcing, and (ii) the adjustment of the parameters controlling the salinity and temperature.

The forcing of the tide was prescribed by imposing 19 harmonic constituents at the boundary, calculated from a 366 day record where water level was sampled at the mouth of the lagoon each 6 min between 31/12/2002 and 31/12/2003 (Vaz et al., 2005). Their phases were changed to account for the distance between the lagoon's mouth and the offshore boundary, and the amplitude adjusted to reflect the depth gradient between the boundary and the mouth of the lagoon.

A set of runs with the duration of 90 days was performed, forcing only the tide at the boundary and comparing the model predictions against the tide calibration dataset. The original uniform bottom roughness was adjusted according to the fitness of the shallow water harmonic constituents. In its final form, bottom roughness was prescribed using a spatially-varying Manning coefficient as a truncated function of depth (Picado et al., 2010). The bathymetry was corrected locally, where the interpolation method misrepresented the finer scale surveys.

After these corrections, the representation of the tidal response by the model showed an excellent to very good fit at most stations (skill > 0.95 and RMSE < 0.2 m), with less impressive performance on isolated inner meandering regions. Figure 2.1 shows the comparison between model predictions and observations for the main diurnal, semi-diurnal and shallow water harmonic constituents. The model performs with excellent agreement at most stations when representing semi-diurnal tide (85% of the variance), and a good agreement at most stations when representing diurnal tide (7% of the variance). Exceptions to this are the results for the stations closer to the head of the channels. This can be attributed to (i) the resolution of the numerical grid in these regions; and (ii) the quality of the observation data there with shorter time series and less than perfect sampling (Araújo, 2005). The poor agreement of the quarter-diurnal (5% of the variance) is caused by the uncertainty in describing the profile of the intertidal flats due to the absence of detailed up-to-date topographic surveys there.

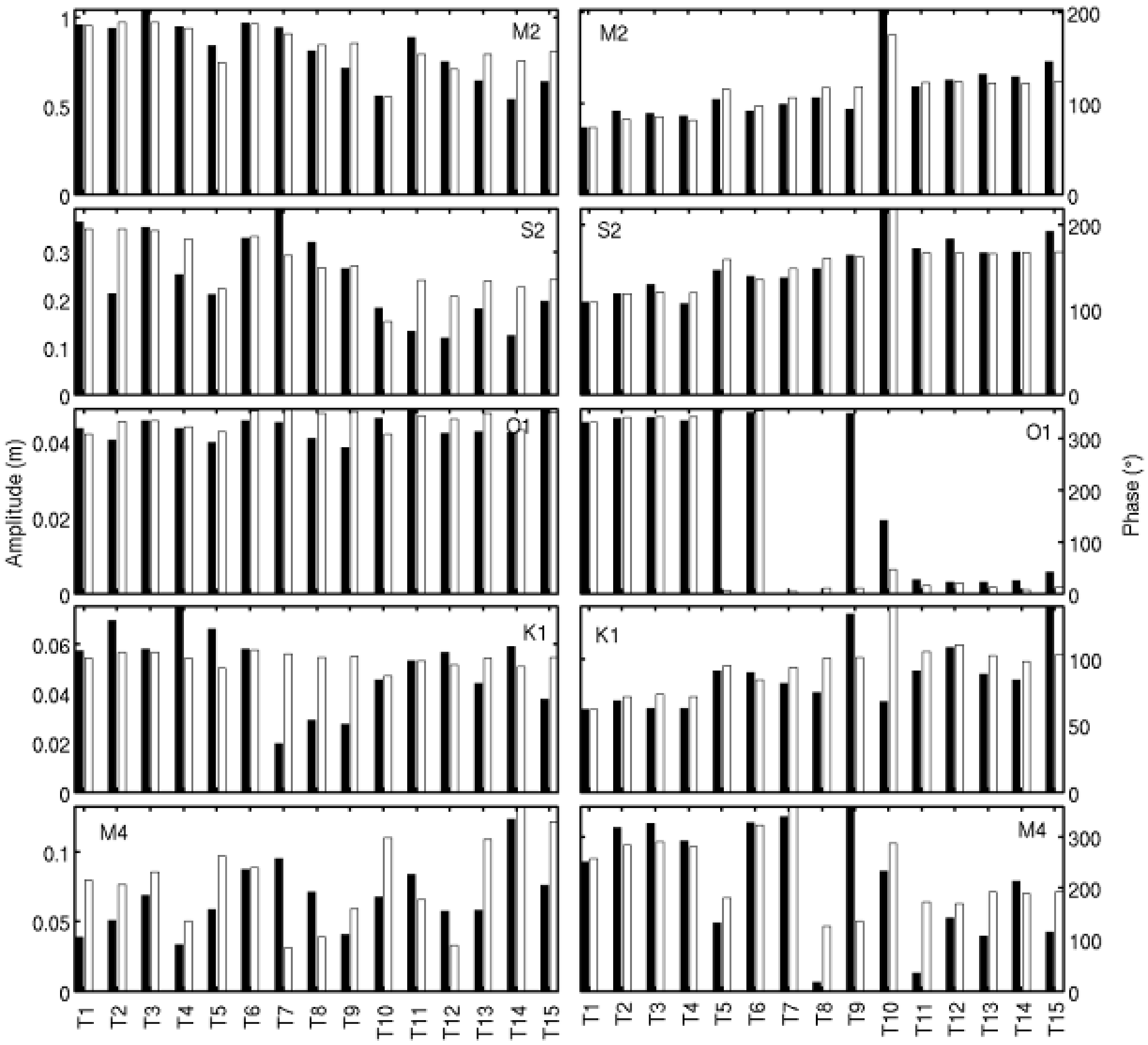


Fig. 3.1. Hydrodynamic model calibration results: (a) harmonic comparison for 15 tidal stations (black – observed, white – modelled).

The calibration of salinity and water temperature was performed by testing the model response to ocean boundary conditions, horizontal diffusion and vertical resolution. Hence, in one configuration, boundary conditions for salinity (36) and temperature (15 ºC) were kept constant for the duration of the run (runs CA7 to CD7 of Table 3.1), and in another configuration, a time-varying vertical profile of the HYCOM model (Cummings, 2005) was forced at the ocean boundary (runs CE7 to CJ7). Values of 1, 10 and 100 $m^2 s^{-1}$ were used for horizontal diffusion in order to test the model's parameterization of the sub-grid transport processes. Although Ria de Aveiro is considered a vertically mixed system for most of the time, there are records of transient vertical stratification due to freshwater input. In order to test the validity of the 2-dimentional assumption, a set of runs were performed, where 10 uniformly-spaced σ-layers were used. The response of the model to different catchment conditions was tested using a legacy dataset produced with the SWAT model (Soil and Water Assessment Tool, Neitsch *et al.*, 2011), and the LAGOONS WP5 results from the SWIM model.

Table 3.1. Specification of changed parameters for salt and heat calibration runs.

Run ID	Watershed Model	T Ocean	S Ocean	Dim	Kxy (ms^2)	Notes
CA7	SWAT	15	36	2D	10	
CB7	SWIM	15	36	2D	10	
CC7	SWAT	15	36	2D	100	
CD7	SWAT	15	36	2D	1	
CE7	SWAT	HYCOM	HYCOM	2D	10	
CF7	SWIM	HYCOM	HYCOM	2D	10	
CG7	SWAT	HYCOM	HYCOM	3D	10	
CH7	SWIM	HYCOM	HYCOM	3D	10	
CI7	SWAT	HYCOM	HYCOM	2D	10	Insulated Espinheiro
CJ7	SWIM	HYCOM	HYCOM	2D	10	Insulated Espinheiro

Results using a constant ocean boundary for water temperature and salinity were encouraging, with salinity and temperature following the observed annual cycle. However, a point to point analysis shows that there were significant departures from the observation. The examples showed in Fig. 3.2 highlight the consequences of using an invariable ocean boundary for temperature, and the significant improvements gain with the addition of the HYCOM series.

Changing to time-varying boundary conditions for salinity and temperature produced small improvements in the fitness of the salinity results, due to the inability to reproduce the low salinities at the upper reaches. This was significantly improved when a no-flow-through condition was imposed on the channel walls in the upper reaches of Espinheiro Channel. No significant gains were obtained using a 3-dimensional configuration.

The mean spatial and seasonal skill and RMSE were calculated for temperature and salinity. The seasonal estimator calculates the mean of the skills and RMSE for each section surveyed, thus establishing a system-wide seasonal fitness of the model. The spatial estimator calculates the mean of the skills and RMSE for each date surveyed, thus establishing a system-wide spatial fitness of the model. In Fig. 3.3 these two estimators are plotted against each other giving a broad view of the results for each of the calibration options tested. Hence, this diagram supports the conclusions that: (i) the SWIM model is superior to the legacy SWAT model; (ii) the best diffusion was 10 $m^2 s^{-1}$; (iii) there was no substantial improvement in using a 3-dimentional setup; (iv) there was a significant improvement with the addition of the HYCOM model at the ocean boundary; and (v) morphologic adjustments at the head of the channel marginally improved the fitness.

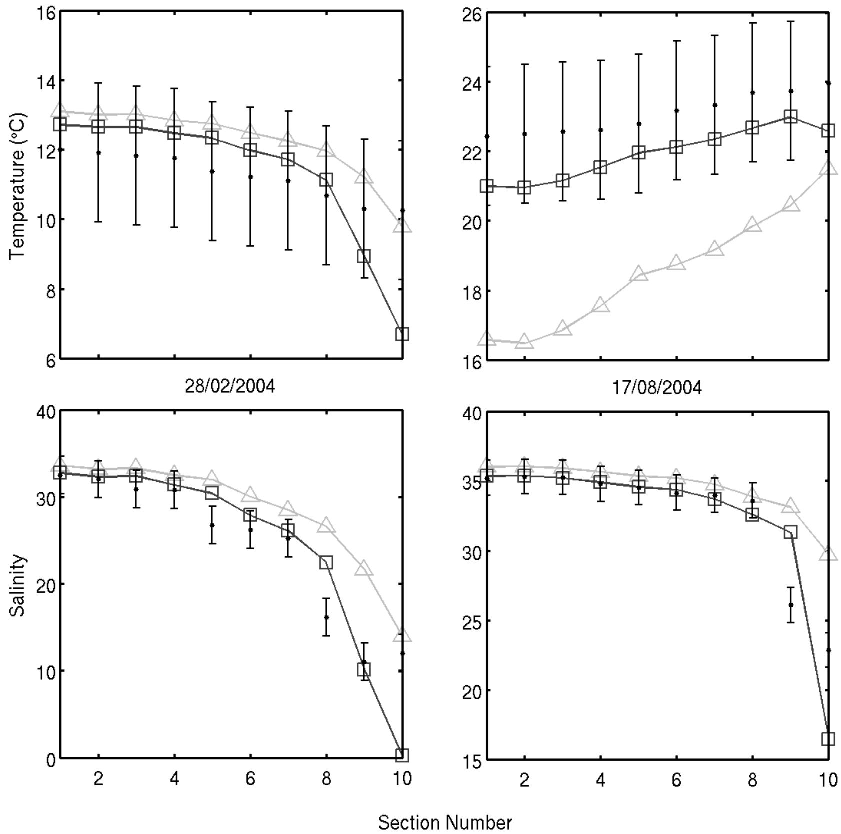


Fig. 3.2. Subset of the modelling results for the 26 surveys analysed for the Espinheiro Channel representing temperature and salinity surveys in winter and summer (observed – points and error bars, CB7 – gray line, CJ7 – black line).

Taking this into consideration, the best overall run was CJ7 which outperformed all others in skill and RMSE. This run reproduces well the seasonal cycle, with an average skill of 0.98 for temperature and 0.86 for salinity. The seasonal-averaged RMSE, bias and Mean Absolute Error (MAE) were 1.1 ºC, 0.1 ºC and 0.9 ºC for temperature, respectively. For salinity, these values were 4, 0.1 and 3. Generally, in terms of survey to survey spatial fitness of the temperature and salinity gradients, the model under-performed for temperature (skill = 0.55) and showed poor results for salinity (skill = 0.75). The poorer spatial agreement was mainly due to difficulties in

representing sections 8 – 10 (Fig. 1.1c). This is an expected result due to the uncertainty of the SWIM daily outputs. This uncertainty is felt to a greater extent nearer the river mouths, whilst farther downstream tidal dispersion acts as a low-pass filter in the time domain.

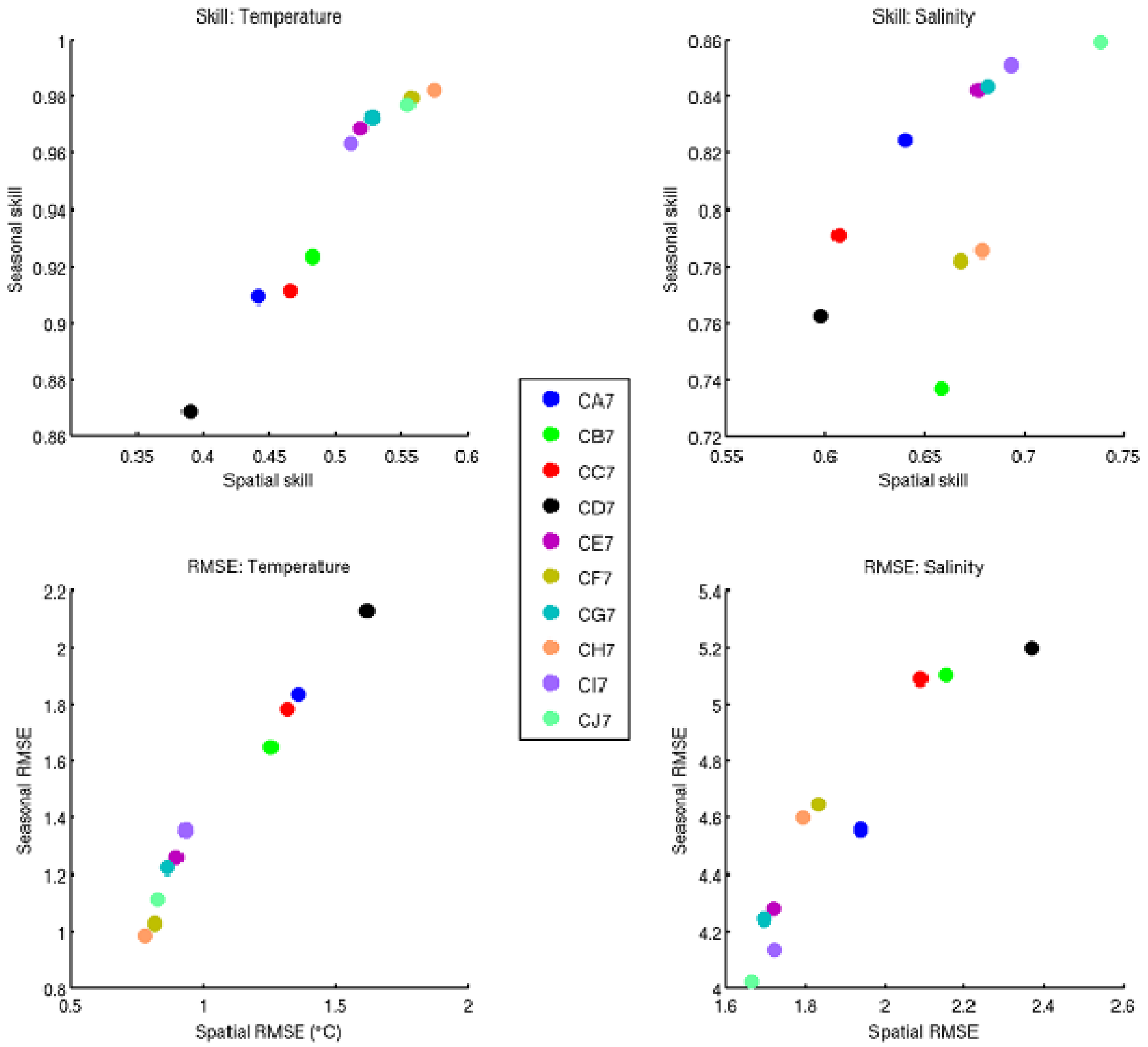


Fig. 3.3. Seasonal and spatial skills and RMSE compared at the Espinheiro Channel for all heat and salt calibration runs.

3.2 Validation methodology and results

Due to the strong tidal influence of the tide in the Ria de Aveiro, controlling more than 90 % of the variance, only a change in mean sea level, bathymetry or bottom roughness would change the character of the tidally-varying sea surface elevation and velocities. Since neither of those characteristics of the study area changed between the available observational datasets, there was no added value in analysing the tidal response of the hydrodynamic quantities for an additional time interval.

The same does not apply to temperature and salinity. Therefore, a validation run was performed for the interval between November 2000 and October 2001, and the results for salinity and temperature are shown in Fig. 3.4 for the stations T1, T11 and T13. The clear seasonal trend of salinity and temperature is reproduced by the model. However, inferior results were attained in comparison to the calibration interval. It is worthy of note that several constrains contribute to degrade the model fitness for this dataset: (i) the high spatial and time uncertainty of the dataset; and (ii) the extreme character of the rainfall during the interval analysed. This is especially relevant at station T1 during the winter of 2000-2001, where salinity values were measured only at the surface. Here the depth of the channel is ~20 m, and recorded values of 10 at the surface can only occur with a significantly stratified water column. Thus a strong bias is present in the observations, leading to their underestimation of salinity. Under such strong freshwater input, the uncertainty of the observational dataset is maximised and should be taken into consideration when comparing with a depth-averaged model.

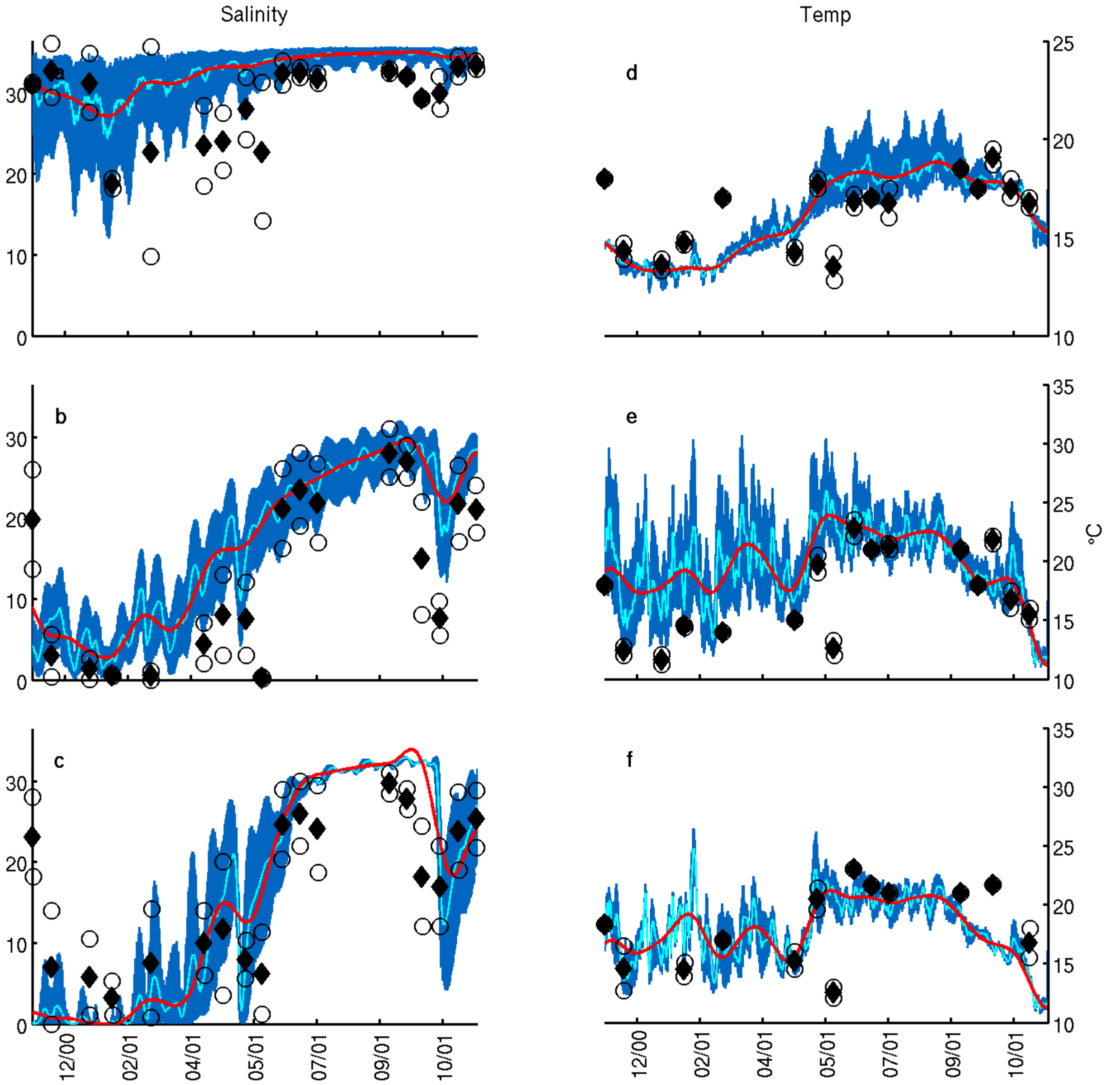


Fig. 3.4. Validation results for salinity and temperature for stations T1 (a, d), T11 (b, e) and T13 (c, f). Observations (circles and diamonds); model (blue and red lines).

4. Ecological model calibration and validation

4.1 Main calibration steps

The water quality model was calibrated in the following main steps:

1. determine initial sediment distribution, its dynamic characteristics and background optical properties of the water;
2. adjust bottom content of particulate organic matter according to the recorded values of organic fraction;
3. adjust primary consumers growth to account for phytoplankton losses by consumption;
4. load test for model over-training;
5. adjust phosphorous mineralisation rates to fine tune the mean PO_4 concentration at the head of the channels.

Due to the uncertainty of the composition of bottom sediments in the Ria de Aveiro, an initial distribution of cohesive sediments had to be extrapolated from historical data.

Using Rodrigues *et al.* (2011), a relation between maximum velocity and the fraction of fines in the erodible bottom sediment was used to build the initial distribution of fines based on the model's prediction of velocity maximum for each of the calculation points. For that, an erodible 0.05 m layer was assumed, and cohesive sediment thickness calculated based on the fraction predicted by the relation in Fig. 4.1.

To test the characteristics of the sediment, the erosion and deposition critical shear stresses were varied according to Table 4.1, assuming a moderate sedimentation speed of 0.5×10^{-3} ms^{-1}. The results of the final distribution after a 15-day run with no sediment input are plotted against the velocity maximum for each point of the domain and the regression lines compared with the linear model used to generate the initial condition.

Due to the inability of the SWIM catchment model to produce solid load results for this region, there was a need to infer these values in order to maintain the lagoon's sediment budget. Following Lencart e Silva *et al.* (2013), the solid load (Q_s) entering from the catchment was prescribed as a value predicted from a relationship between historical river flow and total suspended solids (TSS):

$$Qs = \alpha Q_m^{\beta} ,$$

where Q_m is the flow from the SWIM model, $\alpha = 9.327$ and $\beta = 1.063$.

To account for stabilisation of the sediment distribution within a full hydrological cycle, the initial sediment distribution fed into the water quality model was taken after a 18 months simulation of sediment transport using Delft3D-FLOW.

Table 4.1. Erosion τ_{ce} and deposition τ_{cd} critical shear stress for sediment calibration runs.

τ_{ce}	τ_{cd} (Nm^{-2})	0.30	0.45	0.60
0.075		A	D	G
0.150		B	E	H
0.300		C	F	I

The fraction of POM in the sediment was prescribed as the mean of the values observed in the calibration dataset. Distribution of POM by carbon, nitrogen and phosphorus fraction was prescribed according to the WAQ model default stoichiometric mass constants of C:N:P of 1:0.2:0.02.

The primary consumer seasonal curves and density were adapted from França *et al.* (2009) work in the Tagus estuary. These curves were fed into the model as forcing functions and undergo a 9-step iterative process to reproduce the grazing activity of zooplankton and benthic invertebrates (Deltares, 2013):

1. conversion of the biomass forcing function input to the desired units;
2. adjustment (if necessary) of the imposed grazer biomass according to growth and mortality constraints;
3. calculation of the consumption rates for detritus and algae;
4. calculation of the rates of food assimilation and detritus production;
5. correction of the assimilation rates for respiration;
6. adjustment of the grazer biomass;
7. calculation of the detritus production rates according to the food availability constraints;
8. evaluation of the total conversion rates as additional output parameters; and
9. evaluation of the grazer biomass concentrations as additional output parameters.

A load test was performed to test the model's response to very different forcing conditions by increasing the input of the catchment loads to extreme values. The model responded by outputting a proportional increase in the values of variables inside the lagoon, thus showing that the calibration did not over-parameterise the model, preventing it from responding to extreme forcing.

In order to fit better the mean PO_4 concentration at the head of the channels, the target rate for the mineralization of organic phosphorous at 20 °C was set at 0.08 day^{-1}.

4.2 Calibration methodology and results

In Fig. 4.1 the results from the testing of critical shear stresses for erosion and deposition detailed in Table 4.1 are compared to the Rodrigues *et al*. (2011) surveys (Fig. 4.1, dashed line). The scenario I of Table 4.1 shows that the closest fit is for the maximum of both critical shear stresses, representing the sediment with least mobility.

Fig. 4.2 to Fig. 4.4 show the results for 3 stages of the calibration for the available observed parameters: (i) the left column shows results prior to grid correction and adjustment of the nitrification rate and resuspension of POM; (ii) the middle column shows results after grid correction and prior to the adjustment of the nitrification rate and resuspension of POM; (iii) the right column shows results after grid correction and adjustment of the nitrification rate and resuspension of POM.

The results show that the model represents broadly the seasonal cycle and range of each of the variables analysed. A clear deficit of salinity, DIN and PO_4 is visible in the first column for the Ílhavo Channel for the results before the refining of the grid (Fig. 4.2 panels g), indicating a dilution of the river water in the misrepresented morphology. After the correction of the channel's volume, the dilution effect was successfully eliminated. A choice was made to adjust the mineralization rate of particulate organic phosphorous (POP) to fit the available PO_4 at the area affected by Antuã river, given that this is a larger contributor to the lagoon in comparison to the Ílhavo channel (Fig. 3.2, 2nd and 3rd columns).

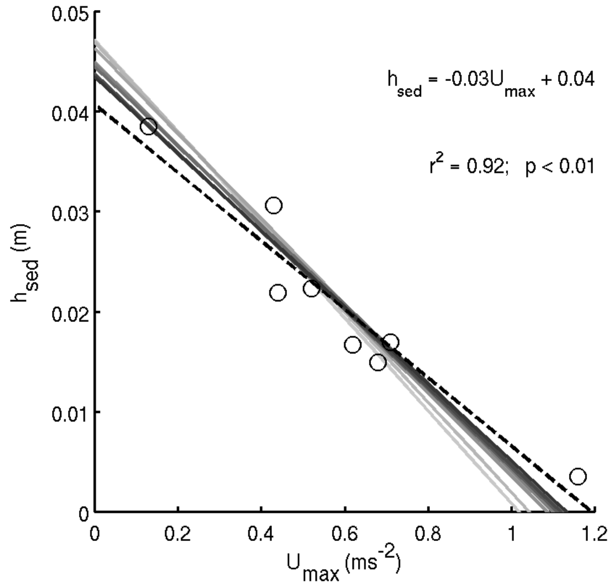
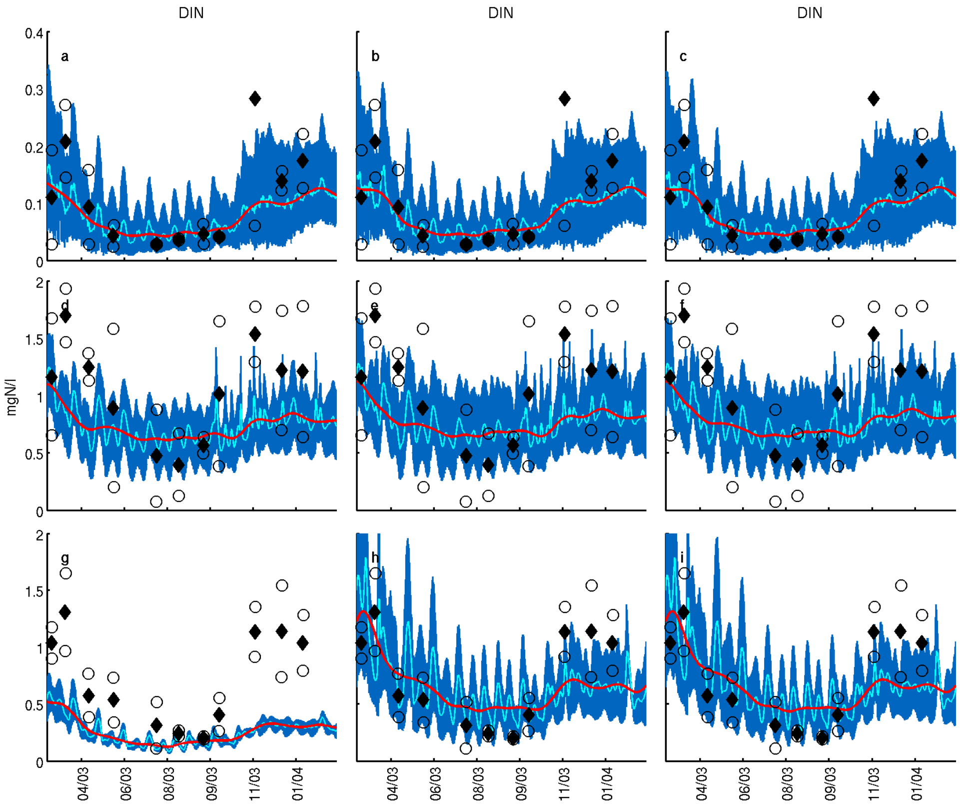


Fig. 4.1. Relation between local velocity maxima and local cohesive sediment thickness at the bed. Circles and dashed line: results and regression model from Rodrigues et al. 2011; gray lines from light to dark: runs A to I of Table 4.1. Adapted from Lencart e Silva *et al*. (2013).

Overall, after these adjustments, the nutrients in the lagoon are in range and phase with the observations. Exceptions to these are: (i) the last winter peak in nitrogen is present but underestimated; (ii) station T11 in the Laranjo area is underestimating the results for nitrogen and this deficit cannot be accounted by the fractions produced inside the model.

Regarding primary production, the model behaves well overall with a tendency to overestimate the first peak of chlorophyll in the inner-most stations. However, the most significant station, T1, shows a very good annual correlation and amplitude. With regard to TSS, there is a significant uncertainty given that the observations were mainly performed under weak mixing conditions. The model seems to agree in such conditions, but the range of variation within the semidiurnal and spring-neaps cycle is unknown. However, given the good results achieved with primary production, this setup seems to reproduce proficiently the light climate in the water column.



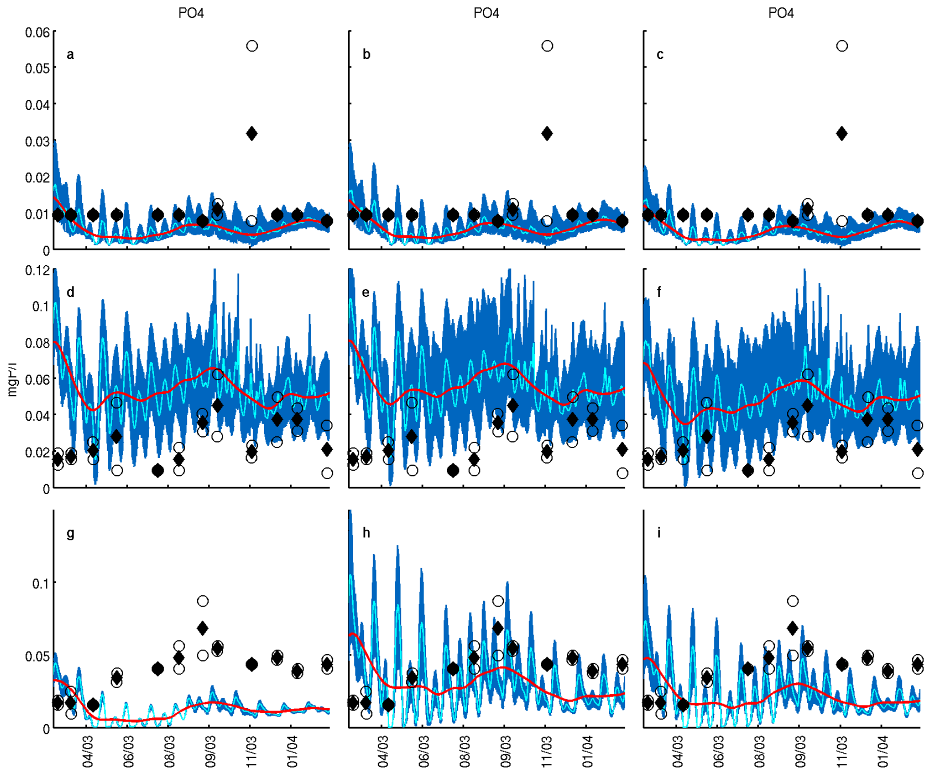
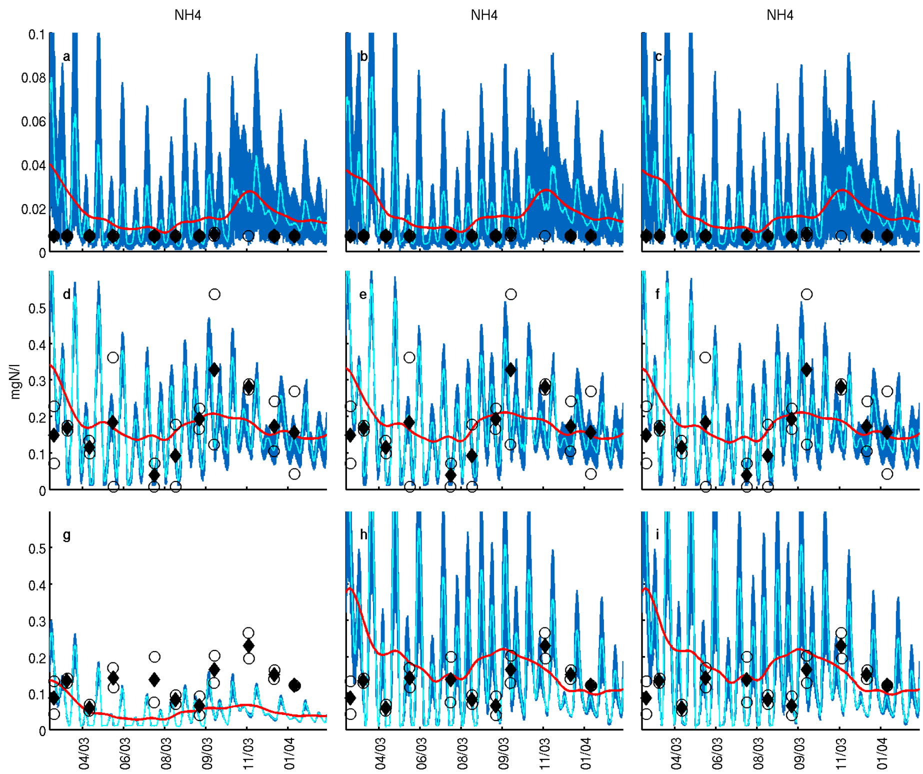


Fig. 4.2. Calibration results for DIN and PO_4 for stations T1 (a, b, c), T11 (d, e, f) and T13 (g, h, i). 1st column: no adjustments; 2nd column: morphological adjustments of the Ílhavo Channel; 3rd column: morphological, POP mineralization rate adjustment. Observations (circles and diamonds); model (blue and red lines).



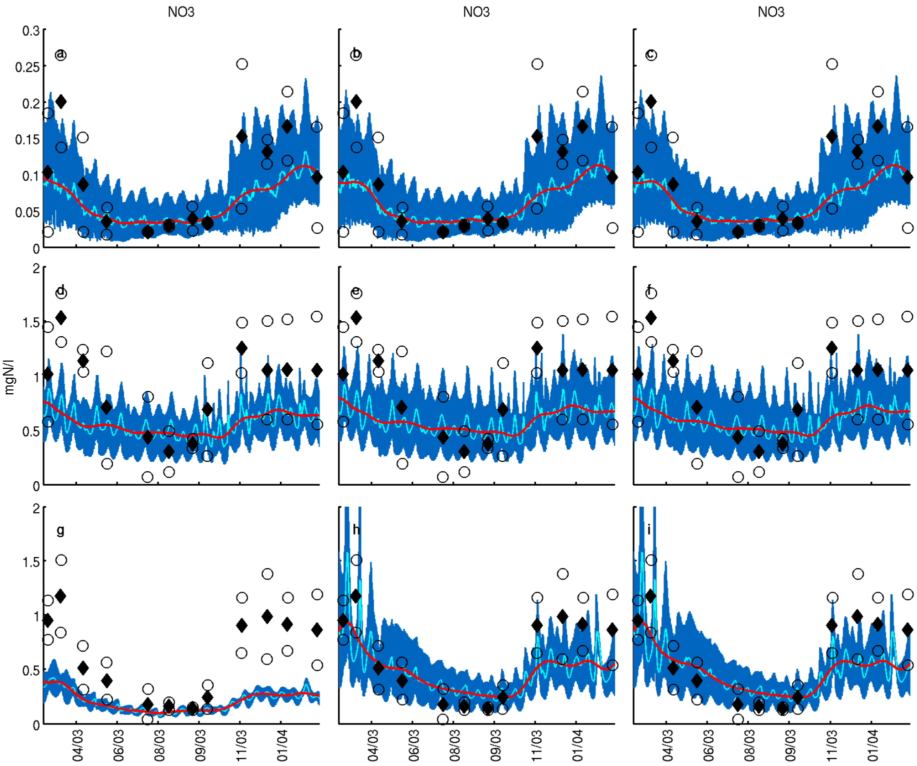
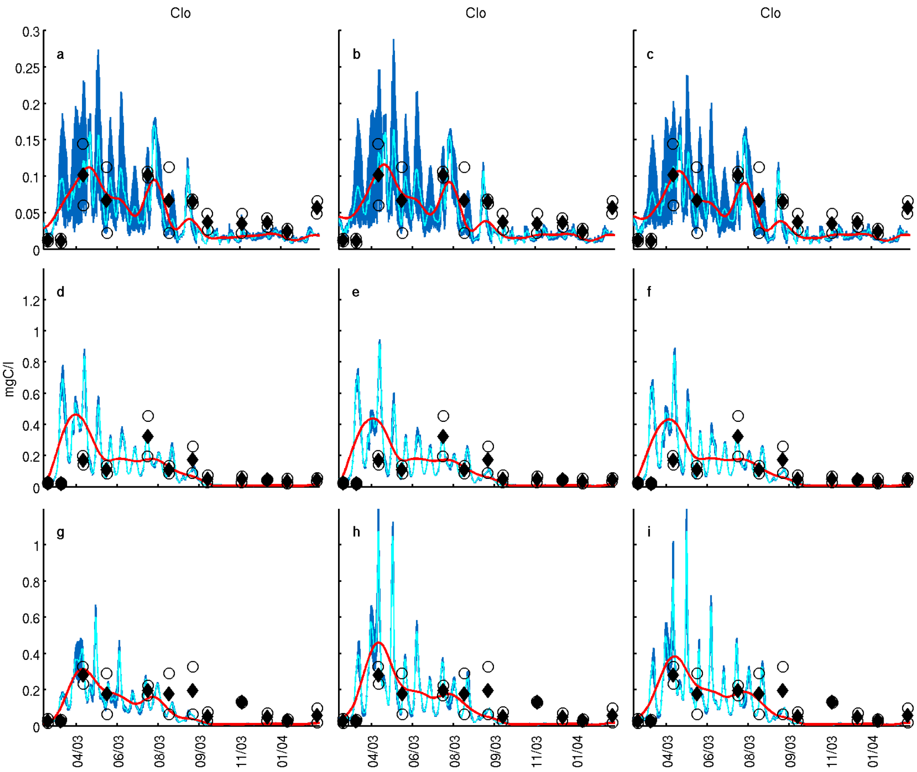


Fig. 4.3. Calibration results for NH_4 and NO_3 for stations T1 (a, b, c), T11 (d, e, f) and T13 (g, h, i). 1st column: no adjustments; 2nd column: morphological adjustments of the Ílhavo Channel; 3rd column: morphological, POP mineralization rate adjustment. Observations (circles and diamonds); model (blue and red lines).



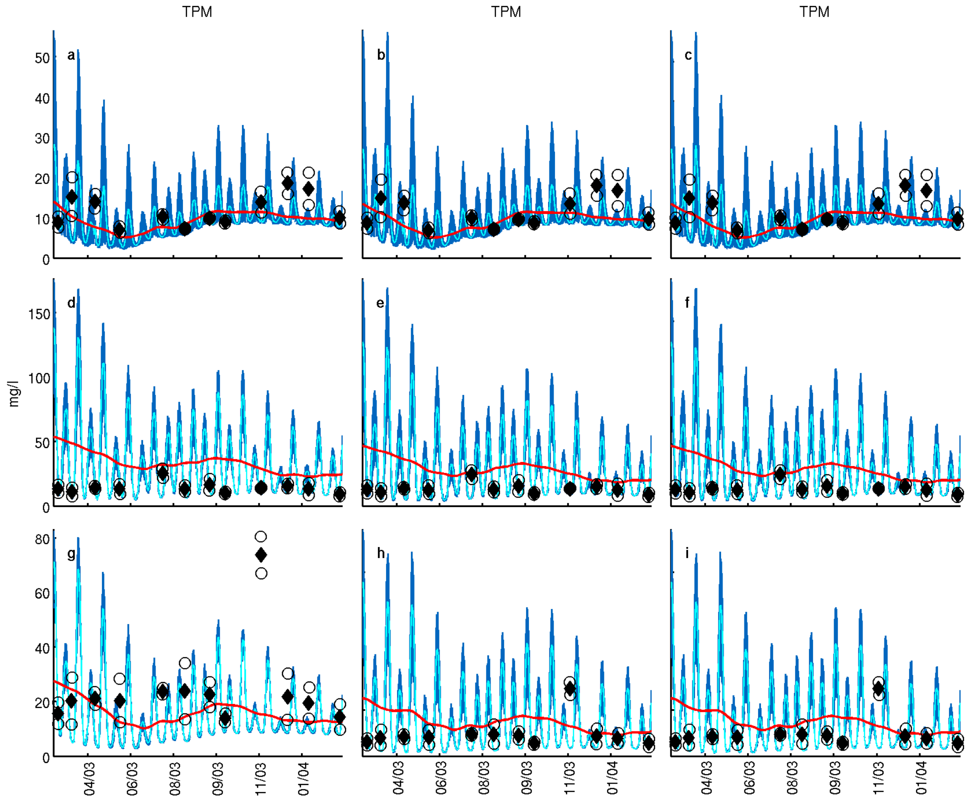


Fig. 4.4. Calibration results for chlorophyll a and TSS for stations T1 (a, b, c), T11 (d, e, f) and T13 (g, h, i). 1st column: no adjustments; 2nd column: morphological adjustments of the Ílhavo Channel; 3rd column: morphological, POP mineralization rate adjustment. Observations (circles and diamonds); model (blue and red lines).

4.3 Validation methodology and results

Fig. 4.5 shows that the dynamic range and seasonal cycle of DIN at T1 has a good fit for the validation results, with exception to the large peak values during the spring of 2001. The absence of peak values between December 2000 and April 2001 is more pronounced at the head of the channels at T11 and T13 for both DIN and PO_4, implying that the loads from the Vouga seem to compensate this absence despite the Antuã and the Boco load underestimation.

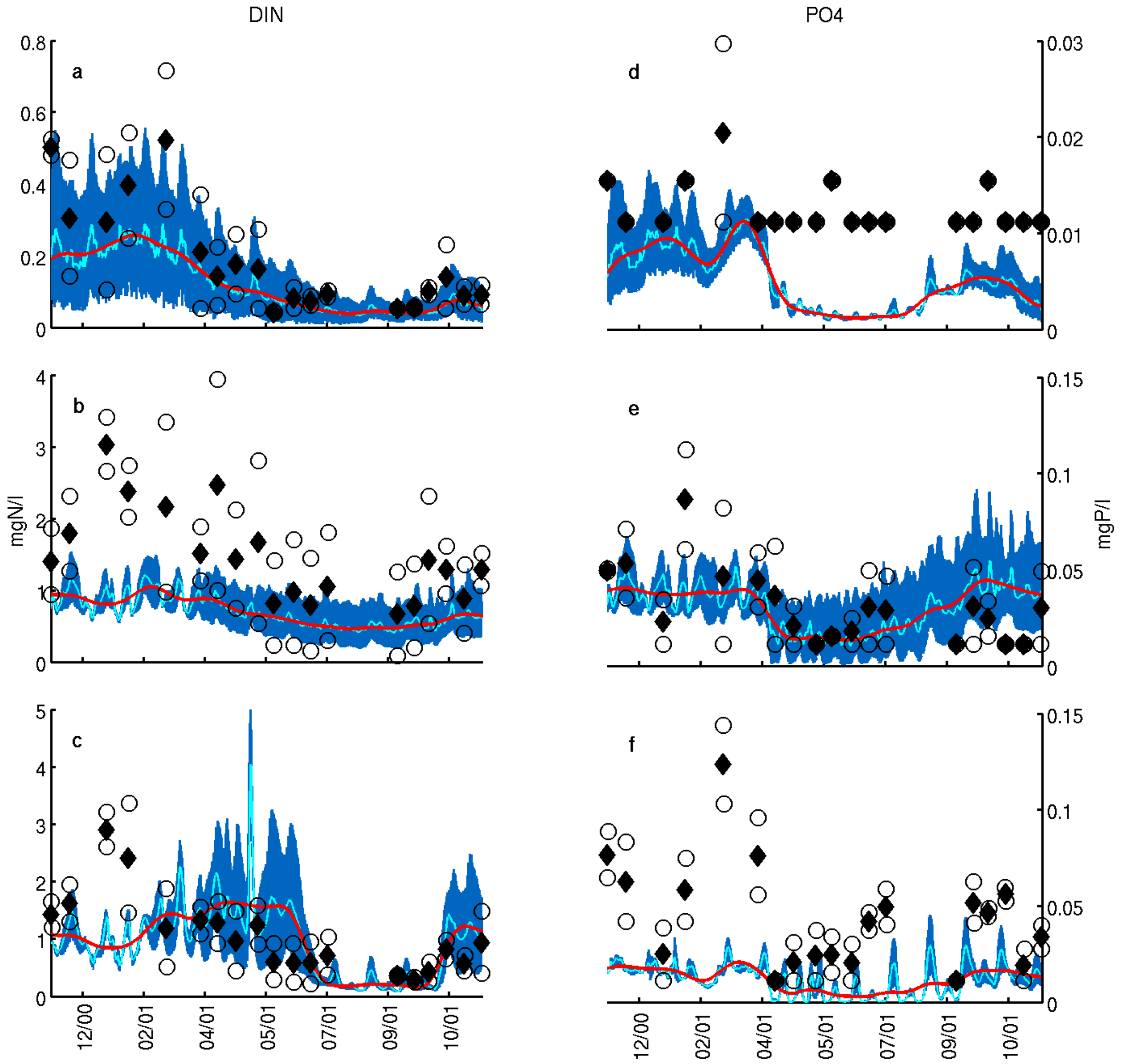


Fig. 4.5. Validation results for DIN and PO_4 for stations T1 (a, d), T11 (b, e) and T13 (c, f). Observations (circles and diamonds); model (blue and red lines).

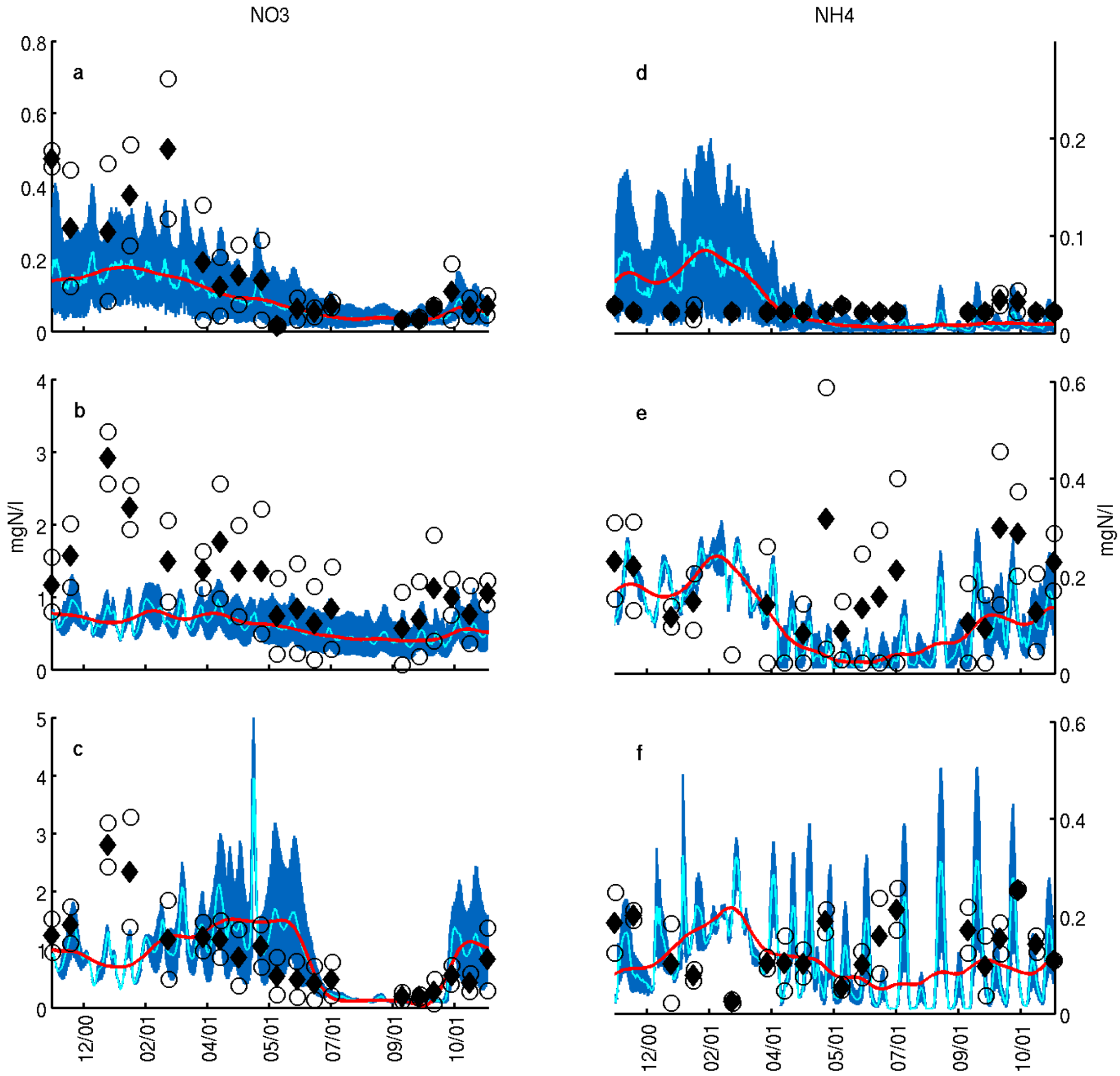


Fig. 4.6. Validation results for NO_3 and NH_4 for stations T1 (a, d), T11 (b, e) and T13 (c, f). Observations (circles and diamonds); model (blue and red lines).

PO_4 at T1 was always under the observations' detection level, with exception to November and March campaigns, with the model exhibiting a rise in range during the winter, but not reflecting the peak values. Considerable underestimation of PO_4 concentration occurs at T13 throughout the most of the validation run. However, the values reflect well the input from the catchment with values rarely exceeding 0.02 mgP/l.

The contributions of NO_3 and NH_4 to DIN are shown in Fig. 4.6, where an overestimation of the NH_4 load is clear in relation to NO_3 during the peak flows. Primary production (Fig. 4.7) showed good results in the validation runs, both in terms of season cycle and range, with a tendency to overestimate slightly chlorophyll at T11.

Overall, the model seems to respond to a long term varying mean change in conditions that the exceptional hydrological year of 2000–2001 represented, but, as in most models, it fails to depict exactly the exceptional peaks during very high river flow conditions. However, some of

this underestimation of peak values of river-borne substances at T1 during low salinity conditions can be attributed to steep vertical profiles, which are depth-averaged in the model, but the observations only sampled the surface water (~0.2 m). This bias under high freshwater input was already explained in Section 2.2.

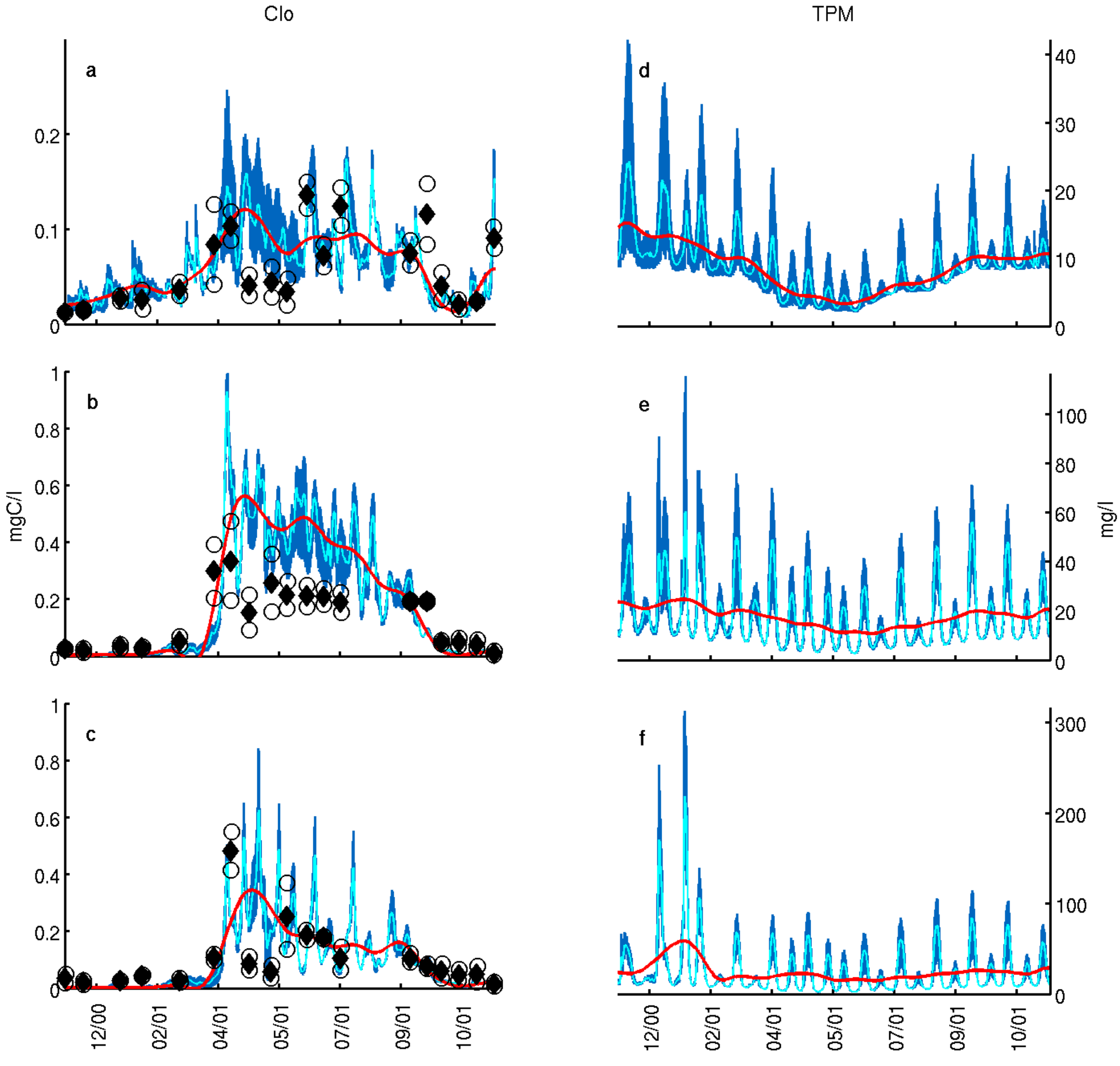


Fig. 4.7. Validation results for chlorophyll a and TSS for stations T1 (a, d), T11 (b, e) and T13 (c, f). Observations (circles and diamonds); model (blue and red lines).

5. Problems and recommendations

As it stands, the coupled hydrodynamic-transport-water quality modelling suite fulfils the need for a comparative analysis between scenarios within the LAGOONS project regarding water column concentrations. Despite the model shortcomings, the results presented herein constitute the achievable accuracy with the available data for the lagoon and surrounding catchment. The responsiveness of the model, the very good description of the transport in the water column, its fair account of the annual cycle and range of most parameters, and its fair independence from the initial conditions make the model suitable for differential comparison between projected scenarios and reference condition..

However, the following points should be highlighted to assist the users in their interpretations of the results:

i) The description of the bottom boundary of the model was used as a black box to calibrate the water column. Thus, oxygen consumption by sediment oxygen demand is not validated.

ii) As was clearly shown in the calibration of salinity, the uncertainty of the model increases towards the heads of the channels for all river-borne variables.

iii) Particulate organic matter was not modelled at the catchment and the model does not model explicitly macrophytes. This prevents the POM budget to be fully independent from the initial conditions.

iv) The benthic macrofauna was only modelled as modified forcing function. When modelling collapses in these populations, this cannot be done dynamically, but only prescribed as a forcing function.

In the light of the above points, the following future improvements can be made once there is data to assist these developments:

i) Explicit modelling of the sediment with a set of layers of varying thickness and erodibility. This means the availability of the data detailing the spatial distribution of the physical properties of the sediment, its organic matter content, and nutrients in the pore water which is currently unavailable.

ii) Instead of relying on catchment modelling data, future calibrations of water quantity and quality should be made using gauged observations with reasonable sampling frequency, and simultaneous at the several river mouths within the lagoon. This currently unavailable dataset should depict the annual cycle in both flow and quality.

iii) To allow a complete independence from the initial conditions of POM in the lagoon, this variable needs to be modelled at the catchment, and salt marshes should be explicitly modelled. This would improve both the POM and the nutrient budget.

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Chapter 3

The Mar Menor Lagoon - Modelling results and recommendations

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1. Introduction

The Mar Menor is a hypersaline coastal lagoon located in a semi-arid region of southeast Spain. The lagoon has a surface of approximately 135 km^2 and a total volume of 610x10^3 m^3 (Arévalo 1988). Maximum depth in the lagoon reaches 6.5 m with an average depth of 3.6 m. The lagoon is isolated from the Mediterranean Sea by a 22 km long and 100 to 900 m wide sandy bar (La Manga), crossed by three shallow channels (Marchamalo, Encañizadas del Ventorillo y La Torre and El Estacio). In the early 1970s, one of these channels (El Estacio) was dredged and widened to make it navigable. Since then, it has become the lagoon's main connection with the sea.

Water exchange with the adjacent Mediterranean Sea mainly occurs through El Estacio channel. Small tides, mainly diurnals, are responsible for high frequency dynamics through the channel, but the main force agent is, by far, the variations in atmospheric pressure. Winds are responsible for main water circulations within the lagoon, which, in average, shows an anti-clockwise circulation pattern. Water residence time in the lagoon has been estimated as 0.79 yr (Arévalo 1988).

The lagoon is located at the end of a watershed delimitated by a group of mountain ranges (Escalona, Algarrobo, Cartagena) that surround the Campo de Cartagena, an extent plain of about 1440 km^2. Freshwater inputs into the lagoon are restricted to six ephemeral watercourses called 'wadis' or 'ramblas'. These wide, shallow gullies are generally inactive, but can carry great quantities of water and sediment during flood episodes. The torrential nature of the supplies is aggravated by the impermeable soils and scarce vegetation cover of the watershed areas.

El Albujón wadi is the principal watercourse responsible for major inputs of organic and inorganic nutrients that flow into the lagoon (Velasco et al. 2006, García-Pintado et al. 2007). It drains a surface of about one third of the total surface of the adjacent agricultural area (Campo de Cartagena). The principal source is drainage from irrigated crops, but sometimes waste-water treatment plants located in the watershed area discharge large amounts of untreated or insufficiently treated water into the channel. This situation has led to the appearance of certain eutrophication symptoms in the lagoon, such as several changes in the phytoplankton size spectrum or the undesirable jellyfish blooms that occur every summer. An extensive description of the principal lagoonal characteristics, its climate, its natural values and environmental problems is compiled in the LAGOONS Report D2.1 available at http://lagoons.web.ua.pt/.

Despite our current understanding of main environmental problems in the Mar Menor and our increasing knowledge of lagoonal ecosystem functioning and its threats (mainly eutrophication and climate change impacts), a quantitative evaluation of the degree of possible alteration of the lagoonal ecological quality status in a range of future scenarios is still lacking. In this sense, the use of coupled hydrodynamic and ecological ecosystem modelling constitutes an exceptional tool for the quantification of future trends and the understanding of the repercussions in the lagoon of changes in the socio-economic and natural environments.

For the Mar Menor case study the model selected for both the hydrodynamic and ecological models was MOHID water modelling system. The MOHID system includes a baroclinic hydrodynamic module for the water column and 3D for the sediments and the corresponding Eulerian transport and Lagrangian transport modules. Parameters and processes involving non-conservative properties are object of specific modules (e.g. turbulence module, water quality, ecology, etc.).

Due to its shallow depth, the water column of the Mar Menor lagoon displays a good vertical mixing and stratification does not occur. According to these facts and in order to simplify our calculations and improve the performance of the models, a 2-D approach was selected. The hydrodynamic and water quality models were applied on an orthogonal continuous grid defined by squares of 175 x 175 m. Bathymetric data is the base for all modules of the MOHID system.

The spatial discretization in MOHID is based on a finite volume approach. Bathymetric data is stored in the grid by assigning a depth point to each of the grid points considered, generating finite volume elements or cells where model calculations are made. The total number of cells in the Mar Menor lagoon is 12250 (Fig. 1.1).

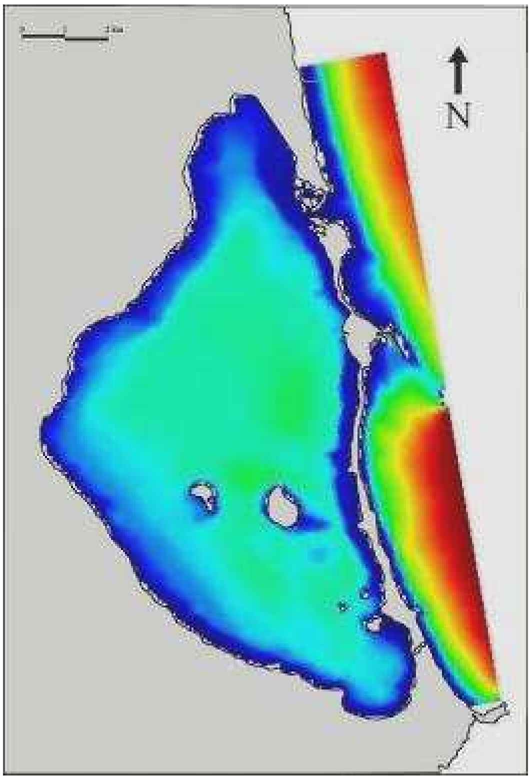

Fig. 1.1. Modelled area defined by the applied 175 x 175 m grid and resultant finite volume elements or cells with depth data.

The hydrodynamic model applied in the Mar Menor lagoon is able to simulate the flow of water masses and calculate current velocities and water column levels in the study area. The model is able to quantify water exchanges between the lagoon and the adjacent Mediterranean Sea and therefore calculate water residence time and its variation through time. The model also allows to characterize water circulation within the lagoon and solute transport. The interaction of water masses with the lagoon bottoms is also modeled and erosion and deposition processes are quantified. The high evaporation rates in the Mar Menor and their influence on the salt balance and water exchanges are also modeled. The most important processes considered are the heat and salt fluxes (basic to determine the evolution of water temperatures and salinities in the lagoon) and the calculation of water residence time (of enormous importance to determine the magnitude of water exchanges and the ability of the ecosystem to store and/or export land-derived substances and materials).

In the Mar Menor lagoon the ecological model calculates nitrogen and phosphorus concentrations, phytoplankton densities, *Caulerpa prolifera* biomasses and water transparency. To achieve this, the biogeochemical cycles of carbon, nitrogen and phosphorus are incorporated by considering the following processes:

- Mineralization of particulate and dissolved organic matter, including nitrification and denitrification.
- Sedimentation and resuspension of phytoplankton and particulate matter.
- Phytoplankton primary production and nutrient uptake.
- Effect of phytoplankton and particulate matter concentrations on water column light attenuation.
- Macroalgal primary production and nutrient uptake.

A more detailed description of the hydrodynamic and ecological models set up and parametrization can be found in the LAGOONS Report D6.1 available at http://lagoons.web.ua.pt/. A list of all the equations, assumptions and parameters used for both the hydrodynamic and ecological models can be found at www.mohid.com.

2. Data overview and analysis

2.1 Climate data

A set of climate variables were used to feed both the hydrodynamic and ecological models as input variables in order to simulate processes occurring at the water-air interface:

- Wind direction and Wind speed: Responsible for the momentum exchange between air and water masses and water circulation in the lagoon.

- Atmospheric pressure: Responsible for low frequency water exchanges between the lagoon and the adjacent Mediterranean sea due to its effect on water levels.

- Air temperature: Responsible for the heat exchange between air and water, key for simulating water temperatures in the lagoon as well as evaporation rates and their influence on lagoonal water salinities.

- Relative humidity: Important for the simulation of evaporation rates in the lagoon.

- Solar radiation and Cloud cover: Both variables combined determine the amount of light that reaches the water-air interface and were used to simulate light availability for planktonic and benthic macroalgae photosynthesis in the lagoon.

Daily averaged data for all these variables were obtained from the closest meteorological station located in San Javier 37º47'20''N / 0º48'12''W (Fig. 2.1).

Fig. 2.1. Map showing the location of San Javier meteorological station (red).

Climate data was analysed in order to find out if the years selected for calibration and validation of the model can be considered 'typical' or 'unusual'. Air temperature and precipitation, the most important variables that determine hydrological conditions in the area, were selected for this analysis. Mean annual temperature (MAT), Average summer temperature (AST), Total annual precipitation (TAP) and Occurrence of extreme rain events (OER >20 mm day^{-1}) were calculated for selected years and contrasted with the same data analysed for the 30-yr period 1981-2010. Results are shown in the following Table:

Table 2.1. Results of the analysis of climate data for selected years.
(HD-M: Hydrodynamic model, Eco-M: Ecological model)

Year	**MAT (ºC)**	**AST (ºC)**	**TAP (mm)**	**OER (#)**
2002 (HD-M / Eco-M Calibration)	18.07	24.43	203	2
2003 (HD-M / Eco-M Validation)	18.29	25.75 **	377	6
2007 (HD-M Calibration)	18.18	24.90	329	3
Average 1981-2010	17.64	24.50	313	3.7

** Values above the 95% or below the 5% percentiles of the distribution

According to the analysis of climate data, the years 2002 and 2007 can be considered as 'typical' for all the parameters analysed (contained within the central 90% of data distribution). In contrast, 2003 is an 'unusual' year with regard to AST. The observed averaged temperature of 25.75 ºC in the summer was above the 95% percentile of the 1981-2010 distribution, being also the hottest summer for the same 30-yr period.

2.2 Hydrological data

Tidal components used for the simulation of tidal forcing in the hydrodynamic model were obtained from Arevalo (1988), who calculated tidal harmonics in the area close to El Estacio channel. The set of nine tidal harmonics used is listed in the following Table:

Table 2.2. Tidal harmonics used in the hydrodynamic model.

Tidal harmonic	Symbol	Amplitude	Period
Solar semiannual	SSA	0.0338	187
Lunar monthly	MM	0.0137	128
Lunar diurnal	O1	0.0267	111
Solar diurnal	P1	0.0138	169
Lunar diurnal	K1	0.0375	171
Principal lunar semidiurnal	M2	0.0307	57
Principal solar semidiurnal	S2	0.0103	51
Larger lunar elliptic semidiurnal	N2	0.0052	45
Shallow water overtides of principal lunar	M4	0.0042	161

Tidal amplitude in the area is very low, a typical characteristic of the western Mediterranean coasts. This fact has a great effect on water exchanges between the lagoon and the adjacent sea since differences in water levels between both water masses are small.

Apart from the tidal and atmospheric forcings, the hydrodynamic model also includes freshwater discharges as input data. The only discharges included in the model were those from El Albujón wadi, the main watercourse that flows into the lagoon and the only wadi that displays a continuous flow. Discharge data were extracted from data of García-Pintado et al. (2007), who sampled this watercourse fortnightly throughout 2002-2004. To feed the model we extrapolated the series to daily data (Fig. 2.2).

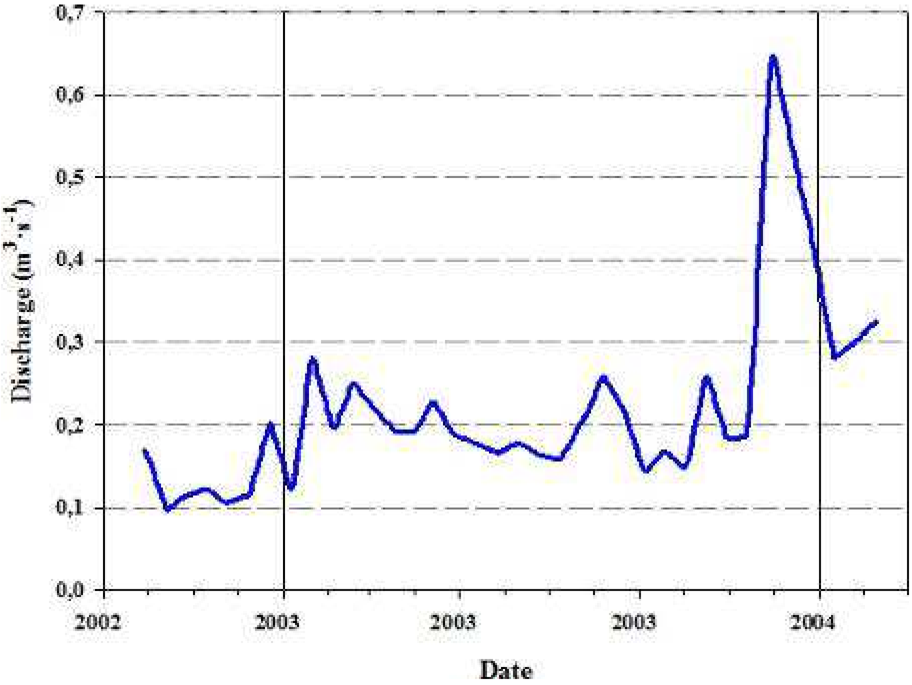

Fig. 2.2. Extrapolated daily discharge data series extracted from García-Pintado et al. (2007).

The extrapolated discharge data series was used directly for the modelling of two of the calibration/validation periods, 2002 and 2003. However, no data was available for 2007, the period selected for the hydrodynamic model calibration. In this case, since the calibration was made on a dry period in July-August 2007, we assumed the same discharge data as in 2003 for these same months, being around the 0.2 $m^3\ s^{-1}$ base flow. The same assumption was made for the period between May and September 2002 to ensure we had enough data for the calibration of the hydrodynamic model since it also corresponded to a dry period in the study area and taking into consideration the small effect that El Albujon freshwater inputs have on salinities and temperatures in the Mar Menor lagoon.

Current velocities used for the calibration of the hydrodynamic model were obtained from the Oceanographic Information Service of Murcia (SIOM) available online at https://caamext.carm.es/siom/. The service provides 10-min current-meter observations in a sampling station located in El Estacio channel for the period between July 3rd and August 5th of 2007. The current-meter located at El Estacio channel, the main inlet that connects the lagoon with the adjacent Mediterranean Sea, provides valuable data for the calibration of the model and the estimation of water exchanges in the area (Fig. 2.3).

Initial and boundary conditions for current velocities were set to 0. The model was allowed to run the whole year 2007 period with real climate data to ensure stability of the results during the modelling of the selected calibration period.

Fig 2.3. Location of the SIOM sampling station for current velocities used for the hydrodynamic model calibration.

Water temperature and salinity data series in the area were obtained from different sources. Surface water temperatures and salinities used for the ocean boundary condition were obtained from data of the RADMED project of the Spanish Oceanographic Institute (IEO) available at http://www.ma.ieo.es/gcc. The website provides monthly averaged data for both variables at a station located in Cabo de Palos, close to our study area (Fig. 2.4). The high surface/volume ratio of the Mar Menor lagoon and the extremely long water residence time in the lagoon, due to the reduced water exchange with the Mediterranean Sea and the microtidal regime in the area, justify the use of monthly averaged data for the ocean boundary condition in this case.

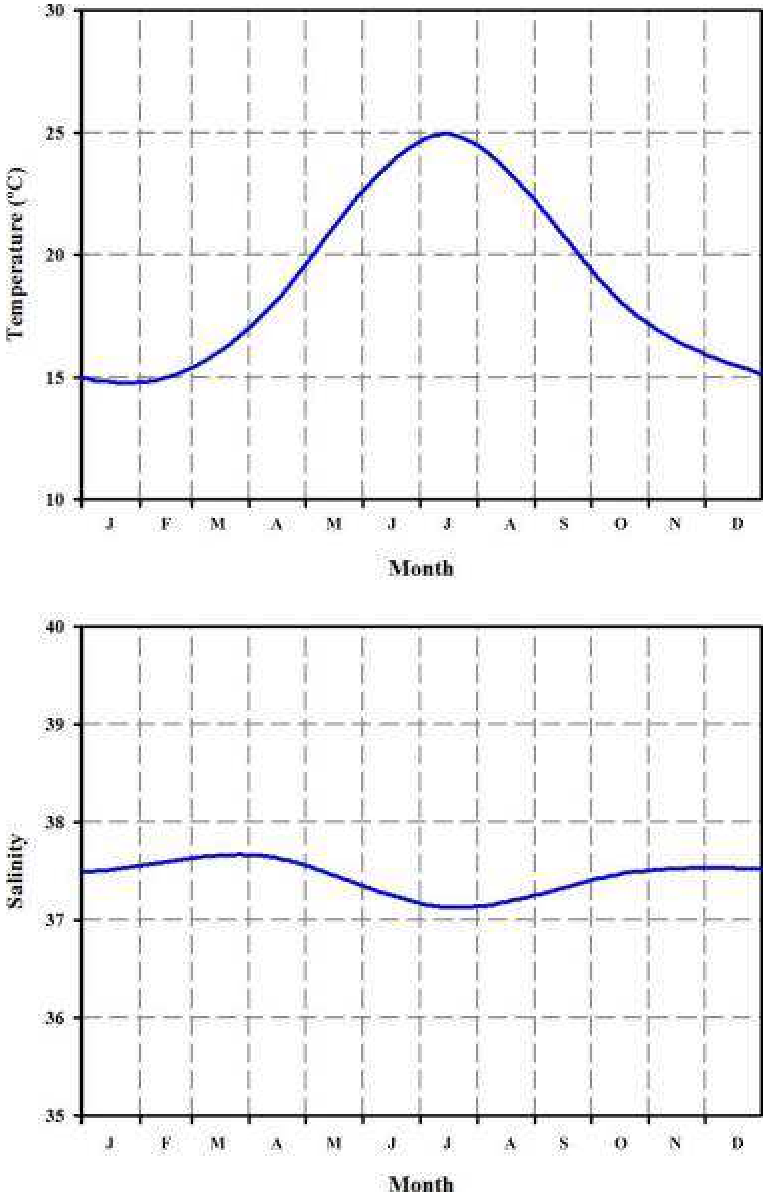

Fig. 2.4. Water temperatures and salinities at Cabo de Palos used as ocean boundary condition for these variables.

Values for temperature and salinity of freshwater inputs through El Albujon Wadi were obtained from Velasco et al. (2006) who sampled the mouth of the wadi between September 2002 and October 2003. The authors reported little variations in salinity ranging from 3.60 to 7.90. In order to simplify our calculations, and considering the little effect that El Albujon inputs have on lagoonal salinities, we assumed a constant salinity of 6.16 for wadi's inputs, reported by the cited authors as the annual average. During the same study temperatures ranged from 11.70 ºC in the winter to 24.40 ºC in the summer, being extremely similar to those observed in the lagoon. For this reason, and in order to simplify our calculations, input temperatures were not included as a 'discharge' in our model, since little to none effect is expected.

Lagoonal water temperature and salinity data available in the literature, technical reports or web-based applications are scarce and mainly correspond to samples collected in random

months/years and locations, rather than yearly data series in fixed locations appropriate for the calibration/validation of the model. In this case, data series for water temperature and salinity in the lagoon used for the calibration of our hydrodynamic model were extracted from Perez-Ruzafa et al. (2005) available in the literature, and correspond to five locations sampled fortnightly in the lagoon from May 2002 to April 2003 (Fig. 2.5). The distribution of sampling stations for this data set seems to be sufficient to represent spatial variability in the lagoon, and periodicity of the sampling seems also adequate to at least discern major temporal patterns. There are however some gaps in the series.

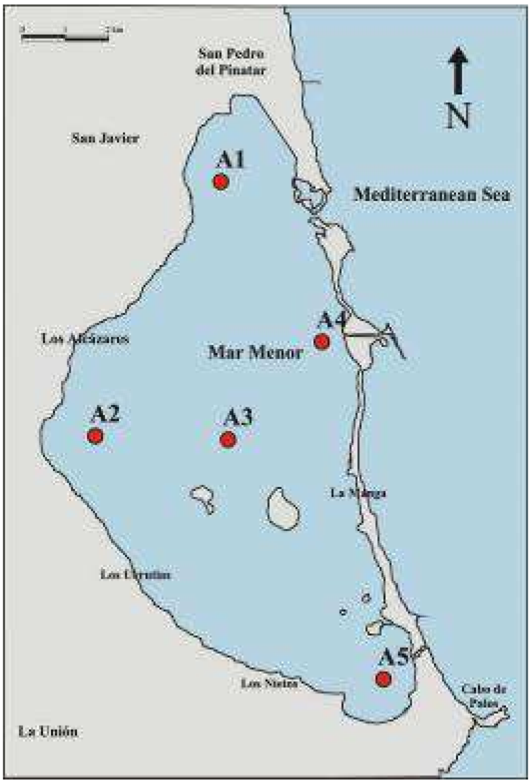

Fig. 2.5. Location of the sampling stations form Perez-Ruzafa et al. 2005 (red) used for the hydrodynamic model validation and ecological model calibration.

A second series corresponded to own data for the same variables from January to November 2003 in six sampling stations, sampled bi-monthly (Fig. 2.6). Sampling stations, although scarce and located in the western and central part of the lagoon, represent well the main environmental gradients in the Mar Menor lagoon (Lloret et al., 2005, Velasco et al. 2006). Periodicity of the sampling was lower for this series but ensured some data for the validation of our model.

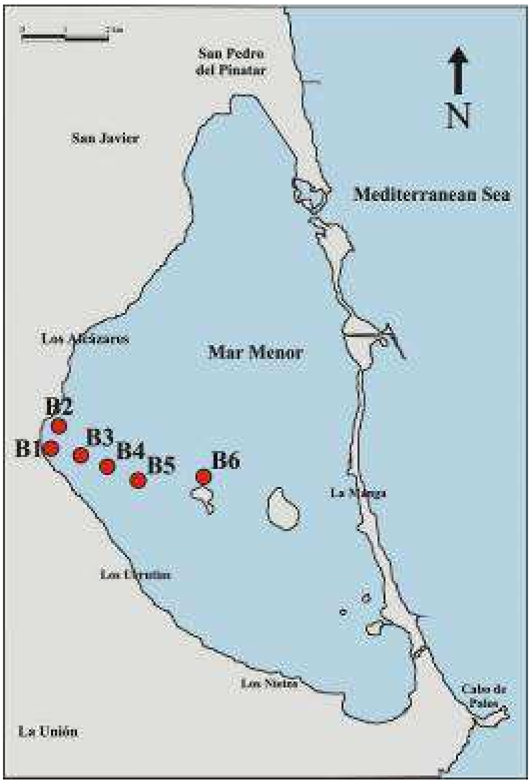

Fig. 2.6. Location of the sampling stations (red) used for the ecological model validation.

Our own data from January 2003 were used as model initial conditions for temperature and salinity in the lagoon, although the model was allowed to run a whole year prior to the calibrated/validated periods to ensure model stability.

2.3 Ecological data

Concentrations of major inorganic nitrogen and phosphorus and chlorophyll concentrations used as the ocean boundary condition for the ecological model were obtained from the Oceanographic Information Service of Murcia (SIOM) available online at https://caamext.carm.es/siom/. Due to the extremely low concentrations, the limited lagoonal water exchanges with the adjacent Mediterranean Sea and the scarce variability of major nutrients at the ocean boundary condition, their concentrations were considered constant throughout the year at around 0.02 mg/l of nitrate and 0.0015 mg/l of inorganic phosphorus. Chlorophyll-*a* concentrations used as the ocean boundary condition are presented in Fig. 2.7.

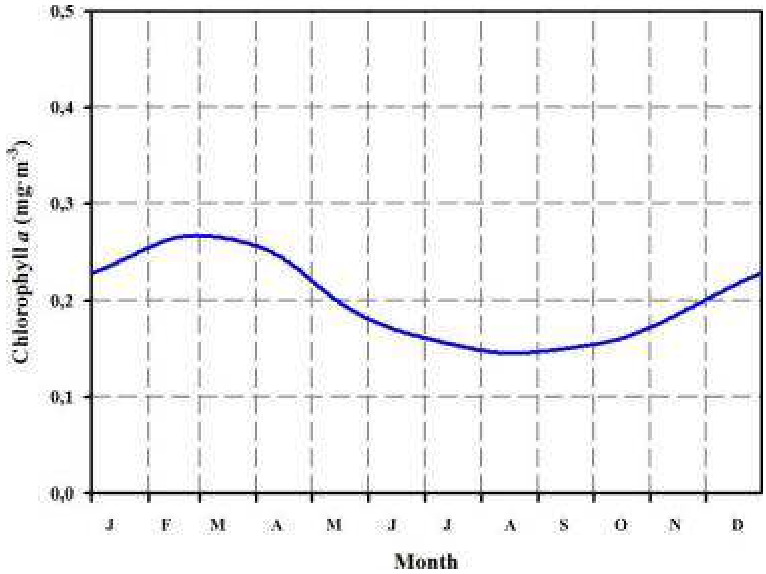

Fig. 2.7. Chlorophyll-*a* concentrations used as ocean boundary condition for this variable.

Nutrient input data from El Albujon wadi were obtained from Garcia-Pintado et al. (2007). These authors sampled nutrient concentrations fortnightly in the mouth of the wadi from 2002 to 2004. Data was extrapolated to generate daily time series for nitrate, nitrite, ammonia and inorganic phosphorus concentrations to feed our models. A gap in the nitrate series from October 2002 to January 2003 was corrected by assuming proportional concentrations to those observed in other nitrogen forms and the tendencies observed for the same period in 2003-2004 (Fig. 2.8).

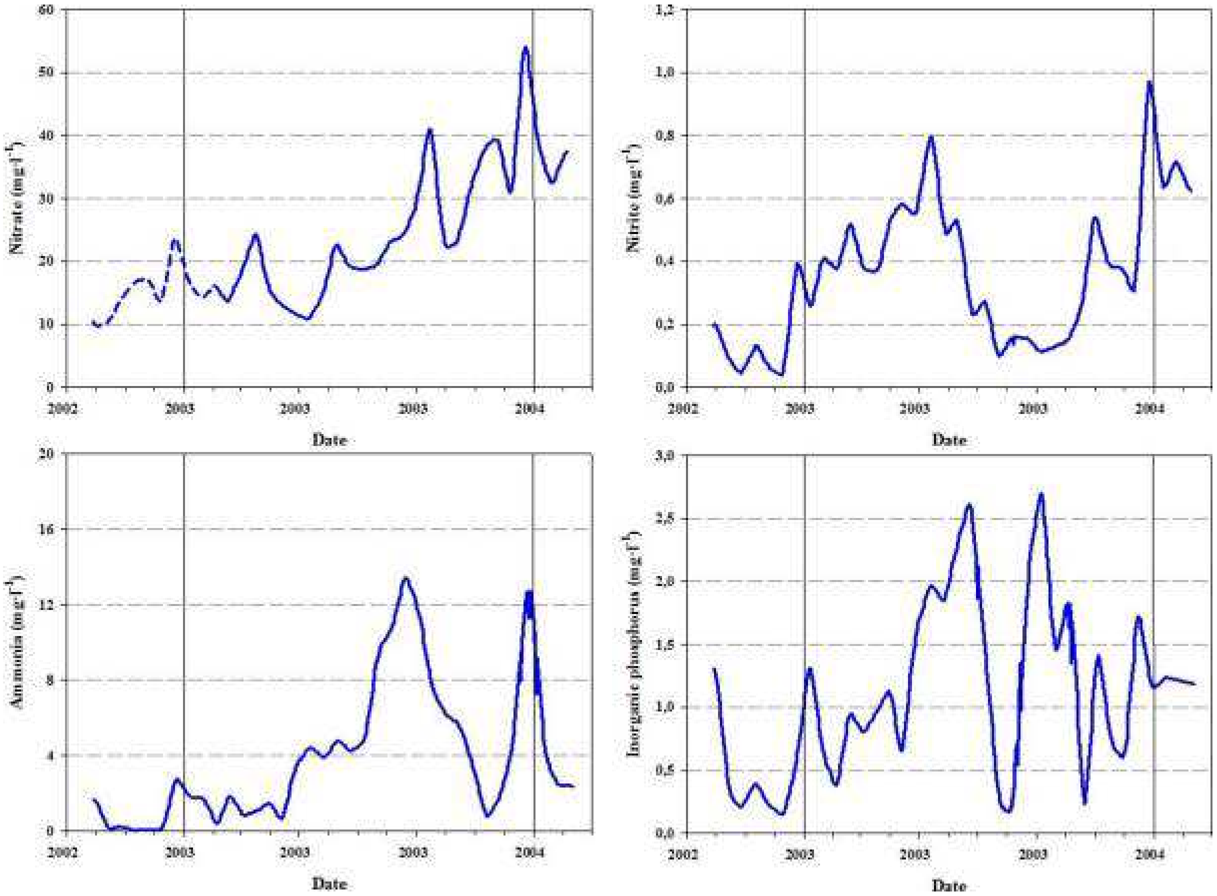

Fig. 2.8. Extrapolated daily inorganic nutrient concentration data series extracted from García-Pintado et al. (2007). Dashed line in the nitrate series represents assumed concentrations for this period.

As occurred for temperature and salinity, data for nutrient and chlorophyll concentrations in the Mar Menor lagoon mostly correspond to random surveys at different locations. In this case only two data series were available for nutrient and chlorophyll concentrations in the lagoon. The first series was extracted from data of Perez-Ruzafa et al. (2005) available in the literature, and correspond to concentrations of nitrate, inorganic phosphorus and chlorophyll-*a* sampled fortnightly in five locations within the lagoon throughout May 2002 and April 2003 (see Fig. 2.5). The distribution of sampling stations for this data set is sufficient to represent spatial variability in the lagoon and periodicity of the sample seems to be adequate. There are however some gaps in the series. Furthermore, in this case, we were only able to use data from October 2002 to April 2003 for our ecological model calibration, since no data was available for freshwater and nutrient inputs from El Albujon wadi for the period between May and September 2002.

The second series corresponded to own data for the same variables from January 2003 to November 2003 in six sampling stations, sampled bi-monthly (see Fig. 2.6). Sampling stations, although scarce and located in the western and central part of the lagoon, represent well the main environmental gradients for nutrients and chlorophylls in the Mar Menor lagoon (Lloret et al., 2005, Velasco et al. 2006). Periodicity of the sampling was lower for this series but ensured some data for the validation of our model.

Despite the fact that our ecological model is able to compute different forms of particulate, dissolved, organic and inorganic nutrients, data availability only permitted the calibration of

nitrate, inorganic phosphorus and chlorophyll-*a* concentrations. Nitrate and inorganic phosphorus are the major forms of dissolved inorganic nutrients in the lagoon and, together with chlorophyll concentrations, serve as good indicators of the trophic status of coastal areas.

Our own data from January 2003 were used also as model initial conditions for nutrients and chlorophylls in the lagoon, although the model was allowed to run a whole year to ensure model stability.

Only one data series was available for *Caulerpa prolifera* biomass in the lagoon and corresponded to our own data from January 2003 to November 2003 in six sampling stations, sampled bi-monthly (Fig. 2.6). Other data on *Caulerpa prolifera* biomass found in the available literature are scarce and mostly correspond to random samples collected in very shallow locations of the lagoon. Our series was the only data that permitted the comparison of our model results with observed algal biomasses.

Years selected for the calibration and validation of our ecological model can be considered as 'typical' and no particular 'eutrophication events' or 'unusual' concentrations of nutrients or phytoplankton were recorded during these periods.

3. Hydrodynamic model calibration and validation

3.1 Calibration methodology and results

Current velocity calibration was carried out by comparing our model results with current velocities obtained from the Oceanographic Information Service of Murcia (SIOM) available online at https://caamext.carm.es/siom/. The service provides 10-min current-meter observations in a sampling station in El Estacio channel for the period between July 3rd and August 5th of 2007 (see Fig. 2.3).

Reference density and reference specific heat were obtained from Arevalo (1988) and values are presented in the following Table 3.1. Calibration of bottom rugosity was done manually until a good fit with the data was achieved; other parameters included in the model were set as default as defined in the MOHID Description Document available at http://mohid.com.

Table 3.1. Parameters used in the hydrodynamic model.

Parameter	Value
Reference Density	$1031\ g \cdot l^{-1}$
Reference Specific Heat	$3985\ J \cdot cm^{-3} \cdot K^{-1}$
Bottom Rugosity	0.0025 m

The model was able to represent current velocities in El Estacio channel for the calibrated period in terms of magnitude, direction and periodicity. Values of mean and standard deviation of computed and measured velocities were very similar (Table 3.2).

Table 3.2. Current mean and standard deviation for the calibrated period at El Estacio channel. *(n=4888 observations).		
Parameter	**Measured**	**Computed**
Mean current velocity modulus ($m\cdot s^{-1}$)	- 0.005	- 0.016
Standard deviation ($m\cdot s^{-1}$)	0.418	0.442

The comparison between computed and measured water velocities in El Estacio channel for the calibrated period is presented in the following Figs 3.1 and 3.2. In general, the model provides a good reproduction of water currents at El Estacio channel.

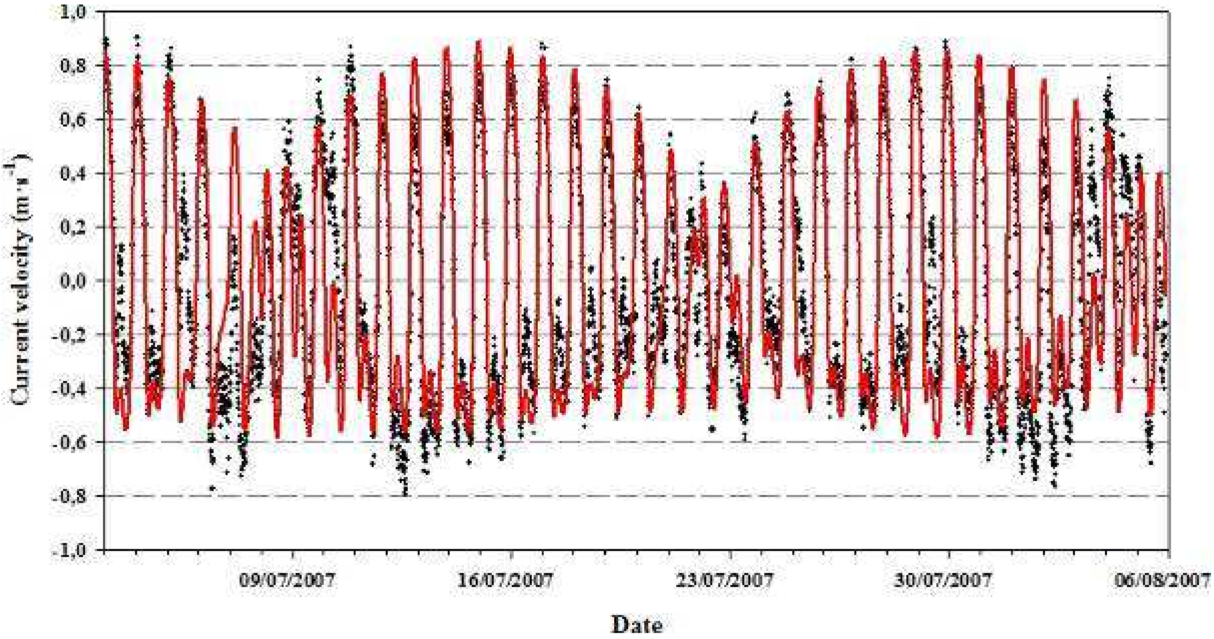

Fig. 3.1. Computed (red line) and measured (black points) current velocities at El Estacio channel during the calibrated period.

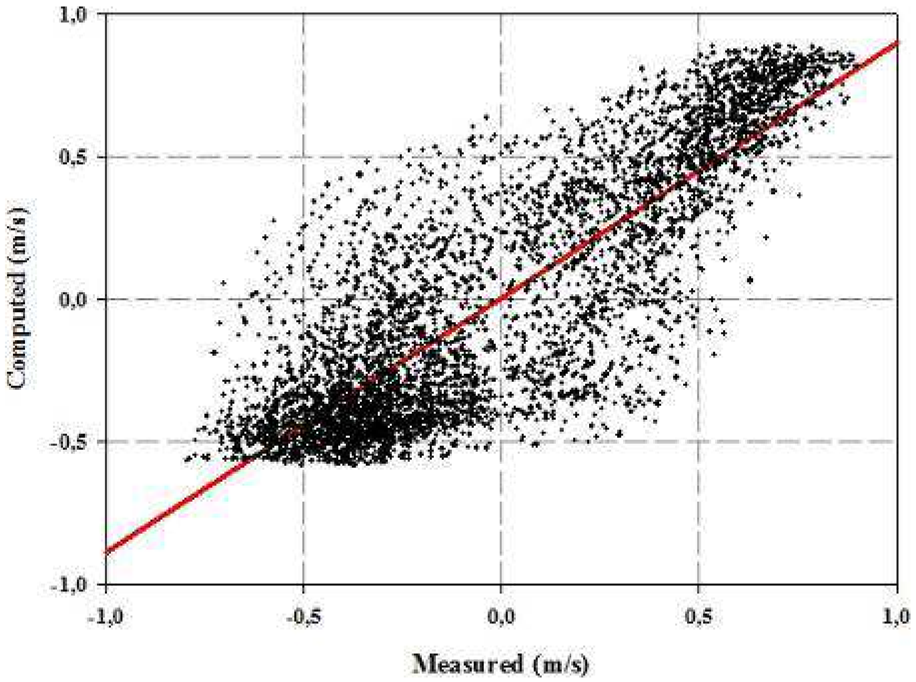

Fig. 3.2. Comparison between computed and measured velocities at El Estacio channel. Red line represents adjusted linear regression (R^2 = 0.715).

In order to better quantify the capacity of the model to reproduce current velocities, the values of the average error (RMSE), normalized averaged error (NRMSE) and R^2 were computed and reported in the following Table:

Table 3.3. RMSE, NRMSE and R2 for current velocities in the calibrated period *(n = 4888 observations).

	Current velocity
RMSE	0.240 $m \cdot s^{-1}$
NRMSE	0.141
R^2	0.715

In order to calibrate water temperature and salinity, the model simulated the period from May 2002 to April 2003 and computed values of temperature and salinity were compared with the data collected by Perez-Ruzafa et al. 2005 at five sampling stations in the Mar Menor (See Fig. 2.5).

Results showed a good agreement with the observations for both variables and the model reproduced well the evolution of temperature and salinity of the Mar Menor during the calibrated year. A summary of the calibration metrics is presented in the following Table:

Table 3.4. Calibration metrics for temperature and salinity in the validated period.

Variable	Metric	Value	
		Measured	Computed
Temperature (n = 54)	Mean	21.15	19.96
	S.D.	6.35	6.48
	RMSE	1.995	
	NRMSE	0.108	
	R^2	0.938	
		Measured	Computed
Salinity (n = 94)	Mean	45.14	45.15
	S.D.	1.33	1.20
	RMSE	0.717	
	NRMSE	0.103	
	R^2	0.600	

Results of the NRMSE calculation for temperature and salinity at each individual station are presented in Table 3.5. The model is able to reproduce the spatial variation of both variables during this period.

Table 3.5. NRMSE values for temperature and salinity at individual stations in the calibrated period.

	NRMSE				
Variable	**A1**	**A2**	**A3**	**A4**	**A5**
Temperature	--	0.102	0.108	0.075	0.179
Salinity	0.168	0.095	0.211	0.246	0.197

A comparison between observed and computed values of temperature and salinity for the individual stations during the calibrated period is presented in Fig. 3.3.

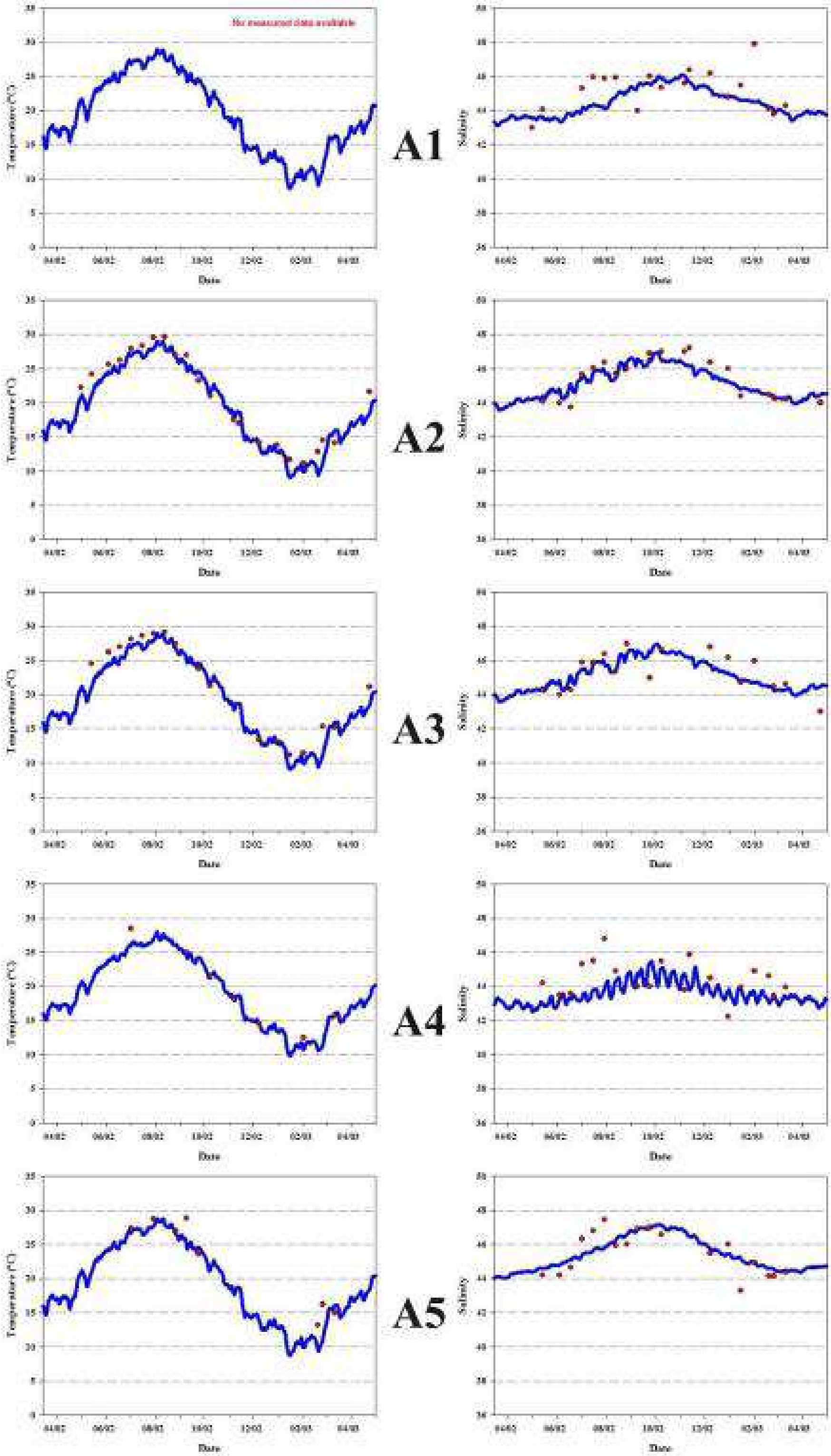

Fig. 3.3. Comparison between computed (blue) and measured (red) temperature and salinity for the calibrated period.

In general, the model accurately describes temperature and salinities in the lagoon. Metrics used to estimate the accuracy of the results of the validated period displayed better agreement for temperature than salinity. Although the calculated values for NRMSE at individual stations for both variables are acceptable, it seems that certain ‘outliers’ in the salinity series are responsible for such a deviation from the computed values. The highest NRMSE score was observed at A4 station, located close to El Estacio channel, a location that is highly influenced by the daily exchanges of seawater with the adjacent Mediterranean Sea. Since the model computed daily average data for salinity, the differences between observed and computed data may be greater in this case, depending on the time of the day samples were collected, biasing our comparison results.

Computed water temperatures ranged between 10ºC in winter and 30ºC in summer, in agreement with the general temperature pattern observed in the Mar Menor (Fig. 3.4). Computed salinities also reproduced well the general patterns in the area (Fig. 3.4) and the observed salinity gradient from the northern areas of the lagoon, more influenced by the exchanges with the Mediterranean, and the southern part of the lagoon, more isolated from these exchanges and displaying in general higher salinities (Fig. 3.5).

Both variables displayed a clear seasonal pattern in the lagoon (Fig. 3.4). Temperature reaches its maximum in July-August and its minimum in January-February. Salinity reaches its maximum in September-October and its minimum in March-April. This seasonal pattern is clearly defined by the seasonal variability of atmospheric forcings, including solar radiation, heat exchanges at the water-air interface and evaporation rates. Freshwater inputs and water exchanges with the Mediterranean seem to have little influence on the seasonal dynamics of both variables, although their influence (particularly for salinity) is more evident in areas located either very close to the mouth of El Albujon, or in the northern areas of the lagoon close to El Estacio channel and Las Encañizadas inlet. Apart from the cited spatial differences in salinity in the north-south direction, no other significant spatial differences for temperature and salinity were identified. Although there is certain evidence that temperatures can reach values either higher than 30 ºC or below 10 ºC in very shallow areas of the lagoon, this pattern cannot be observed in our model due to the coarse grid used in the modelling.

El Albujon wadi freshwater discharges displayed little influence on water salinities in the lagoon (Fig. 3.5). This result is justified by the relatively low volume discharges from the wadi (around 0.2 $m^3 \cdot s^{-1}$ base flow) compared to the total volume of the lagoon of approximately $630 \cdot 10^6$ m^3. The effects of these inputs are very local and only affect the area located very close to the mouth of the wadi.

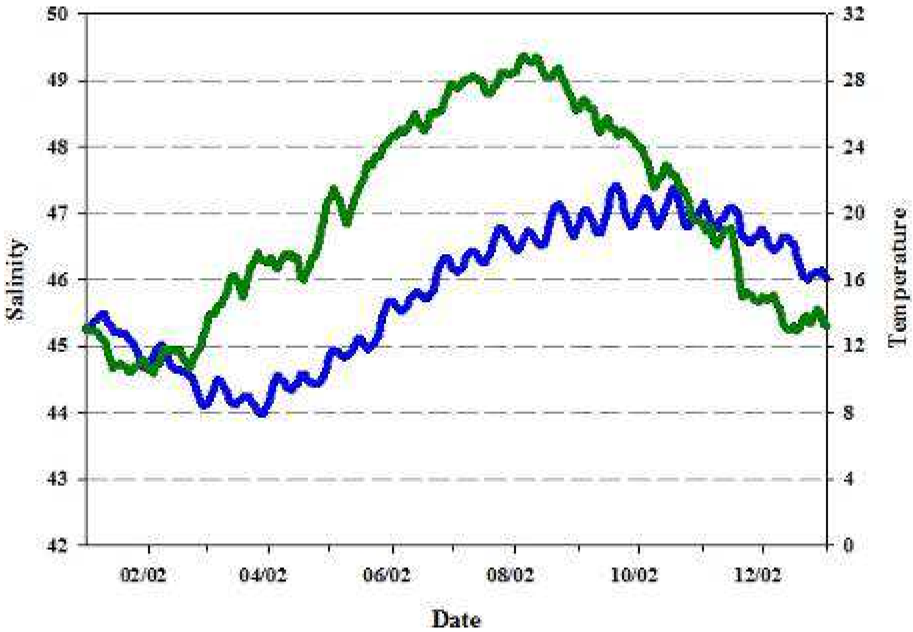

Fig. 3.4. Annual variation of computed temperature (green) and salinity (blue) averaged for the whole basin during 2002.

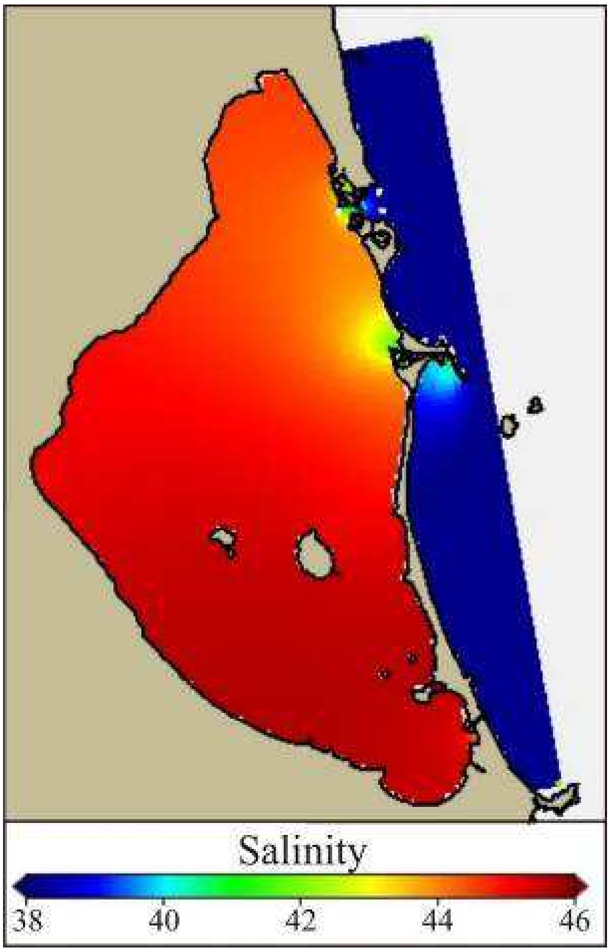

Fig. 3.5. Yearly averaged salinity in 2002 computed by the hydrodynamic model displaying a clear gradient from north to south.

3.2 Validation methodology and results

After the hydrodynamic model calibration, in order to validate our results, the model simulated the period from January to November 2003, and computed values of temperature and salinity were compared with the data collected by our team at six sampling stations in the Mar Menor (see Fig. 2.6). Results of the validation metrics are presented in the following Table:

Table 3.6. Calibration metrics for temperature and salinity in the validated period.

Variable	Metric	Value	
Temperature (n = 30)		Measured	Computed
	Mean	21.09	19.74
	S.D.	7.49	7.09
	RMSE	1.672	
	NRMSE	0.078	
	R^2	0.984	
Salinity (n = 30)		Measured	Computed
	Mean	44.93	45.30
	S.D.	1.72	1.87
	RMSE	1.087	
	NRMSE	0.134	
	R^2	0.700	

Although the reduced number of samples did not allow the calculation of validation metrics at individual stations, the results obtained in the comparison of our model results with observations in the validated period were again satisfactory, confirming the ability of our hydrodynamic model to reflect major patterns in water temperature and salinity in the lagoon.

To further validate the hydrodynamic model, we calculated water residence time in the lagoon for the year 2003 and compared our results with previous estimations. The method is based on the dispersion of Lagrangian particles (tracers) as defined in Braunschweig et al. (2003) (Fig. 3.6).

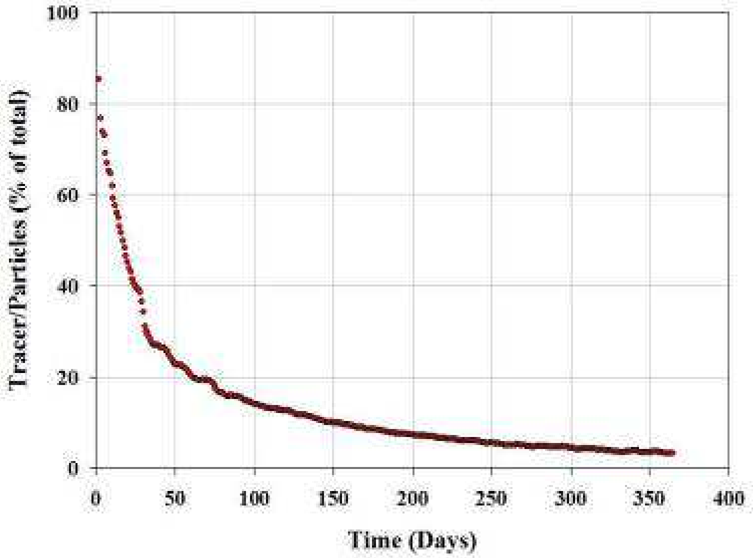

Fig. 3.6. Dispersion of Lagrangian particles (tracers) used for the calculation of water residence time in the Mar Menor lagoon.

Our results estimated a residence time of 0.76 yr, very similar to the available estimations of 0.79 yr made by Arevalo (1988). The long water residence time in the lagoon is due to several factors, including the extremely low freshwater inputs and the low water exchanges with the Mediterranean Sea, due to the low tidal amplitude in the area and the shallow and narrow inlets of La Manga.

It can be concluded that the model accurately predicts basic hydrodynamics, water exchanges and the heat and salt fluxes in the Mar Menor lagoon.

4. Ecological model calibration and validation

4.1 Calibration methodology and results

The ecological model calibration was carried out by comparing our model results with nitrate, inorganic phosphorus and chlorophyll-*a* concentrations extracted from Perez-Ruzafa et al. 2005 at five sampling stations in the Mar Menor (see Fig. 2.5). We calibrated the period between October 10th of 2002 and April 23th of 2003.

Previous ecological studies in the area allowed the parameterization of some of the processes modelled. First, the effect of phytoplankton densities on water column transparency was estimated empirically from a regression analysis of our own data collected in 2003. Phytoplankton light extinction coefficient was assigned a value of 0.0833 m^{-1} according to the regression analysis. Furthermore, the study carried out by Terrados (1991) allowed the parameterization of *Caulerpa prolifera* photosynthesis, production and nutrient dynamics in the Mar Menor. Values for *Caulerpa prolifera* parameters included in the model are listed in the following Table:

Table 4.1. Parameterization of *Caulerpa prolifera* modelling.	
Parameter	**Value**
Endogenous respiration rate	0.0123 day^{-1}
Excretion rate	0.008 day^{-1}
Grazing rate	0.0 day^{-1}
Maximum growth rate	0.18 day^{-1}
Natural mortality rate	0.001 day^{-1}
Optimum radiation value	80 $W \cdot m^{-2}$
Photorespiration rate	0.018 day^{-1}
Nitrogen/Carbon ratio	0.071
Phosphorus/Carbon ratio	0.0016
Minimum temperature for growth	10 ºC
Maximum temperature for growth	35 ºC
Optimum minimum temperature for growth	20 ºC
Optimum maximum temperature for growth	30 ºC

Calibration of the principal parameters important for phytoplankton and macroalgal growth in relationship with major nutrient concentrations was done manually; other parameters included in the model were set as default as defined in the MOHID Description Document available at http://mohid.com. Values of the principal parameters were adjusted manually until a good fit with the data was achieved.

The ecological model was able to simulate nitrate, phosphorus and chlorophyll-*a* concentrations in the lagoon for the calibrated period. Values of mean and standard deviation of computed and measured concentrations were very similar (Table 4.2).

Table 4.2. Values of the mean and standard deviation of major nutrients and chlorophylls in the calibrated period.

	Mean		**S.D.**	
Variable	**Measured**	**Computed**	**Measured**	**Computed**
Nitrate ($mg \cdot l^{-1}$)	0.123	0.077	0.126	0.105
Inorganic phosphorus ($mg \cdot l^{-1}$)	0.008	0.009	0.010	0.008
Chlorophyll-*a* ($mg \cdot m^{-3}$)	0.587	0.608	0.280	0.354

Calibration results demonstrated a good agreement between measured and computed data for nutrient and chlorophyll concentrations both in average and deviation values during the calibrated period. The model slightly underestimated nitrate concentrations during the calibrated period, although reproduced well its variability. Calibration metrics are presented in

the following Table 4.3. Due to data availability, metrics could only be calculated for the whole pool of samples rather than for individual stations.

Table 4.3. Calibration metrics for nutrient and chlorophyll concentrations in the calibrated period.

Variable	RMSE	NRMSE	R^2
Nitrate ($mg \cdot l^{-1}$) (n = 45)	0.086	0.198	0.65
Inorganic phosphorus ($mg \cdot l^{-1}$) (n = 44)	0.005	0.119	0.76
Chlorophyll-*a* ($mg \cdot m^{-3}$) (n = 40)	0.242	0.200	0.53

Calculated metrics displayed relatively low values of RMSE and NRMSE, although the computed values for R^2 were relatively low. This result is not surprising due to the low number of samples used for the calibration and the high variability of measured values. The model, however, seems to reproduce well the three variables in the ranges observed during the calibrated period (Fig. 4.1).

Taking into consideration model's assumptions, the results of the calibration can be considered satisfactory. The 2-D approach for our model set-up is far from ideal, but at least computed values compare relatively well with measured variables. Our ecological model results in specific cells are an integration of the concentrations observed in the whole water column, while available data correspond to measurements made at 1-m depth, a fact that can explain a certain degree of the mismatch observed.

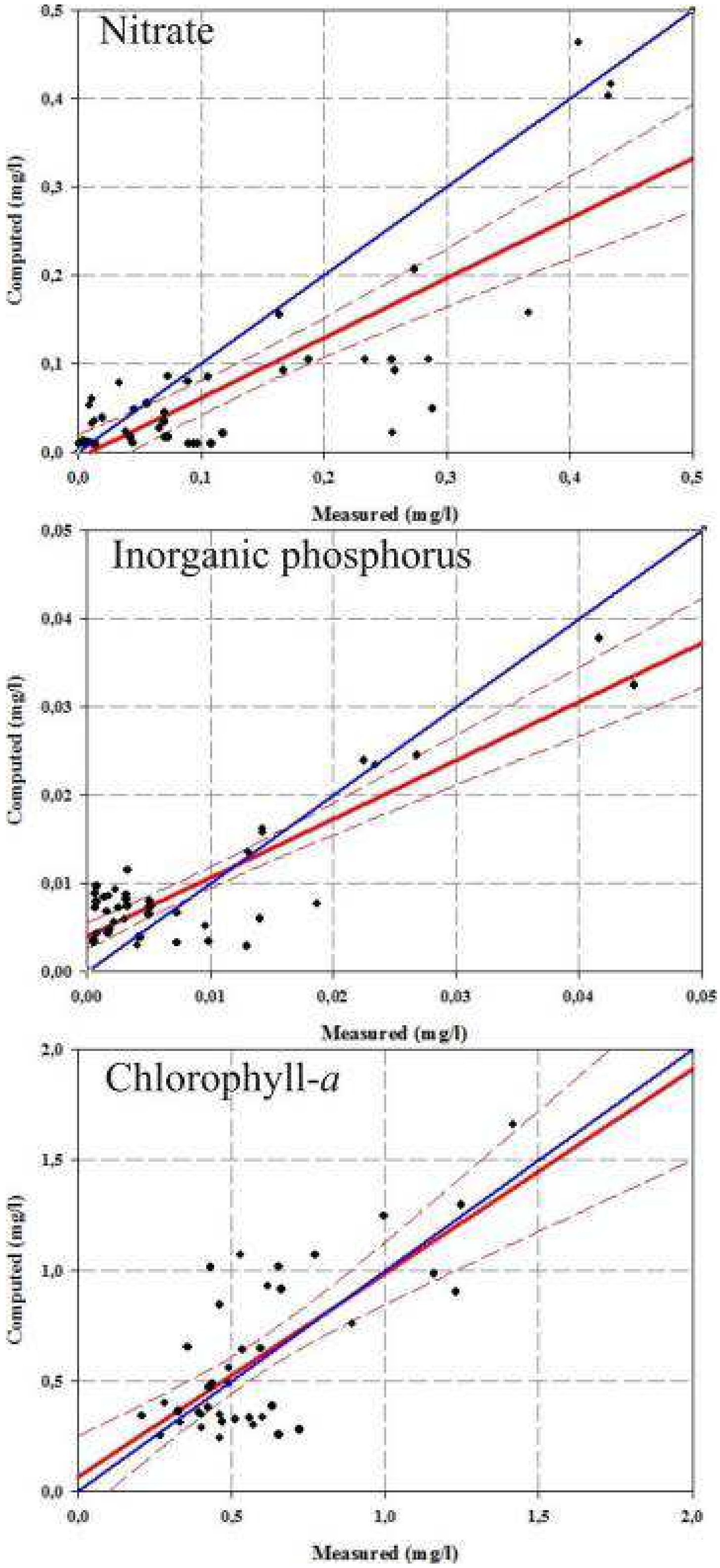

Fig. 4.1. Linear adjustments between measured and computed values of nitrate, inorganic phosphorus and chlorophyll-*a* concentration during the calibrated period (red lines). Blue line represents the 1:1 adjustment. Dashed red lines represent the 95% confidence interval.

In general, the model simulated well the major nutrient and chlorophyll concentration patterns in the lagoon, displaying clear gradients for nitrate, inorganic phosphorus and chlorophyll-*a* concentrations throughout the year, associated to the inputs from the El Albujon wadi (Figs 4.2, 4.3 and 4.4 respectively).

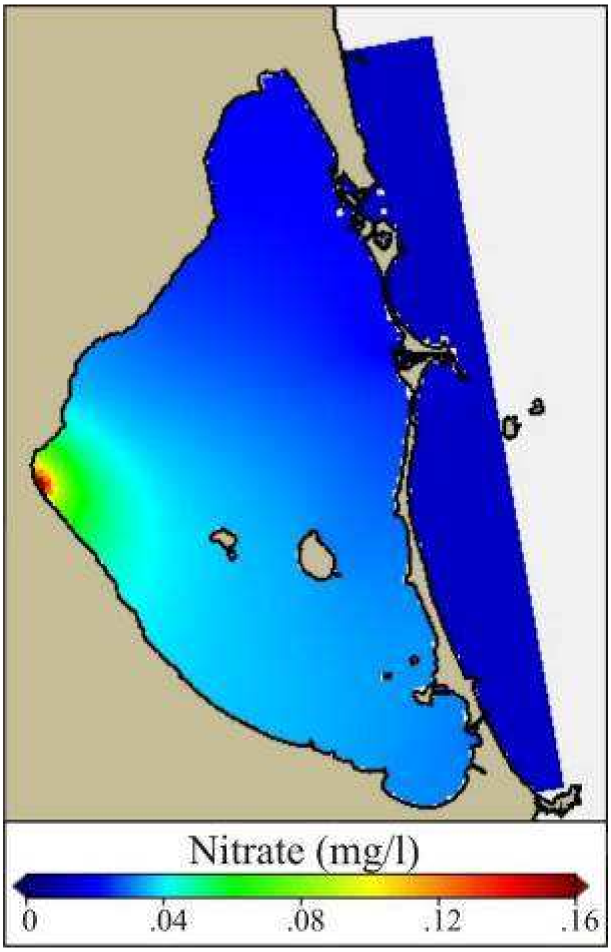

Fig. 4.2. Yearly averaged nitrate concentrations in 2002 computed by the ecological model displaying a clear gradient from the mouth of El Albujon wadi to the centre of the lagoon.

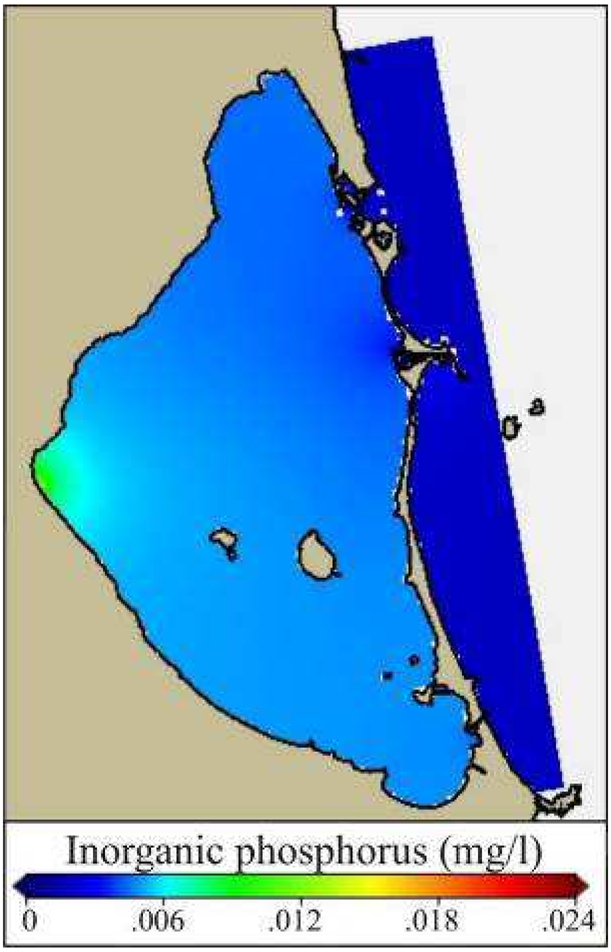

Fig. 4.3. Yearly averaged inorganic phosphorus concentrations in 2002 computed by the ecological model displaying a clear gradient from the mouth of El Albujon wadi to the centre of the lagoon.

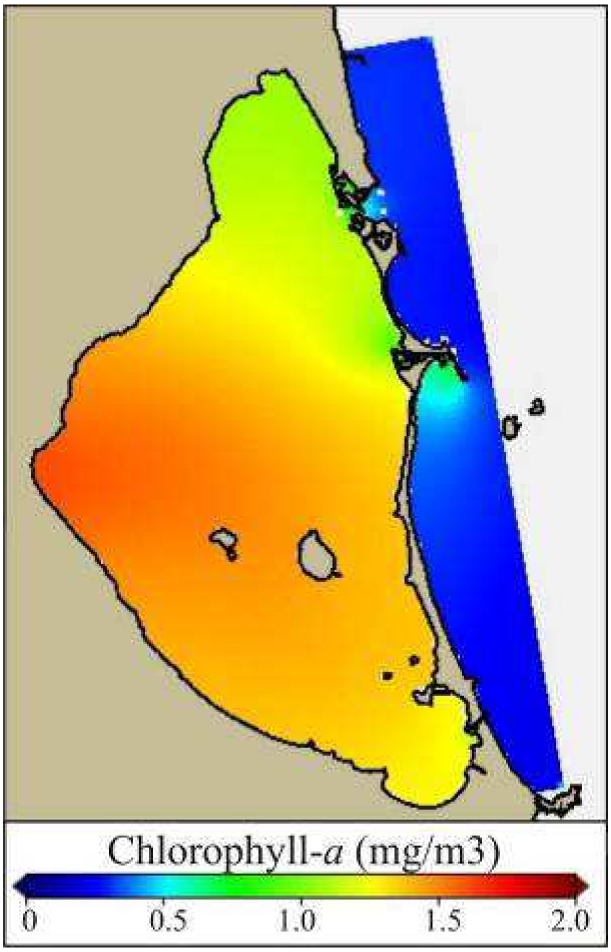

Fig. 4.4. Yearly averaged chlorophyll-*a* concentrations in 2002 computed by the ecological model displaying a clear gradient from the mouth of El Albujon wadi to the centre of the lagoon.

4.2 Validation methodology and results

After the ecological model calibration, in order to validate our results, the model simulated the period from January to November 2003, and computed values of nitrate, inorganic phosphorus and chlkorophyll-a concentrations were compared with the data collected by our team at six sampling stations in the Mar Menor (see Fig. 2.6).

Results showed a good agreement with the observations for all variables, and the model reproduced well the evolution of nutrient and chlorophyll concentrations in the Mar Menor during the validated year. A summary of the validation metrics is presented in the following Table:

Table 4.4. Validation metrics for nutrients and chlorophylls in the validated period.

Variable	Metric	Value	
		Measured	Computed
Nitrate (mg·l^{-1}) (n = 36)	Mean	0.255	0.211
	S.D.	0.386	0.290
	RMSE	0.188	
	NRMSE	0.101	
	R^2	0.79	
		Measured	Computed
Inorganic phosphorus (mg·l^{-1}) (n = 36)	Mean	0.012	0.011
	S.D.	0.013	0.011
	RMSE	0.005	
	NRMSE	0.102	
	R^2	0.86	
		Measured	Computed
Chlorophyll-*a* (mg·l^{-1}) (n = 36)	Mean	1.652	1.729
	S.D.	0.776	0.796
	RMSE	0.304	
	NRMSE	0.113	
	R^2	0.86	

The reduced number of samples did not allow the calculation of metrics for individual stations, but, in the light of the values of the metrics listed above, we can conclude that the ecological model accurately describes major patterns in nutrient and chlorophyll concentrations in the lagoon. Computed metrics displayed even better results for the validated period than those obtained during the calibration of the model, including the linear adjustments and the values for R^2 (Fig. 4.5). This result can be due to the fact that validation was carried out by comparing our model results with data obtained along the main nutrients and chlorophyll gradients in the lagoon.

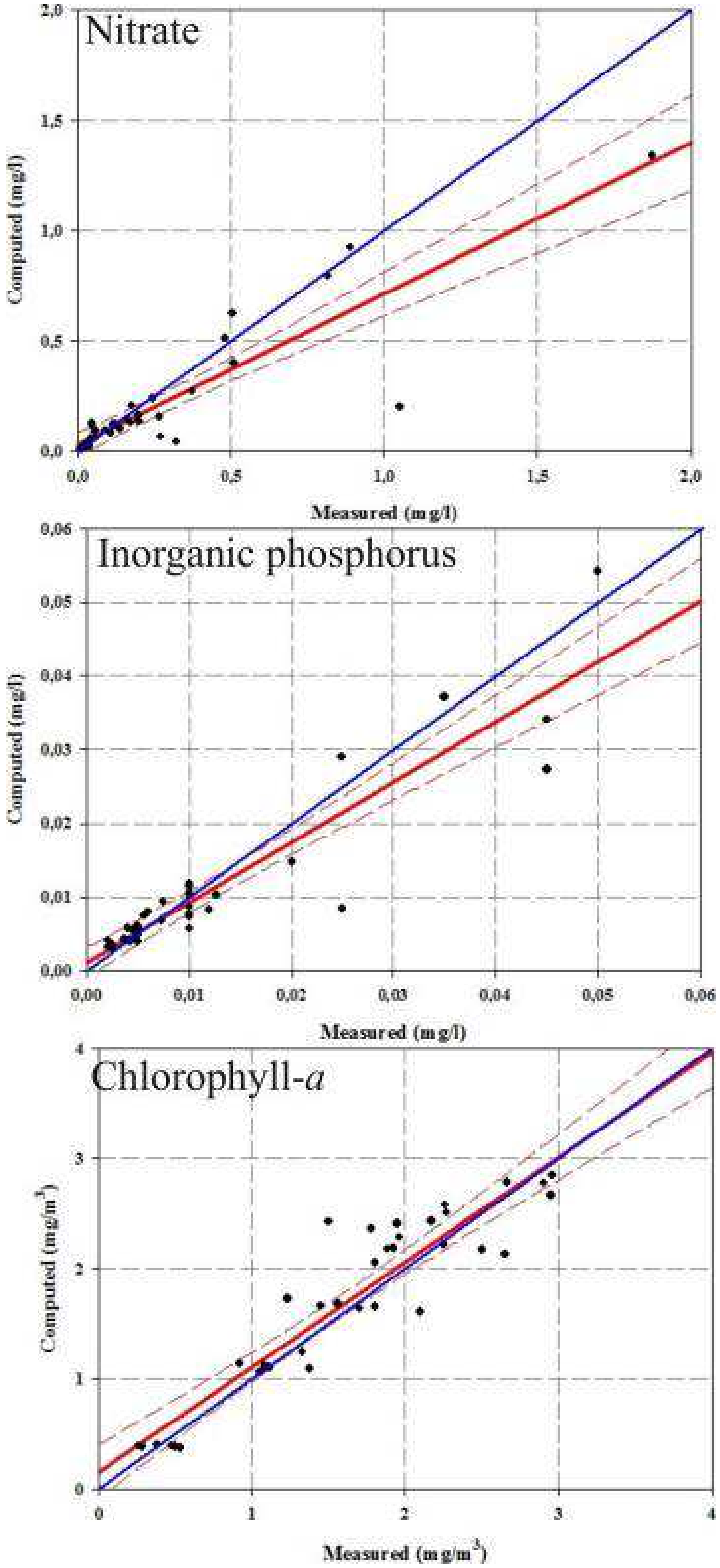

Fig. 4.5. Linear adjustments between measured and computed values of nitrate, inorganic phosphorus and chlorophyll-*a* concentration during the validated period (red lines). Blue line represents the 1:1 adjustment. Dashed red lines represent the 95% confidence interval.

Computed *Caulerpa prolifera* biomass distribution was also compared with measured data during the validated period. Results are shown in Table 4.5. In general, the model accurately reproduces general biomass distribution patterns in the lagoon, displaying higher biomasses in the central part of the lagoon and lower biomass in shallow areas (Fig. 4.6).

Table 4.5. Validation metrics for *Caulerpa prolifera* biomass in the validated period.

Variable	Metric	Value	
		Measured	Computed
Biomass (g·m^{-2}) (n = 23)	Mean	147.6	110.2
	S.D.	89.3	67.0
	RMSE	55.3	
	NRMSE	0.221	
	R^2	0.80	

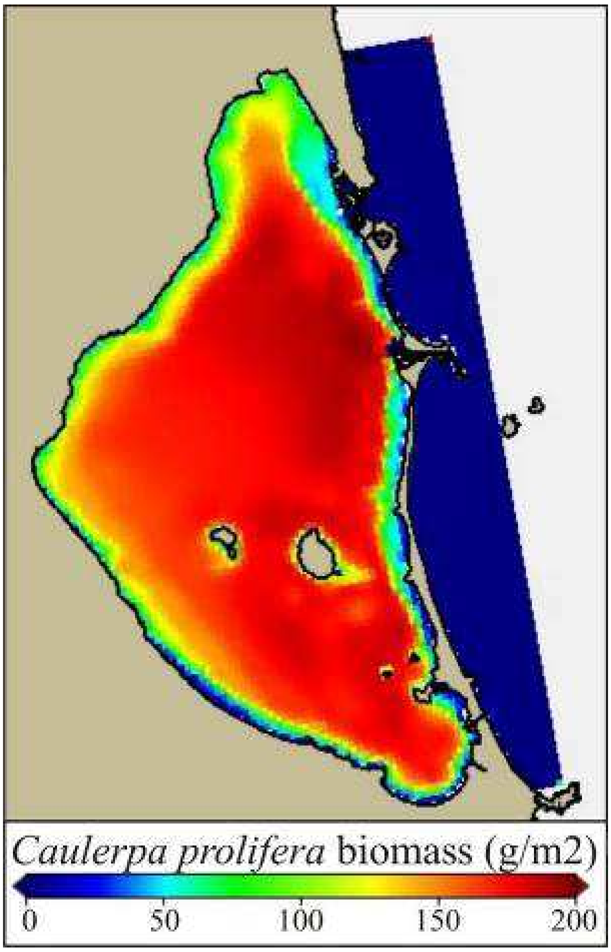

Fig. 4.6. Computed *Caulerpa prolifera* biomass distribution in the Mar Menor lagoon.

In global terms, the model predicts an averaged total algal biomass of approximately 21285 Tons of *Caulerpa prolifera* biomass in the lagoon for the year 2003, a value that is in the same range of previous estimations of 18215 Tons made by Lloret et al. (2008).

It can be concluded that the model accurately describes major patterns in nutrient and chlorophyll concentrations in the Mar Menor lagoon. The model is also able to reproduce *Caulerpa prolifera* bottom distributions. Considering the assumptions and simplifications of our 2-D ecological model for the Mar Menor lagoon, the results of the calibration and validation of the model can be considered satisfactory in order to represent the ecological status of the lagoon.

5. Problems and recommendations

One of the first problems that arose during the preparation of data and set-up of our models was the lack of accurate bathymetric data in the lagoon, in particular for the three main inlets that connect the lagoon with the adjacent Mediterranean Sea. Two of these inlets, El Estacio and Marchamalo channels, have been highly modified, and periodically dredged. The other one, Las Encañizadas, constitutes a natural labyrinth of narrow and shallow channels, not very well described in the literature. More accurate measurements of depth and dimensions of these channels are of extremely importance for the future definition and improvement of our models. A re-design of our original orthogonal grid with more detailed spatial information in these inlets will allow in the future a substantial improvement of our hydrodynamic and ecological model results.

Despite the high number of scientific studies carried out in the Mar Menor lagoon area, one of the main problems for the calibration and validation of our models was data availability. Long term data series for our state variables are scarce and are usually incomplete and contain many gaps. Sampling periodicity was also an added issue for our model calibration/validation, since most sampling efforts were made on a fortnightly or a seasonal basis, being unable to describe properly some of the processes occurring in the lagoon at a much faster temporal scale (e.g. storm events).

Recently, some efforts have been made in this sense, including the creation of a monitoring network in the lagoon that is providing monthly records of salinity, temperature, nutrient and chlorophyll concentrations, organic and inorganic pollutants in a total of 28 stations well distributed in the study area. However, we could not use this data for the calibration or validation of our model due to the inexistence of a gauge station at El Albujon wadi. Despite the low discharge volumes, major gradients for nutrients and chlorophylls in the whole lagoon are strongly affected by El Albujon inputs, so detailed freshwater and nutrient input data series from this wadi are of extreme importance for a correct comparison of modelled data with the observed records for these variables.

Furthermore, some efforts are still necessary in order to better quantify the concentrations of certain nutrient forms in the lagoon. On one hand, some inorganic nutrient forms, such as ammonia and inorganic phosphorus, are usually reported as ‘zero’ or ‘below detection limits’. It seems clear that sampling methodologies and analyses are not accurate enough to describe their concentrations and, although negligible, the proper description of these nutrients will permit a better calibration of the ecological model. On the other hand, particulate forms of nitrogen and phosphorus need to be adequately quantified both in the water column and the

bottoms, and remineralization processes properly described. These processes seem to be extremely important in the lagoon, but they received little attention so far.

Another aspect that requires further research in order to improve the quality of our hydrodynamic and ecological models is the characterization of the influence of storm events on the freshwater, nutrient and particulate inputs from the wadis. The scarce precipitation and the torrential nature of the very few rain events in the area are the reasons that freshwater and nutrient inputs entering the lagoon mainly occur during these particular events that usually take place for a few hours, although their effects can last for several days in terms of their influence on water transparency, and can have a strong influence on the areas located close to the mouth of the wadis (Marin-Guirao et al., 2007).

Some of the previous studies carried out in the Mar Menor lagoon helped the parameterization of some of the processes modelled, such as the mentioned studies of Terrados (1991) for *Caulerpa prolifera* photosynthesis, production and nutrient requirements. However, the area still lacks a better description of some of the processes that determine, for example, phytoplankton and zooplankton dynamics (including jellyfish) or a quantification of nutrient fluxes from the organic enriched sediments in the lagoon. Furthermore, particulate nutrient forms have been insufficiently quantified and their dynamics hardly ever described. However, these particulate forms seem to have an enormous importance in the lagoon, probably affecting transparency in the water column as well as nutrient fluxes to and from the sediments.

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Chapter 4

The Tyligulskyi Liman Lagoon - Modelling results and recommendations

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1. Introduction

For simulation of hydroecological processes in the Tyligulskyi Liman Lagoon, a modified version (Brooks, 2008; Ivanov and Tuchkovenko, 2008) of the three-dimensional numerical non-stationary hydrothermodynamic model (MECCA, Model for Estuarine and Coastal Circulation Assessment) is used as a basic model (Hess, 1985, 1986, 1989, 2000).

Calibration and validation of the hydrothermodynamic model are based on the data of hydrological observations in the lagoon in the spring-summer period of 2010 and 2012. The hydrological conditions in the Tyligulskyi Liman Lagoon in the selected years are characterized by considerable differences in variability of vertical thermohaline structure of water.

An environmental model (for water eutrophication) which is used for the Tyligulskyi Liman Lagoon is the above mentioned hydrothermodynamic model, supplemented by a biogeochemical unit. Mathematical structure of the biogeochemical unit of the water eutrophication model is based on synthesis of well-known models for water quality (RCA - HydroQual, 2004; Cerco and Cole - CE - QUAL - ICM, 1995, Ambrose et al - WASP5, 1993). Previously the model was verified for the north-western part of the Black Sea (Tuchkovenko and Savin, 2006; Tuchkovenko Y.S et al - OSENU, 2011). For the case of the Tyligulskyi Liman Lagoon, the macrophytes were included in the mathematical structure of the biogeochemical unit of the model on the basis of the principles stated in the paper (Muhammetoglu and Soyupak, 2000).

The environmental model parameters were calibrated on the basis of average long-term data on monthly variability in the modelled hydrochemical and hydrobiological characteristics of water in the Tyligulskyi Liman Lagoon during the vegetation season, obtained in the period of 2001–2011.

2. Data overview and analysis

2.1 Climate data

Long-term systematic observations of variability in meteorological parameters are carried out at the three maritime hydrometeorological stations located on the coast in the North-Western part of the Black Sea in relative proximity to the Tyligulskyi Liman Lagoon: Yuzhne, Odessa and Ochakiv (Fig. 2.1).

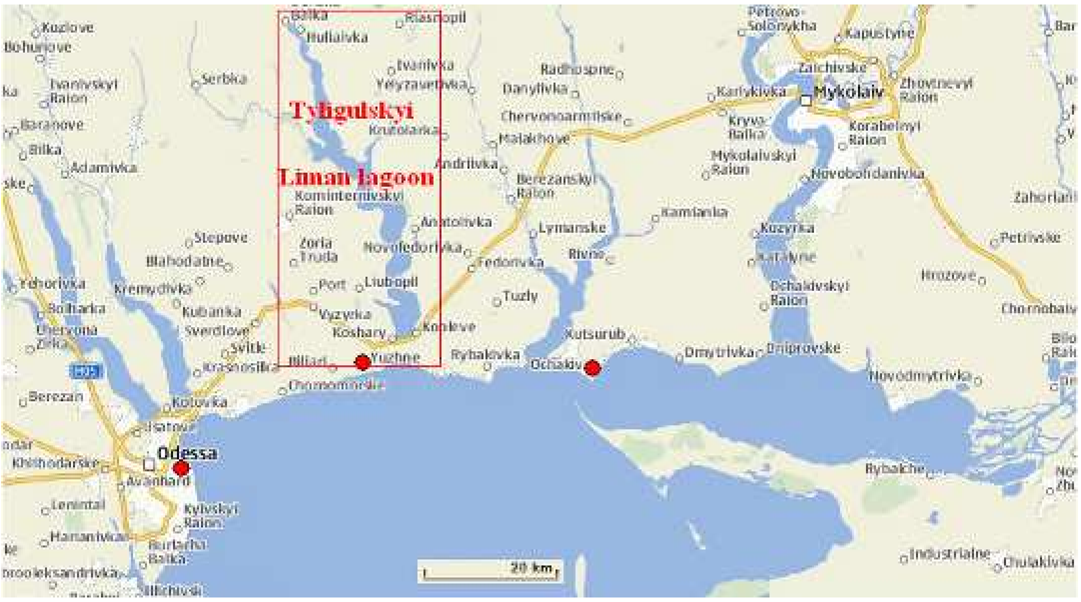


Fig. 2.1. Location of the maritime hydrometeorological stations in the coastal area of the North-Western part of the Black Sea close to the Tyligulskyi Liman Lagoon.

The system of observations at the hydrometeorological stations includes a set of meteorological parameters, needed for hydrodynamic and environmental modelling: wind speed and direction, air temperature, total cloud amount, relative air humidity, and atmospheric precipitation. The observations at the 'Odessa' and 'Yuzhne' stations were conducted with an interval of 6 hours, and at the 'Ochakiv' station – 12 hours. Unlike the 'Odessa' and 'Ochakiv' stations, where observations had been conducted well prior to the early 1960s, the observational series at the 'Yuzhne' station commenced only in the 1980s. Average long-term statistical characteristics of variability in some meteorological parameters observed at the mentioned stations are given in Ilyin at al. (2012); and The Climatic Cadastre of Ukraine (2006).

The observational data from the 'Yuzhne' station, located at the distance of approximately 10 kilometers from the southern boundary of the Tyligulskyi Liman Lagoon, were used as the basic data. The measurements of solar radiation intensity, performed with 3-hour interval at the 'Odessa' station, were also used.

The average monthly observational data from the weather-station of Bolgrad, located at the freshwater lake of Yalpug in the south of the Odessa Region, performed within the period of 1960 through 2010, were used for calibration of evaporation rate for the lagoonal water surface. These values were reduced to the observed values of lagoonal water salinity with the use of a

scaling multiplier (Tuchkovenko, Gopchenko, 2012) $k_s=-0.0033 \cdot S$, where *S is* the water salinity in ‰.

2.2 Hydrological data

Calibration and validation of the hydrothermodynamic model required the use of the observational data on water temperature and salinity in the Tyligulskyi Liman Lagoon obtained by the specialists of the Odessa branch of the Institute of Biology of the Southern Seas (OBIBSS), National Academy of Sciences of Ukraine, in 2002–2012. The major drawback of these observations is their irregularity, as their number varies substantially by years. The most informative are the observations in the shallow coastal zone at the central part of the lagoon, in a district between the Chilova and the Ranzheva spits of 2007–2012 (Fig. 2.2), as well as the observations at the inshore hydrological stations in deep parts of the lagoon, which were carried out in 2010 and 2012.

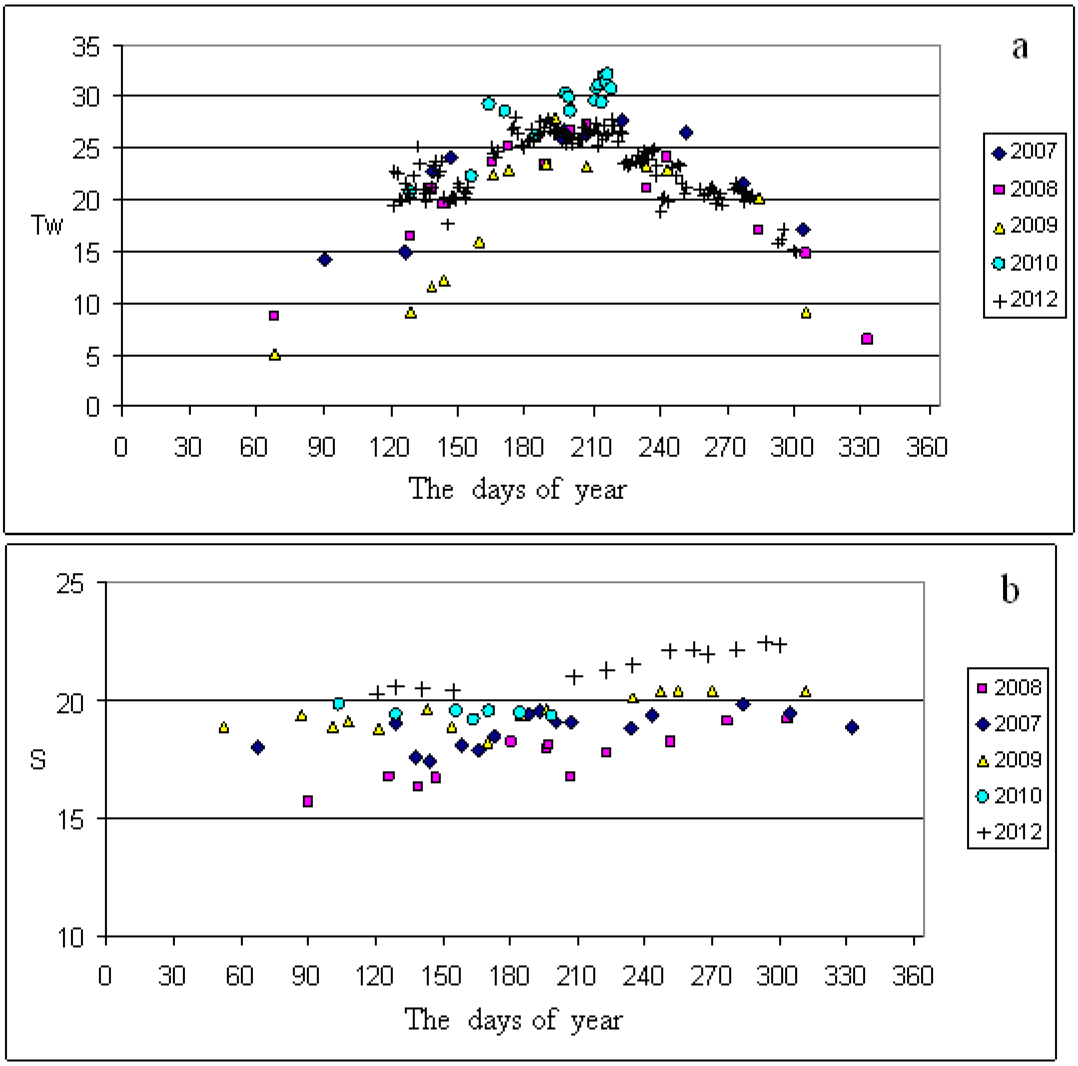


Fig. 2.2. Variability in water temperature (a), °C, and salinity (b), ‰, in the coastal zone of the Tyligulskyi Liman Lagoon between the Ranzheva and the Chilova spits.

A characteristic feature of the thermohaline structure of water in the summer of 2010 was emergence of cold and salt water in the benthic layer of the deep central part of the lagoonal water area. In July-August 2010, under the water temperature of 25–30 °C in the surface layer, the temperature did not exceed 8–9 °C at the depth of 14–15 m. However, the data of hydrological observations carried out in 2012 showed that under recurrent high stormy winds in early May through June, when heating of the surface water layer had not yet reached the maximum values, there occurred an intrusion of heat into the cold benthic layers. As a result, the vertical thermohaline stratification of water in the lagoon is characterized by considerably less vertical gradients of water temperature and salinity. So, in June 2012 the water temperature increased up to 20 °C at the depths of more than 10 m, and in August 2012 the distribution of water temperature by depth was almost homogeneous (Fig. 2.3). These properties of variability in the thermohaline structure of water in the lagoon, depending on the hydrometeorological conditions, were used for validation of the hydrothermodynamic model.

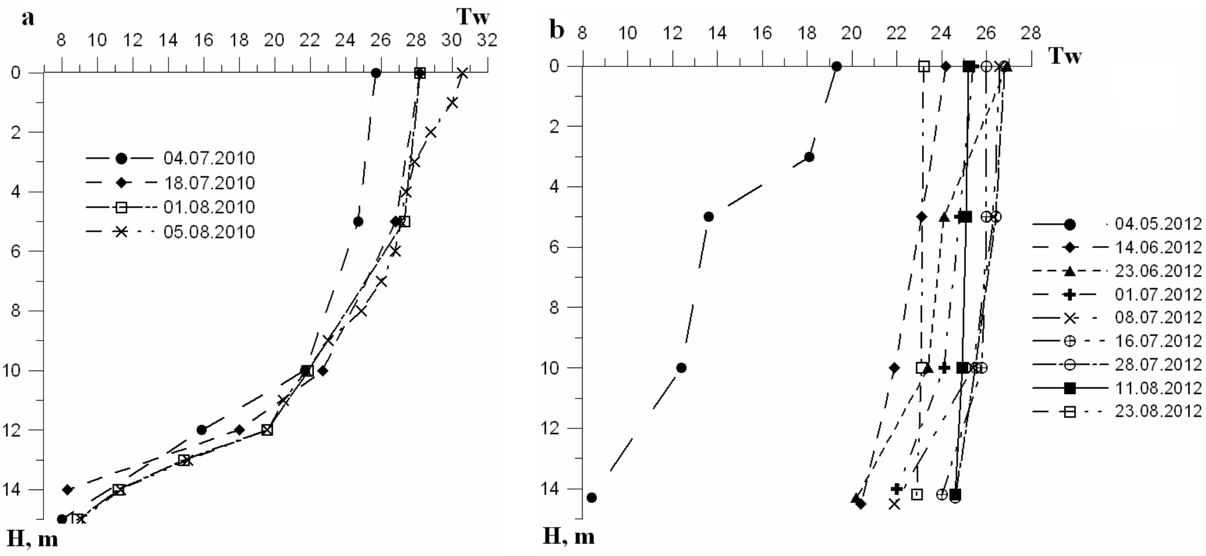


Fig. 2.3. Variability of the vertical thermal structure of water in the Tyligulskyi Liman Lagoon in (a) 2010 and (b) 2012.

In order to specify boundary conditions at the open sea boundary of the artificial canal, connecting the lagoon with the sea, the data of systematic observations of the fluctuations in the sea level (with the measurement interval of 6 hours), sea water temperature and salinity (average ten-day values), made at the ‘Port Yuzhnyi’ maritime hydrometeorological station, were used.

Specification of depths in the lagoon (Fig. 2.4) was based on generalization of the surveying works performed in the autumn of 2010 and 2012 by means of Fishfinder-250 (Garmin) electronic fathometer. Local positioning was being made with the use of GPS-72 (Garmin) navigator.

The data on long-term systematic observations of the water level in the lagoon at the ‘Koblevo’ water station in the period of 1936 through 1987 and incidental observations of the water exchange through the artificial connecting canal and the lagoonal water level in 2010 and 2012 were also used for calibration of the model.

The discharges of the Tyligul River (average monthly values, and in 2010 – average ten-day values) were specified on the basis of observational data obtained at the 'Berezivka' water station located 15 kilometres away from the upper reaches of the lagoon.

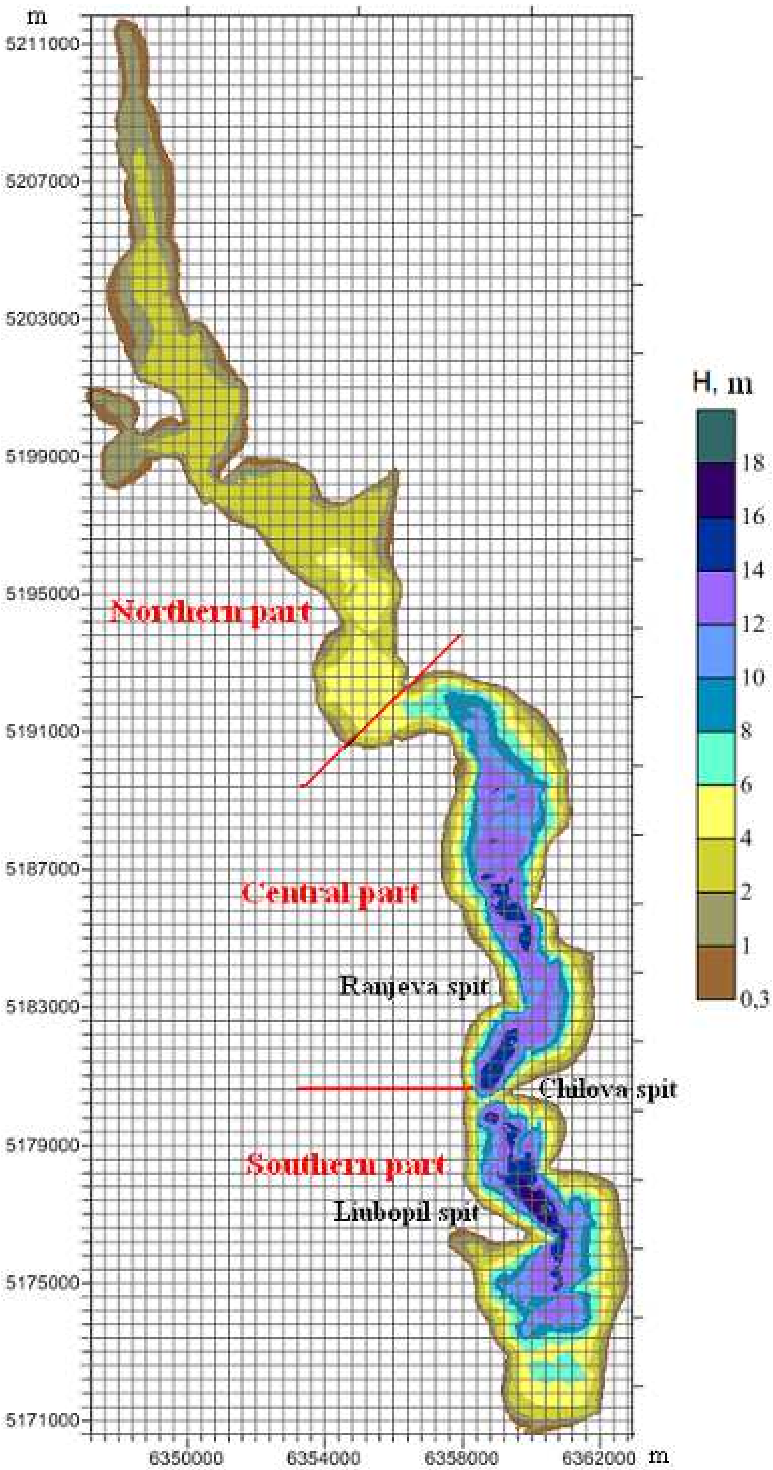


Fig. 2.4. Bathymetric chart in the WGS-84 coordinate system and division of the Tyligulskyi Liman Lagoon into areas.

2.3 Ecological data

The data of the hydrochemical and hydrobiological observations, which had been collected in the lagoon by the specialists of the Odessa branch of the Institute of Biology of the Southern Seas in the period of 2001–2010, were used for calibration of the ecological model. The system of observations of hydrochemical parameters of the lagoonal water included determination of concentrations of dissolved mineral forms of nitrogen (ammoniacal NH_4^+, nitrite NO_2^- and nitrate NO_3^-) and phosphorus (PO_4^{3-}), total nitrogen (N_{TOT}) and phosphorus (P_{TOT}), dissolved organic matter (*DOM*), and dissolved oxygen (O_2). The concentrations of organic nitrogen and phosphorus were calculated by the difference between the total content and the concentration of mineral forms: $P_{org} = P_{TOT} - P_{MIN}$, $N_{org} = N_{TOT} - N_{MIN}$.

The system of hydrobiological observations included determination of the concentrations of chlorophyll a, and sampling of phytoplankton and macrophytes (in the coastal shallow zone).

The major disadvantage of the hydroecological monitoring of water of the Tyligulskyi Liman Lagoon in the last decade is that it has been performed irregularly, predominantly in the coastal zone of the lagoon (Fig. 2.5), without a strictly established plan or scheme. The observations are of episodic nature and are non-uniformly distributed along the lagoonal water body. Their number significantly differs by years and months (Tables 2.1, 2.2). In certain years, the observations were not made at all. The hydrochemical and hydrobiological observations were often asynchronous.

In the course of analysis of the average long-term within-year variability of hydrochemical characteristics, to increase statistical reliability of the average values of concentrations, the data at the stations No. 1-3 and 4-8 were combined as the ones relating to the northern and the southern parts of the lagoon, respectively.

Hydrochemical characteristics of the Tyligul River water were assigned on the basis of observational data from the station of ‘Berezivka’, located 15 kilometres away from the upper reaches of the lagoon, for the period of 2001-2010, with the discreteness of once in a season.

The concentration of biogenic substances in the salt water, which inflow into the lagoon through the artificial connecting canal, were assigned on the basis of the data given in Hydrological and hydrochemical indicators (2008) and Zaitsev et al (2006).

The lagoonal ecosystem is not balanced on the content of basic biogenic elements - nitrogen and phosphorus. A characteristic feature of the hydrochemical regime of the lagoonal water is a high concentration of mineral phosphorus as compared to the mineral nitrogen (Figs 2.6, 2.7). Besides, the correlation between the nitrogen and phosphorus concentrations in the lagoonal water averages 1:10 for inorganic forms, 9.5:1 - for organic forms, and 3:1 - for total nitrogen and phosphorus.

The Tyligulskyi Liman Lagoon is characterized by the lack of fresh water balance owing to the intensive evaporation in summer and decrease in the Tyligul River runoff as a result of anthropogenic influence and the climate change. Its compensation requires annual replenishment of the lagoon with salt water. Otherwise, the water level in the lagoon may decrease by 1 m a year. Due to intensive evaporation in the summer period, the biogenic substances, inflowing into the lagoon with the lateral fresh water runoff and the sea water, are not taken away from it but accumulate over the years. As a result, the concentrations of mineral

and organic phosphorus in the lagoonal water are much higher than those in the Tyligul River and the sea (Fig. 2.6).

Fig. 2.5. Location of the environmental monitoring stations in the area of the Tyligulskyi Liman Lagoon.

In case of nitrogen, an accumulation of stable organic nitrogen is observed in the lagoon. The lack of mineral nitrogen (in the forms of ammonium, nitrites and nitrates) in the summer months can limit the primary production of organic substance by the phytoplankton. Its concentration in the lagoon is less than in the Tyligul River water, and, in certain months, is less than in the sea (Fig. 2.7).

One of the main environmental problems in the Tyligulskyi Liman Lagoon is the development of oxygen deficit (hypoxia) in the benthic water layer within deep areas of the lagooon in the summer period. The cases of complete lack of oxygen, observed in the areas where deep hollows in relief of the lagoonal bottom are located, had led to the hydrogen sulphide emergence in the water located deeper than the quasi-homogeneous mixed layer (Fig. 2.8).

Table 2.1. Information on the number of hydrochemical observations in the Tyligulskyi Liman Lagoon and their dates in the period of 2001-2010.

Year	Number of stations	Dates	Number of samples
2001	2	19.06	7
		29-30.10	3
2002	2	04.06	9
		13-14.08	22
2003	5	16.03	4
		22.04	8
		22.07	7
		17.09	5
		28.10	2
2004	3	10.06	4
		29.07	4
		23.09	3
2005	3	07.06	4
		28.07	3
		17.10	4
2006	1	31.05	3
2008	1	28.05	6
2010	3	27.06	3
		16.07	10
		22.07	17

Table 2.2. Information on the number of observations of phytoplankton biomass and chlorophyll a concentration in the Tyligulskyi Liman Lagoon in the period of 2001-2011.

Year	Phytoplankton		Chlorophyll a	
	Stations	Samples	Stations	Samples
2001	5	9	2	6
2002	2	7	2	14
2003	3	13	4	11
2004	–	–	1	2
2005	2	5	1	2
2006	3	9	1	3
2008	1	2	1	3
2010	10	11	7	26
2011	4	12	3	10

Yearly variability of phytoplankton biomass and chlorophyll a concentration in the photic layer of the lagoon, used for calibration of the biogeochemical unit of the model, is given in Fig. 2.9. The maximum values of phytoplankton biomass are observed in August, however, the data analysis made separately for the northern and the southern parts of the lagoon showed that the maximum of phytoplankton biomass is observed earlier in the northern, shallower part, of the lagoon, than in the southern part (in July), owing to faster heating of the water and influence of vertical turbulent and diffusion exchange in deep part of the lagoon. The occurrence of two

maxima in chlorophyll a concentration, the spring and the summer ones, draws attention to itself; the first of them is not displayed in the phytoplankton biomass. This fact implies a considerable seasonal variability in correlation between chlorophyll and an organic carbon in the phytoplankton cells (Fig. 2.10).

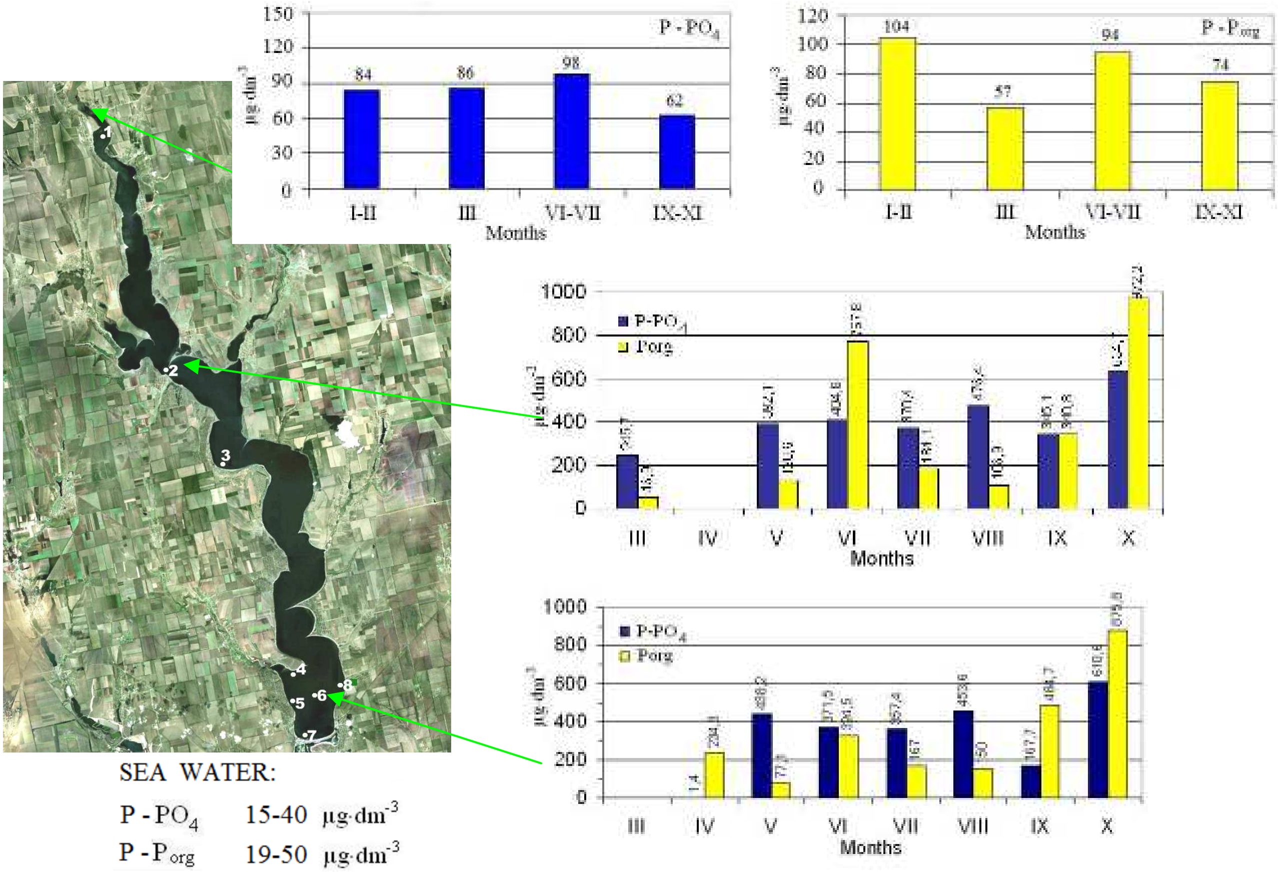


Fig. 2.6. Variability of phosphorus concentrations in the water of the Tyligul River, the northern and southern parts of the lagoon, and the sea water.

The bottom macrophytes are widespread in the significant water areas only in the northern shallow part of the lagoon, and in the southern and the central parts they are widely-distributed only in the narrow shallow coastal zone with the depths of under 4 m (Fig. 2.4), the width of which corresponds to 1-2 cells of the horizontal calculation net for the model (400 m). Seasonal variability of macrophyte biomass in various parts of the lagoon, with regard to its distribution by depths, is given in Fig. 2.11.

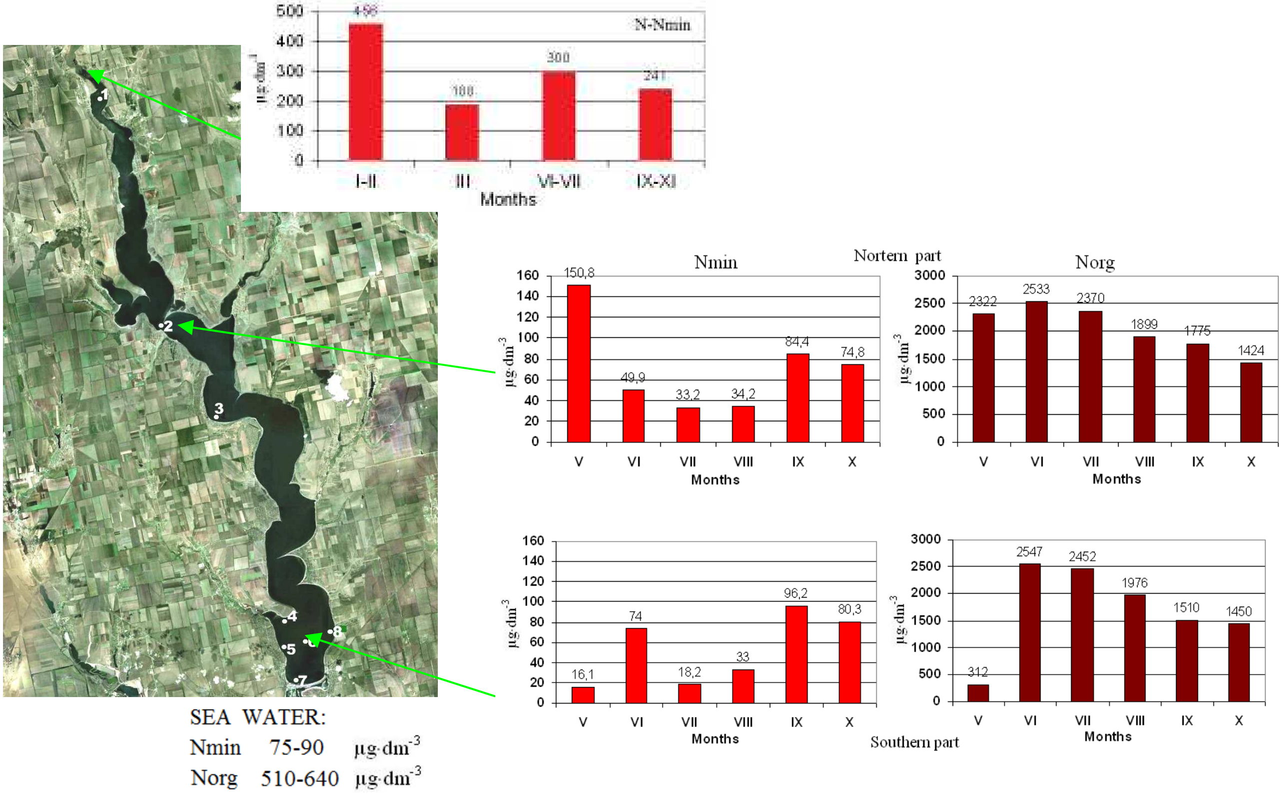


Fig. 2.7. Variability in nitrogen concentrations in the water of the Tyligul River, the northern and southern parts of the lagoon, and the sea water.

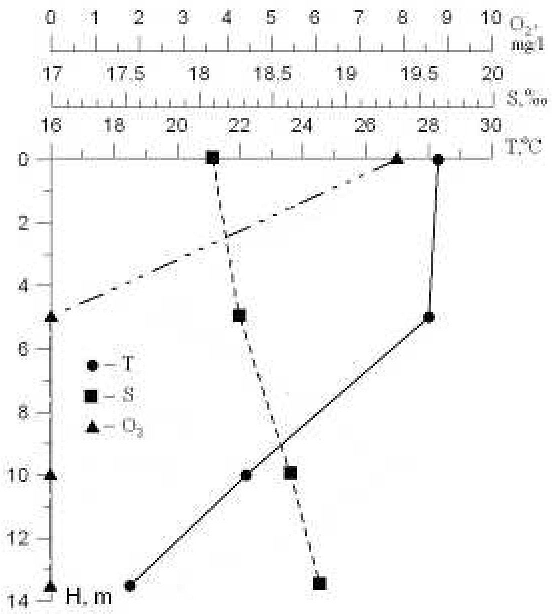


Fig. 2.8. Vertical distribution of water temperature (°C) and salinity (‰), and the content of the dissolved oxygen (mg·l^{-1}) within one of the deep hollows of the Tyligulskyi Liman Lagoon in August 2010.

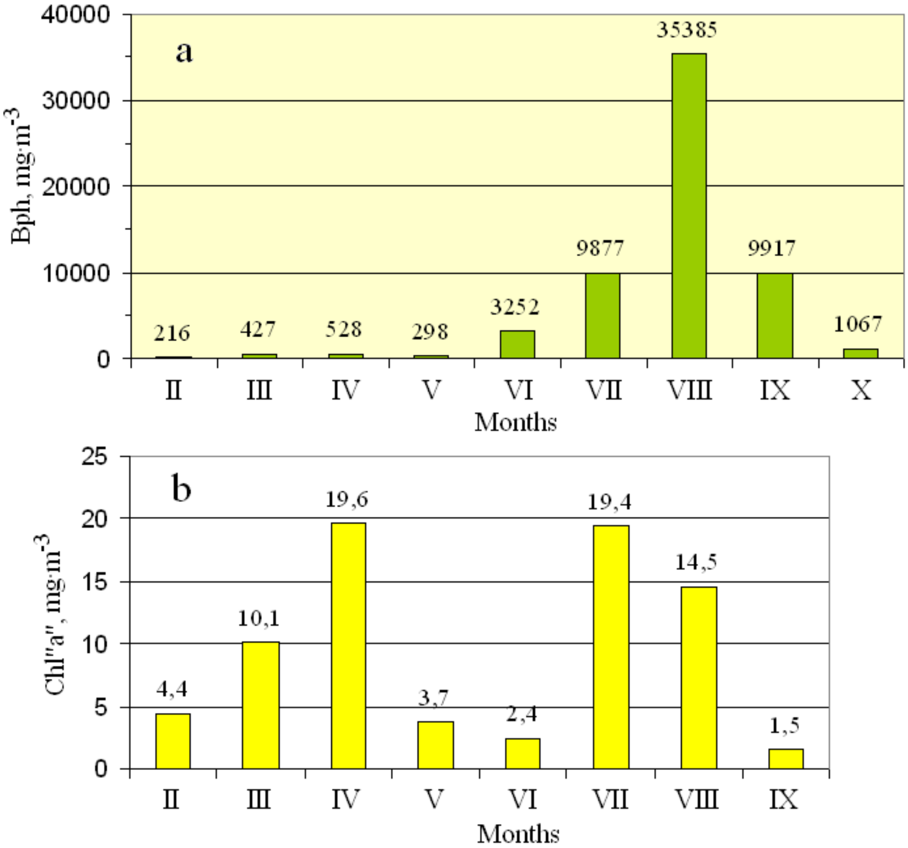


Fig. 2.9. Yearly variability of phytoplankton biomass (a) and chlorophyll “a” (b) concentrations in the water of photic layer in the Tyligulskyi Liman Lagoon, calculated on the basis of the observational data of 2001–2011.

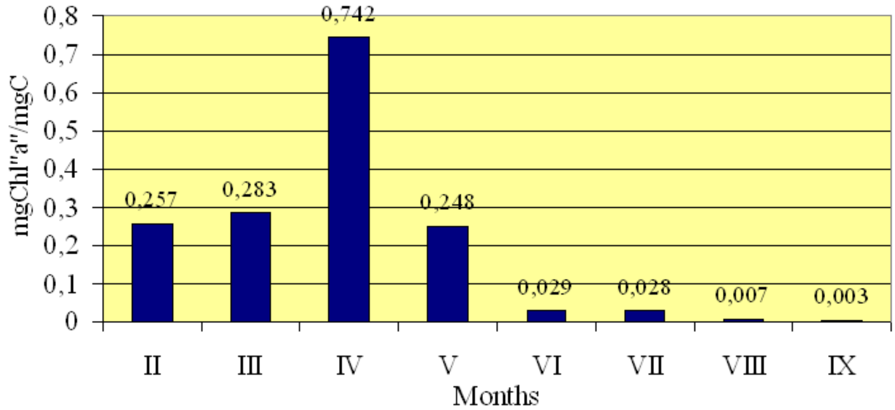


Fig. 2.10. Yearly variability of the ratio of the chlorophyll “a” to the organic carbon for phytoplankton, calculated on the basis of the observational data of 2001–2011.

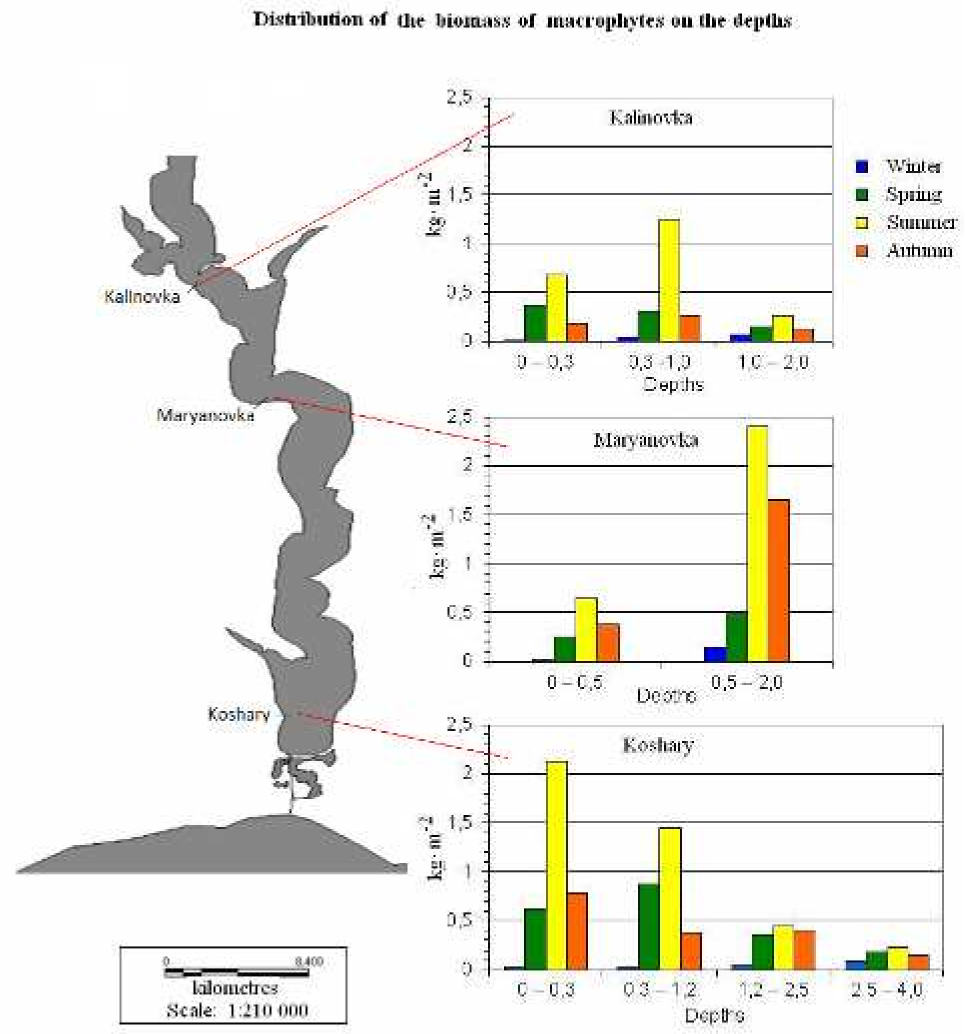


Fig. 2.11. Macrophyte biomass variability in various parts of the lagoon with regards to the depth and seasons, for the data of 2002 through 2011.

3. Hydrodynamic model calibration and validation

3.1 Calibration methodology and results

The model was calibrated in two stages for the conditions of 2010. At the first stage, a 1D version of the model was used (with the vertical axis resolution). In that version, the terms of equations describing a horizontal turbulent exchange and an advective transfer were excluded, and independence of all functions on horizontal coordinates was assumed. The baroclinic wind constituent of a stream velocity, being used for calculation of the coefficients of vertical turbulent exchange and diffusion, is the only wind constituent to be taken into account under such a problem statement. Thus, the problem of the vertical thermohaline water structure, formed as a result of the vertical turbulent impulse exchange and diffusion of heat and salts, was actually solved. The calculations were aimed to study the adequacy of reproduction by the model of the annual variability in the vertical thermohaline structure of the lagoonal water under the wind impact and the heat exchange with the atmosphere.

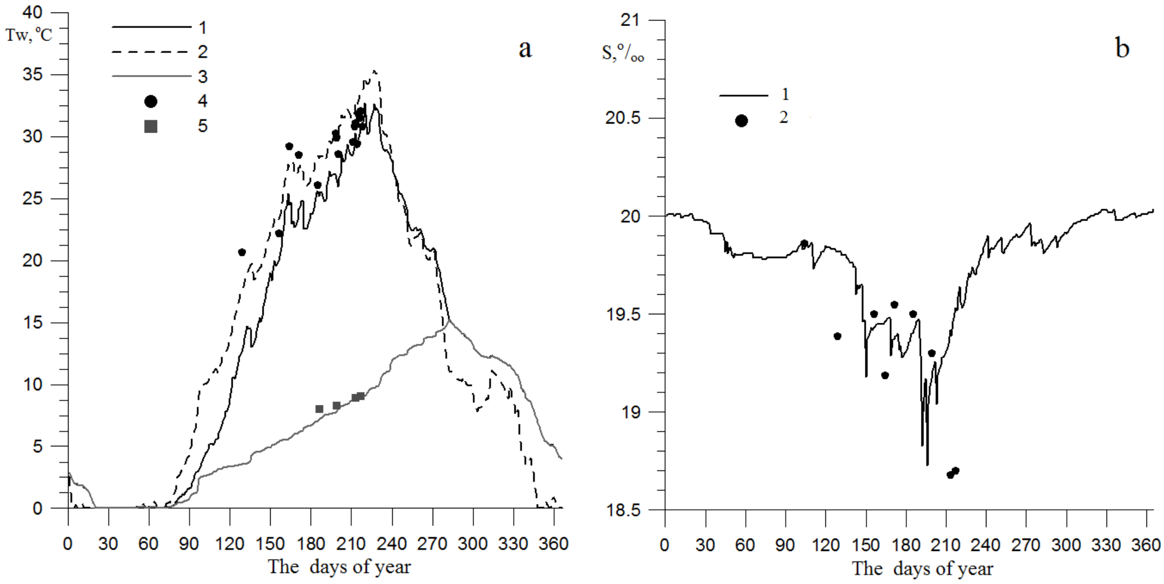
Numerical experiments with the model were made with uptake of the data of systematic 6-hour observations of the air temperature, wind speed and direction carried out at the 'Yuzhnyi' stationary maritime hydrometeorological station. The water columns of 3 m and 15 m depth were considered for characterization of water temperature variability in the shallow and deep parts of the lagoon. In order to take account of the influence of fresh water inflow into the lagoon with the Tyligul River runoff and the salt water through the canal on vertical thermohaline structure of waters in the deep parts of the lagoon, it was assumed that the waters were originally distributed within the limits of the near-surface layer of 1.5 m depth. The area of river water distribution in the northern part of the lagoon was assumed to be equal to 74.6 sq. km, and salt water distribution in the southern and central parts of the lagoon (up to the Kordonska spit) - 74.0 sq. km. Changes in the salinity of the near-surface water layer due to evaporation and atmospheric precipitation were also taken account of. Vertical distribution of the salt water temperature and the salinity was formed by the model in the course of computation.

The calculation results are given in Fig. 3.1 and 3.2. It is evident from Fig. 3.1a that the model correctly describes the annual variation of water in surface and benthic layers in the deep part of the lagoon. In the shallow water, owing to wind-induced turbulent mixing, the water temperature is vertically homogeneous and exceeds by a few degrees the values obtained for the deep part of the water area. This feature is verified by the observational data and can be explained by influence of the heat exchange with colder deep water on temperature of the surface water layer in the deep parts of the lagoon. Since the used observational data for the water temperature were obtained in the shallow coastal zone in deep part of the lagoon (in the area between the Chilova and the Ranzheva spits), alignment of the observed values between the model curves for the water columns of 3 and 15 m depth proves well-grounded. The shallow areas warm up more intensely in the spring-summer period and cool down faster in the autumn-winter period.

A seasonal thermocline is formed in May and breaks down in October (Fig. 3.2). Its location at the depths of 5-13 m matches the observational data.

The 3D version of the model was used at the second stage of calibration. In the course of the calculations the lagoonal water body was covered by a horizontal calculation grid of 41×108 mesh points with the mesh cell width of 400 m. 10 calculation levels along the vertical were used in the σ - system of coordinates. The depths in the lagoon, reduced to the lagoon watermark of -0.4 mBS, were assigned on the basis of the generalized data from the surveying works performed in the autumn of 2010 and 2012 (Fig. 2.4).

Spatio-temporal variability of the water level in the lagoon and the thermohaline structure of water was simulated for the period of 20 April through 31 August 2010 with regard to the Tyligul River runoff, the difference between the monthly totals of atmospheric precipitation and evaporation and water exchange with the sea through the artificial connecting canal. The choice of the above-mentioned time span for simulation is substantiated by several reasons: (1) availability of data of hydrological observations which can be the basis for the model verification; (2) formation and evolution of a seasonal thermocline which determines intensity of the vertical mass and gas exchange between the near-surface (photic) and benthic (aphotic) water layers in deep parts of the lagoon; (3) time of operation of the connecting canal in 2010.



Notation conventions: 1 – the model results for a water column of H=15 m depth, surface layer; 2 – the model results for a water column of H=3 m depth, depth-homogeneous distribution; 3 – the model results for a water column of H=15 m depth, benthic layer; 4 - observations in the coastal zone, in the area between the Chilova and the Ranzheva spits; 5 - observations in the roads of the area between the Chilova and the Ranzheva spits.

Fig. 3.1. Yearly variability of water temperature (a), °C and salinity (b), °/oo, calculated by the model under hydrometeorological conditions of 2010 and determined by the observational data.

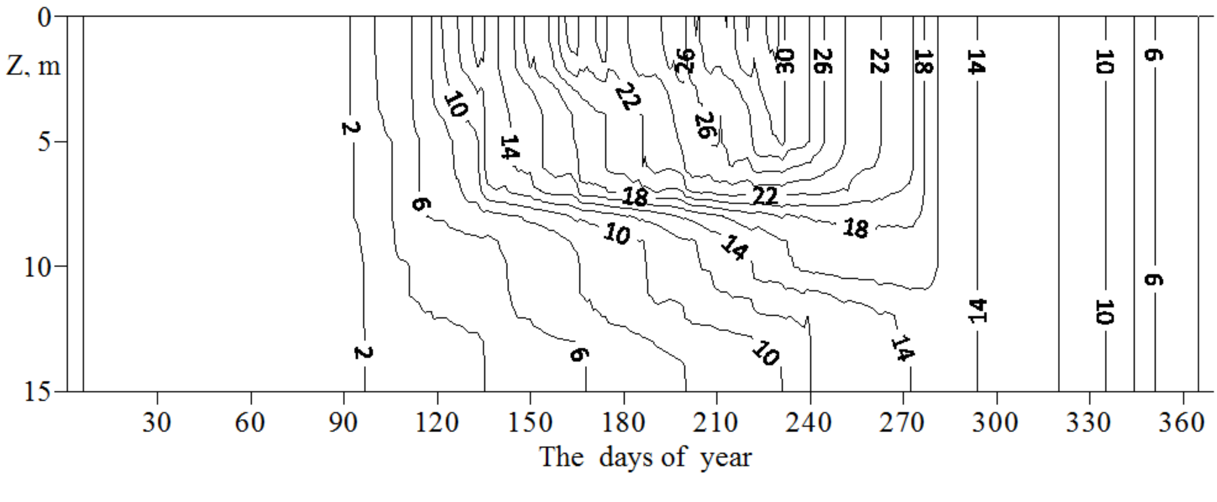
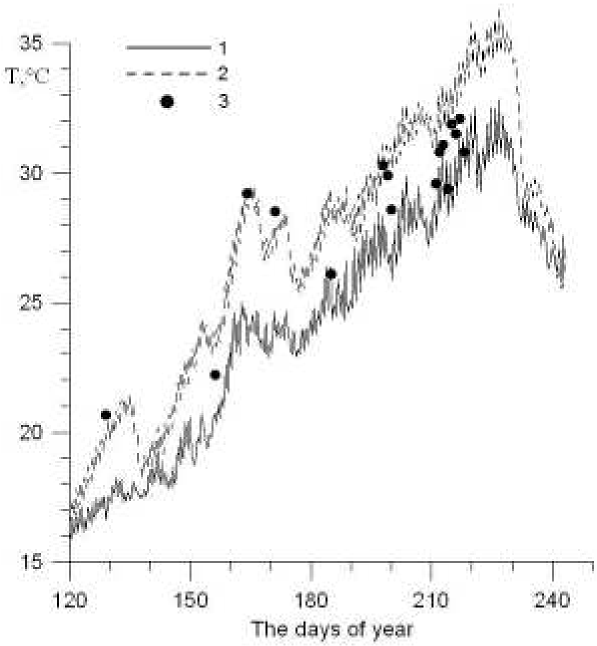


Fig. 3.2. Yearly variability of the vertical distribution of water temperature, °C, in the Tyligulskyi Liman Lagoon, obtained by means of 1D version of the model for hydrometeorological conditions of 2010.

The Tyligul River runoff was specified on the basis of the average ten-day observational data at the ‘Berezivka’ hydrological gauging station, temporal variability of wind direction and speed, air temperature, as well as seamarks (with the interval of 6 hours), daily amount of atmospheric precipitation, sea water salinity and temperature (average ten-day values) at the maritime boundary of the connecting canal – on the basis of the observational data obtained at the

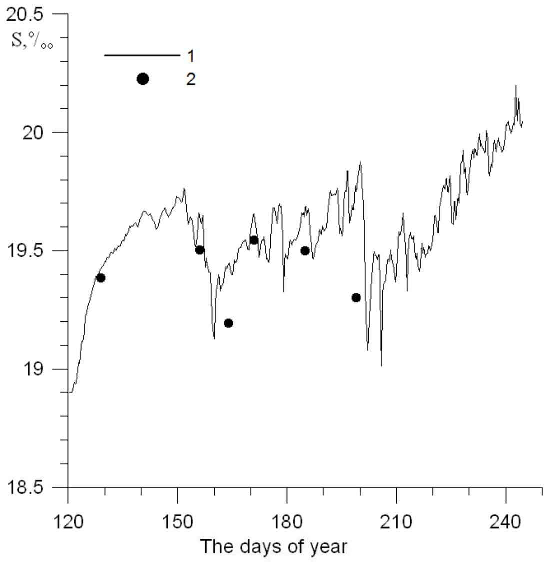
'Yuzhnyi' maritime hydrometeorological station. Evaporation from the lagoonal water surface was assigned on the basis of the average monthly observational data from the meteorological station of Bolgrad, averaged for the period of 1960 – 2010, reduced to the observed salinity of the lagoonal water. The width of the connecting canal was assigned to be equal to 30 m, and its initial depth at the seamark of minus 0.4 mBS – 0.25 m. The initial watermark in the lagoon, according to the observational data, was assumed to be - 0.2 mBS. A drop in watermark in the lagoon due to the difference between monthly totals of atmospheric precipitation and evaporation was taken into account. Vertical distribution of the water temperature and the salinity in the lagoon at the initial time was based on the observational data and assumed to be homogeneous on a horizontal plane.

Fig. 3.3 and 3.4 give a comparison of the variability in water temperature and salinity of the lagoon, obtained as a result of simulation and measured in the coastal shallow zone in the area between the Chilova and the Ranzheva spits in the central part of the lagoon (Fig. 2.4). It is evident that the measured values of water temperature correspond to the range of its spatial variability, calculated by means of the model for the respective points of time. In the period of calms and light winds the observed values are closer to those obtained under simulation for the shallow water areas of the lagoon, and under considerable winds, when horizontal advection of the water intensifies, they are closer to the values obtained for the deep areas of the lagoon. Good agreement is registered between the measured and the simulated values of water salinity.



Notation conventions: 1 – the model results for the deep part of the lagoon; 2 - the model results for the shallow zone; 3 - observations in the coastal zone in the area between the Chilova and the Ranzheva spits.

Fig. 3.3. Temporal variability in the temperature of the surface water layer, °C, in May-August 2010, obtained from simulation, in the deep central part and the shallow zone of the lagoon, and measured in the shallow coastal zone in the area between the Chilova and the Ranzheva spits.



Notation conventions: 1 - the model results; 2 - observations in the coastal zone in the area between the Chilova and the Ranzheva spits.

Fig. 3.4. Temporal variability in the salinity of the surface water layer, $^{o}/_{oo}$, in May-August 2010, obtained from simulation in the deep central part of the lagoon, and measured in the coastal zone in the area between the Chilova and the Ranzheva spits.

As follows from Fig. 3.5, the model satisfactorily reproduces the properties of the vertical distribution of water temperature in the deep central part of the lagoon - on the roads of the village of Pshenianove.

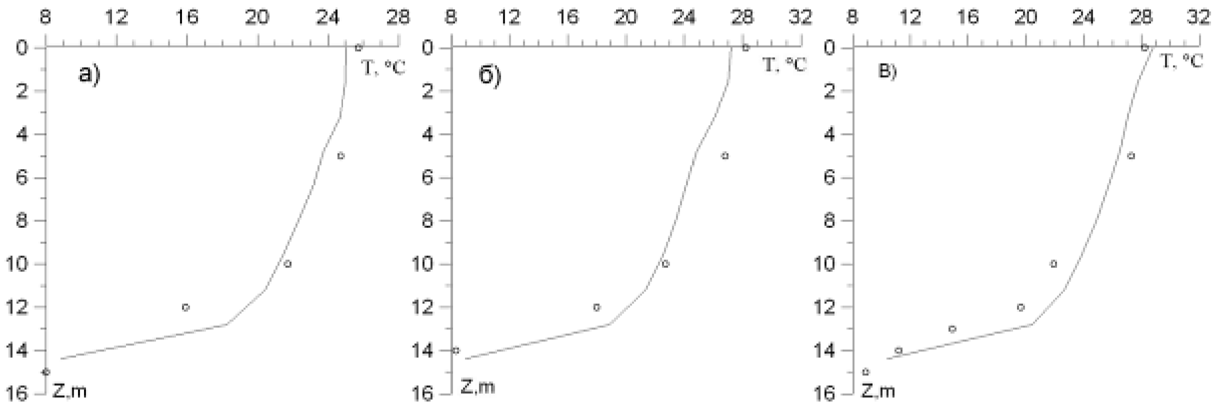


Fig. 3.5. Vertical distribution of water temperature, °C, obtained by the model (curves) and according to the data of observations in the central part of the Tyligulskyi Liman Lagoon (the roadstead between the Chilova and the Ranzheva spits) in 2010: (a) – 04 July 2010; (b) – 18 July 2010; (c) – 01 August 2010.

Variability of the depth-averaged stream velocity and the water discharges in the canal under the specified morphometric characteristics is given in Fig. 3.6. Barotropic streams and water discharges in the canal are characterized by very intense short-period variability, both by value and by direction, which is caused by the combined impact of wind and fluctuations of the water level in the lagoon and the sea. The value of stream velocities and water discharges in the

canal, obtained from the simulation, agree well with the data of a few incidental in-situ observations performed in 2010.

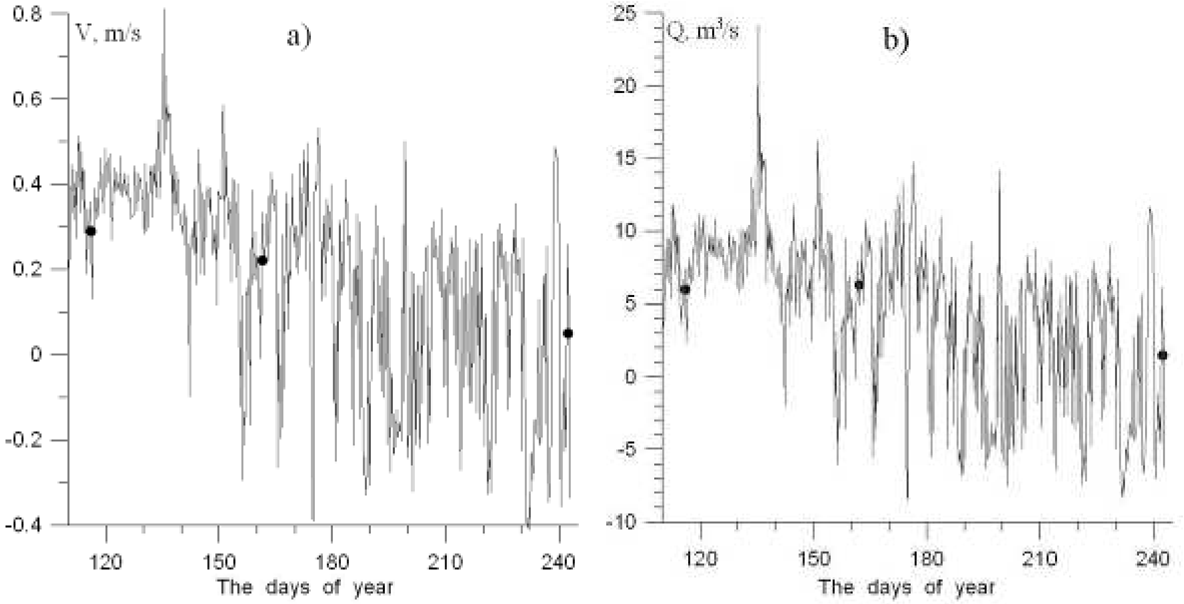


Fig. 3.6. Temporal variability in the speed of barotropic streams, m/s, (a) and the water discharges, m^3/s, (b) in the connecting canal (close to an outflow into the lagoon) at its present-day morphometric characteristics. The positive values correspond to the inflow of water into the lagoon, the negative ones – to the outflow. The dots correspond to the observational results.

Wind forcing exerts predominant influence on the water circulation in the lagoon. Measurements of the streams in the Tyligulskyi Liman Lagoon, conducted in 1979 through 1988, showed that the fields of wind-induced streams had extremely complicated pattern (Timchenko, 1990). Attempts to obtain a detailed picture of streams in the lagoon under stable winds, on the basis of field instrumental observations, did not yield positive results. Unfortunately, the available instrumentation has not changed since then. In addition, there exist problems of organizational and economic nature which do not make it possible to provide multi-day monitoring of streams in the lagoon by means of autonomous current meters. Therefore, the patterns for water circulation in the lagoon were specified only on the basis of the simulation results, which were compared to those obtained earlier by means of barotropic diagnostic models (Timchenko, 1990) and proved a good match.

Figs 3.7 to 3.9 present the fields of depth integral (barotropic) water circulation, typical for the lagoon, as well as the total streams in surface and benthic water layers in the periods of prevailing northerly and southerly winds, the average long-term recurrence of which makes up 32.8 and 20.2 %, respectively, according to the data measured at the 'Port Yuzhnyi' hydrometeorological station (Ilyin at al., 2012). It is clear that the spatial structure of barotropic streams has pronounced cellular nature and consists of a great number of vortical formations (circulation cells), located along the longitudinal axis of the lagoon. Such nature of water circulation is conditioned by the features of geomorphological structure of the lagoon - configuration of shores and the bathymetry along the lagoon. In the shallow coastal zone the total streams are uni-directional by depth and intensify in the areas where the coastline is leeward-oriented. Along the longitudinal axial line of the lagoon, corresponding to the maximum depths in every part of the lagoon, the benthic gradient counterflows with the

windward general direction are formed. These compensative bottom streams have an influence on surface drift flows, thus weakening them.

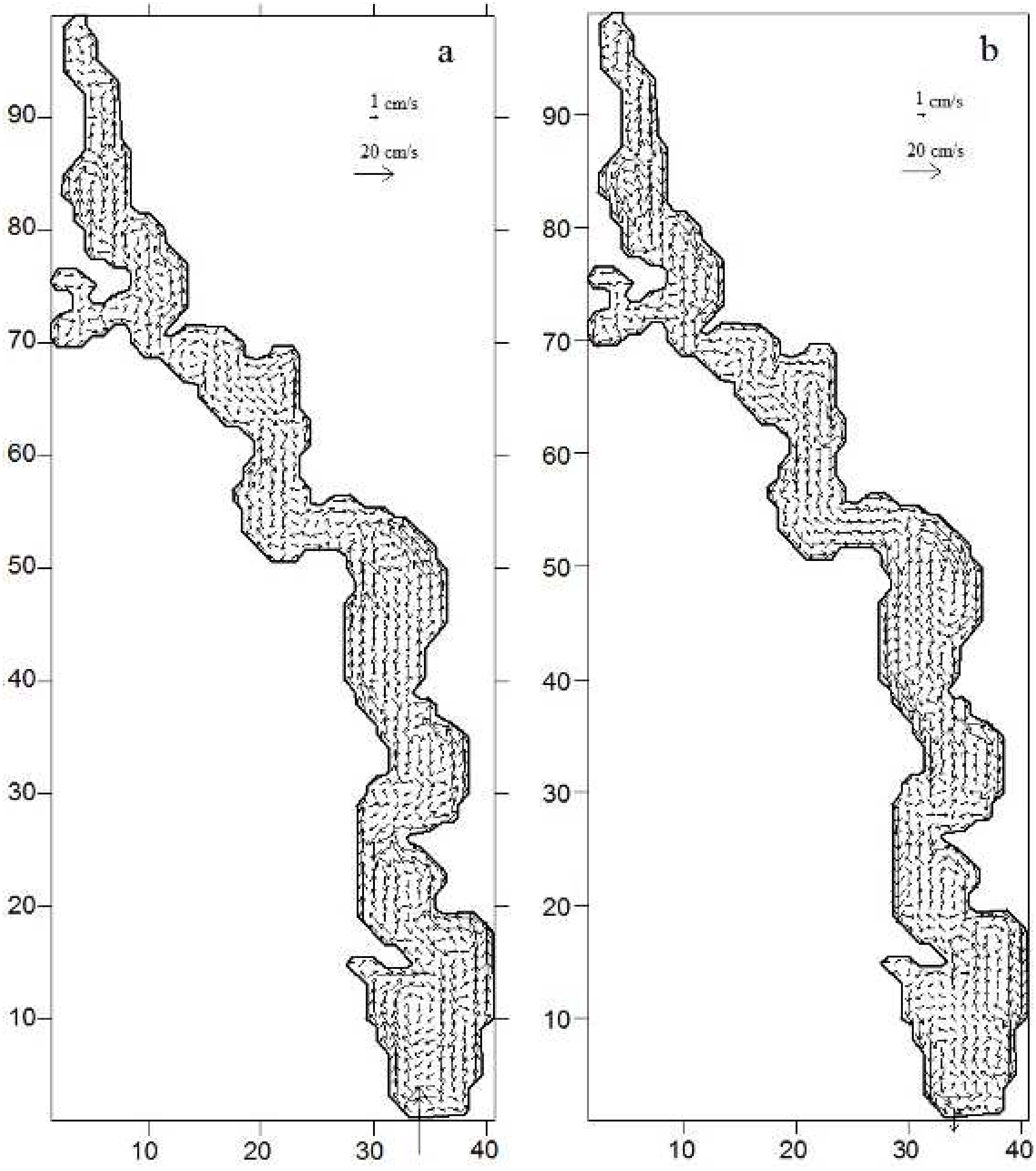


Fig. 3.7. Vector velocity fields for depth averaged streams under the winds with dominant (a) southern and (b) northern constituents, obtained during simulation of the conditions of (a) 17-18 May 2010 and (b) 15-16 June 2010.

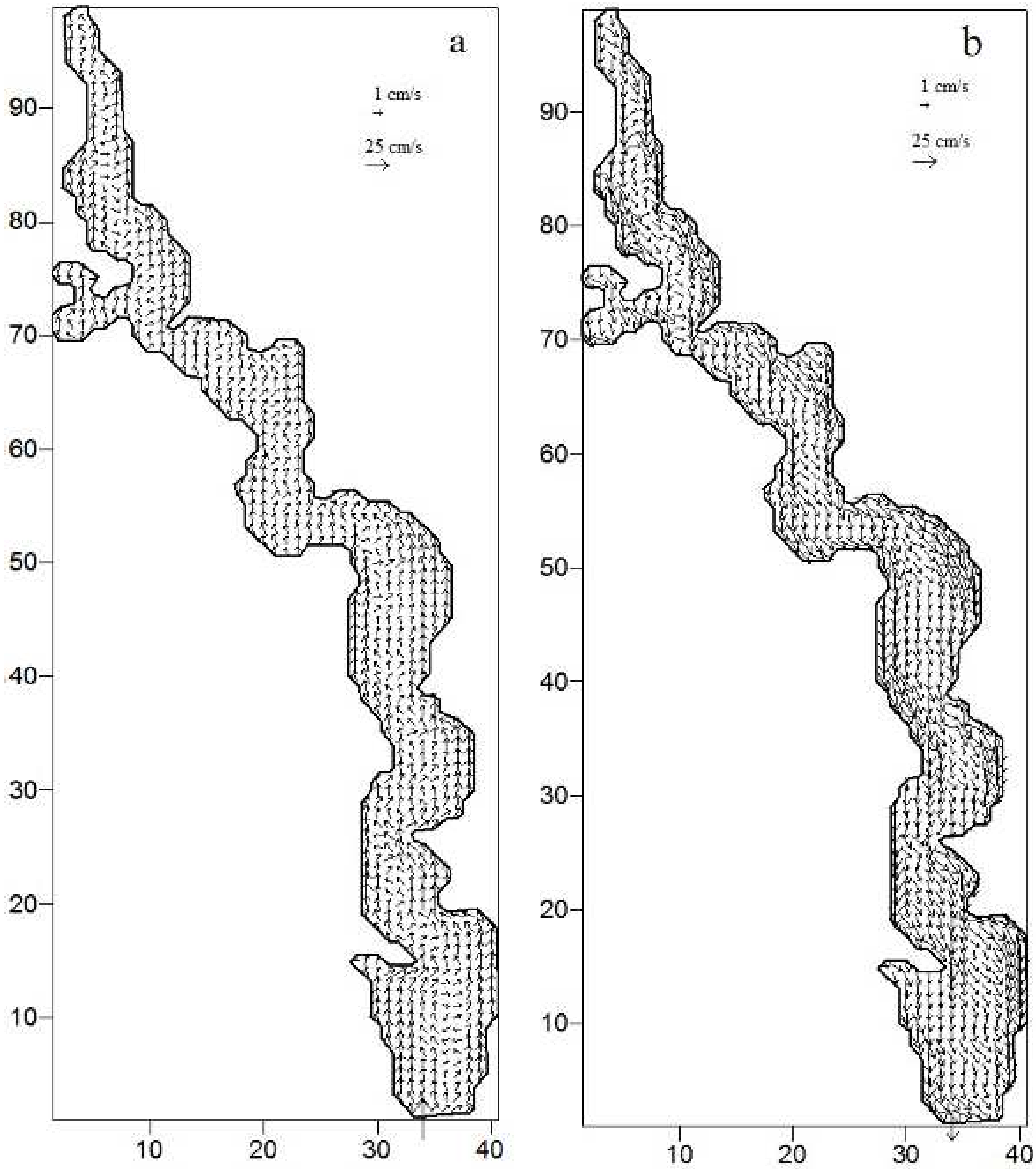


Fig. 3.8. Vector velocity fields for surface flows under the winds with dominant (a) southern and (b) northern constituents, obtained during simulation of the conditions of 17-18 May 2010 for (a) and 15-16 June 2010 for (b).

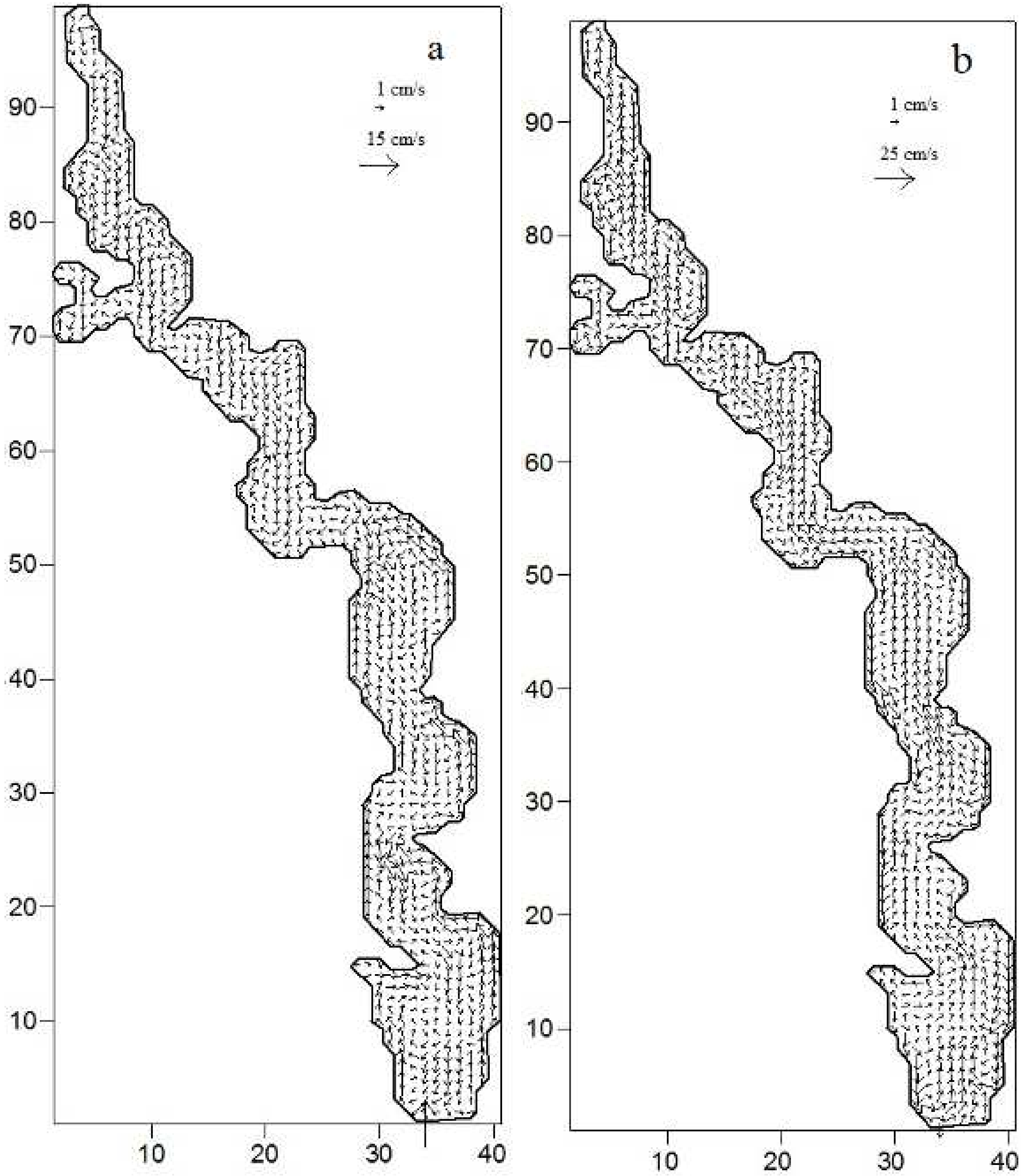


Fig. 3.9. Vector velocity fields for depth averaged streams under the winds with dominant (a) southern and (b) northern constituents, obtained during simulation of the conditions of 17-18 May 2010 for (a) and 15-16 June 2010 for (b).

The variability in spatial distribution of water temperature and salinity in the lagoon in May–August 2010, obtained from the simulations, is given in Figs 3.10 and 3.11.

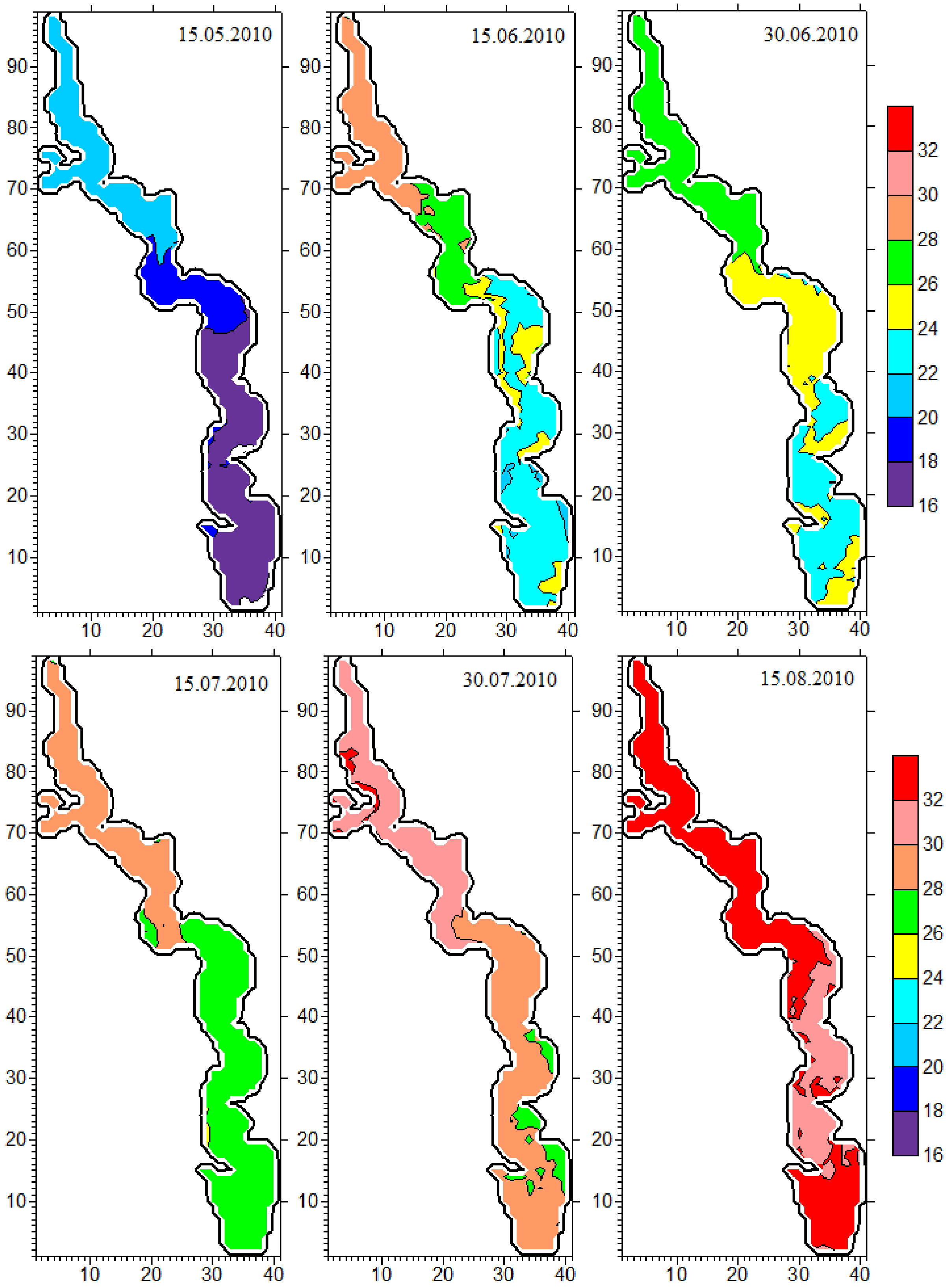


Fig. 3.10. Variability in the spatial distribution of water temperature, °C, of the surface layer in May-August 2010, obtained from the simulations.

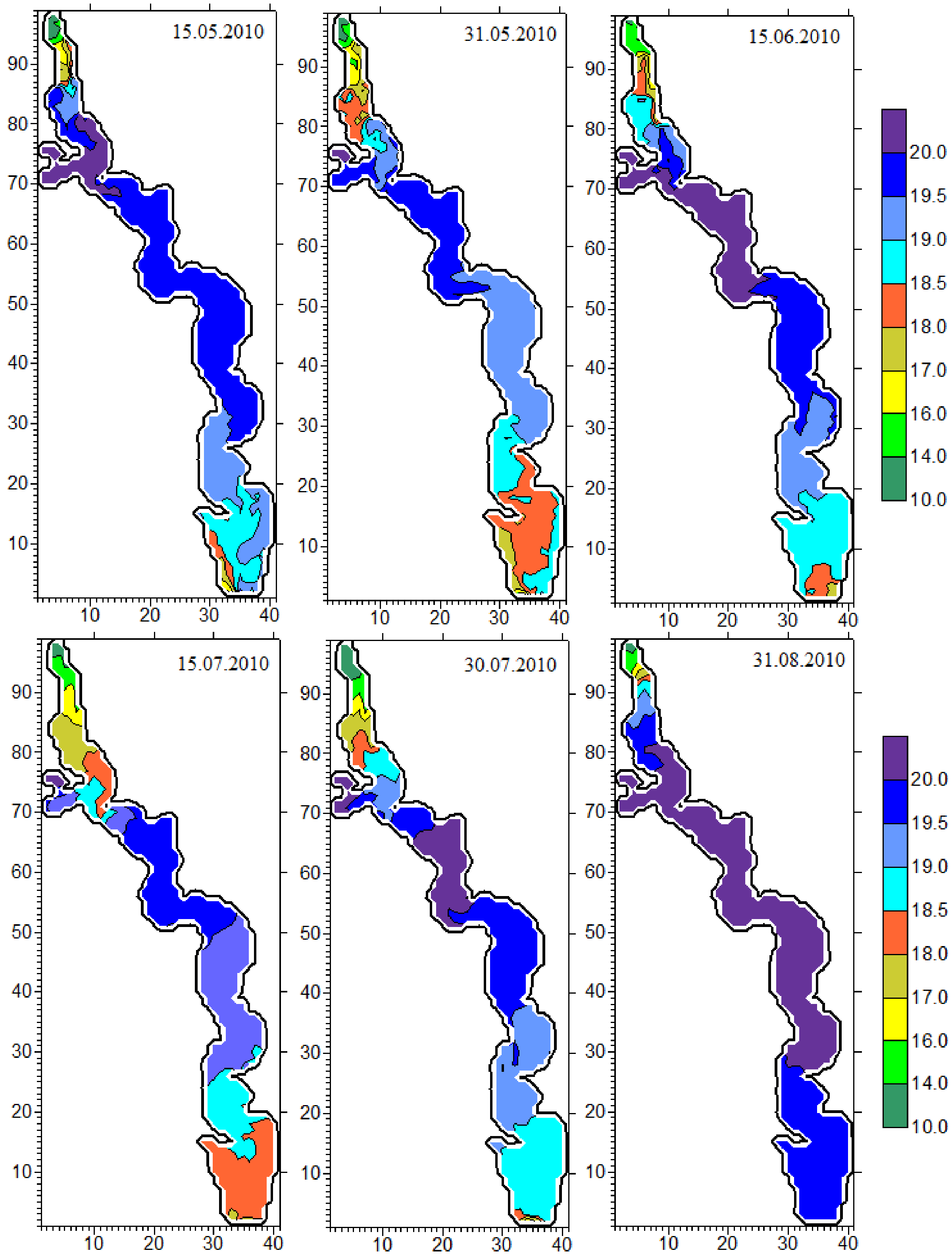


Fig. 3.11. Variability in the spatial distribution of water salinity, $^{o}/_{oo}$, of the surface layer in May-August 2010, obtained from the simulations.

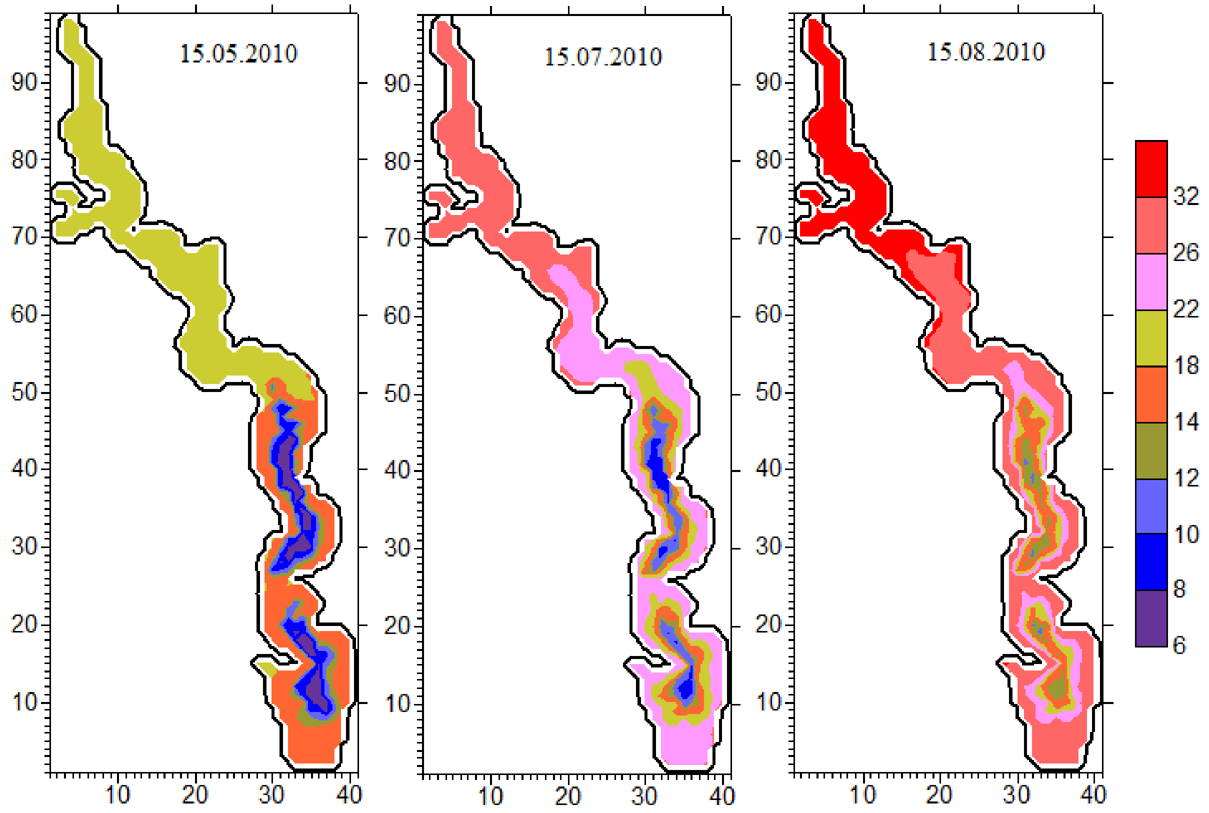


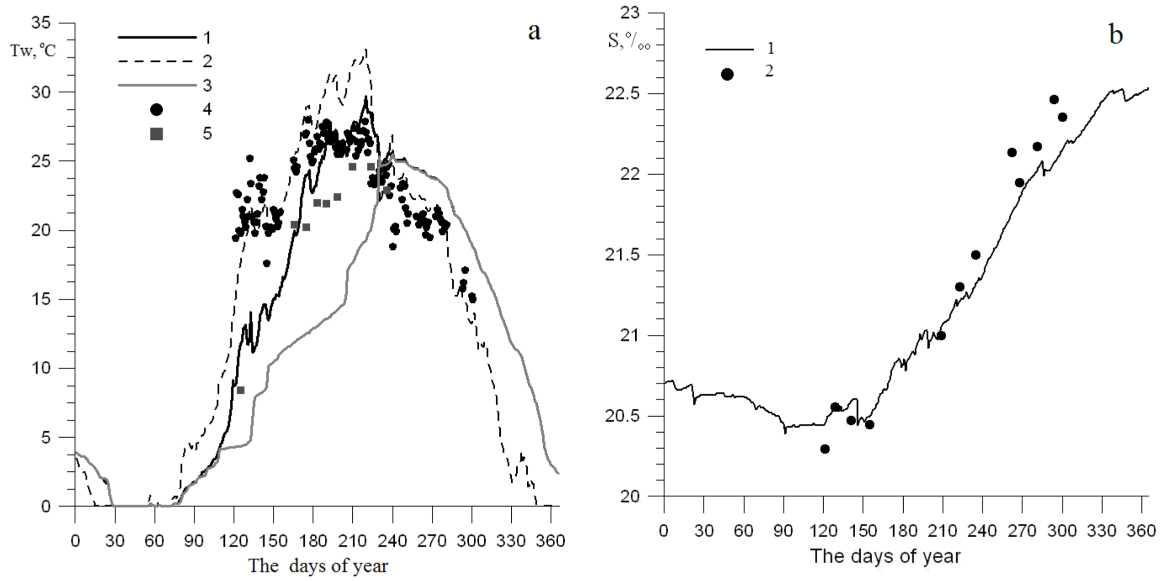
Fig. 3.12. Variability in the spatial distribution of water temperature, °C, of the benthic layer in May-August 2010, obtained from the simulations

3.2 Validation methodology and results

Validation of the hydrothermodynamic model was based on the data for thermohaline structure of water in the summer of 2012. A characteristic feature of the temperature conditions during that year consisted in considerable weakening of the seasonal thermocline in the late June and its almost complete disappearance by August.

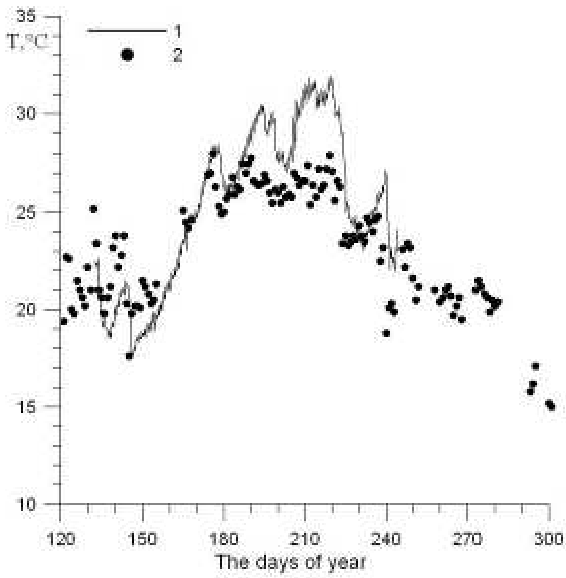
The scheme for model verification was the same as in the case of 2010. The 1D version of the model was originally used. Calculation was made for the period of 12 May through 31 August. The calculation results are given in Fig. 3.13. It is evident that the model satisfactorily simulated the variability in water temperature and salinity in the surface layer, however, though the water temperature in the benthic layer was higher than in 2010 (Fig. 3.1a), it was substantially underrated as compared to the observed values. In our opinion, it is a consequence of the fact that horizontal advection of the water, which resulted in the well heated shallow water transported into the deeper areas of the lagoon, had not been taken into account.

Figs 3.14 and 3.15 present the temporal variability in water temperature and salinity in the surface layer at a roadstead point in the central part of the lagoon between the Chilova and the Ranzheva spits. It is clear that the model describes temporal variability of water salinity well, however it overrates the values of water temperature in July through early August to some extent.



Notation conventions: 1 - the model results for a water column at the depth of H = 15 m, the surface layer; 2 - the model results for a water column at the depth of H = 3 m, the depth-homogeneous distribution; 3 – the model results for a water column at the depth of H = 15 m, the benthic layer; 4 - observations in the coastal zone in the area between the Chilova and Ranzheva spits; 5 - observations on the roadstead of the area between the Chilova and the Ranzheva spits

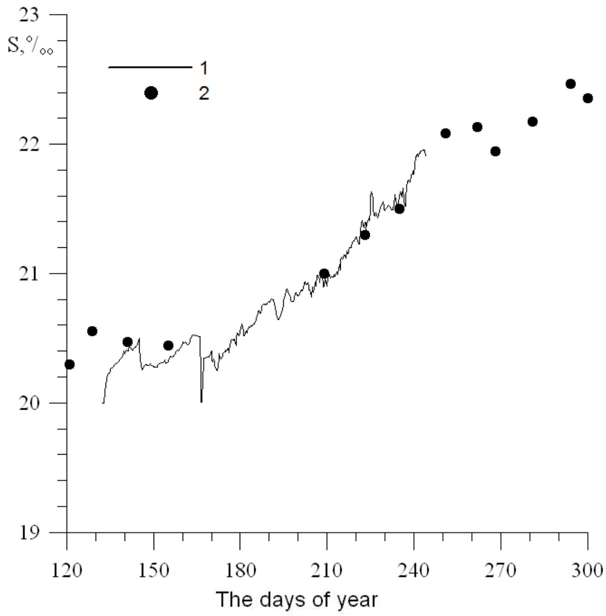
Fig. 3.13. Yearly variability in water temperature (a), °C, and salinity (b), $^{o}/_{oo,}$ calculated by the model under the hydrometeorological conditions of 2012 and determined by the observational data.



Notation conventions: 1 - the model results; 2 - the observations in a coastal zone in the area between the Chilova and the Ranzheva spits.

Fig. 3.14. Temporal variability in water temperature of the surface layer, °C, in May-August 2012, obtained from the simulation, in the deep central part of the lagoon and measured in a coastal zone within the area between the Chilova and the Ranzheva spits.

It follows from Fig. 3.16 that the model simulated the collapse of a cold benthic layer in the spring-summer period of 2012 well.



Notation conventions: 1 - the model results; 2 - the observations in a coastal zone in the area of the Chilova and the Ranzheva spits.

Fig. 3.15. Temporal variability in water salinity of the surface layer, °/oo, in May-August 2012, obtained from the simulations, in the deep central part of the lagoon, and measured in a coastal zone within the area between the Chilova and the Ranzheva spits.

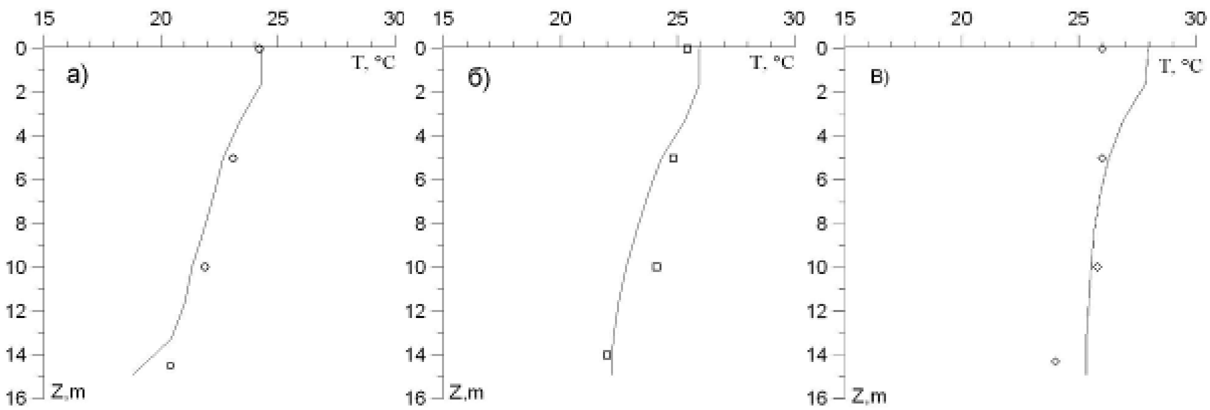


Fig. 3.16. Vertical distribution of water temperature, °C, obtained in the model (curves) and according to the data of model observations in the central part of Tyligulskyi Liman Lagoon (the roadstead between the Chilova and the Ranzheva spits) in 2012: (a) – 14 June 2012; (b) – 01 July 2012; (c) – 16 July 2012.

4. Ecological model calibration and validation

Parameters of the biogeochemical unit of the model were calibrated by the following scheme.

At the first stage, the most probable (typical) values of the parameters, included in the model equations, and the possible range of their variability under conditions similar to the ones observed in the Tyligulskyi Liman Lagoon, are to be determined on the basis of information from scientific literature.

At the second stage, the parameters of the biogeochemical unit are calibrated by means of a 1D (by z coordinate) model variant, where the terms of the hydrothermodynamic model equations, describing a horizontal turbulent exchange and advective transfer, are omitted and independence of all functions on the horizontal coordinates is assumed. Such problem statement takes account of only the drift constituent of current velocity, which is used for calculation of the coefficients for vertical turbulent exchange and diffusion. The main task of the calibration consisted in achievement of the maximum possible equivalence between the observational data and the results of calculations of yearly variability in the modelled variables. To reach this goal, the initial values of constants for the biogeochemical unit, assigned on the basis of the data from literature sources, were corrected within the acceptance limits.

Preliminary use of a 1D model version is called forth by the fact that, under calibration of the model for water eutrophication, it requires noticeably less computing time than a 3D variant. This makes it possible to perform a large quantity of numerical experiments with various combinations of the model parameters and obtain the required pattern of variability in the modelled variables.

In the 1D variant, the parameters of a biogeochemical unit of the model were calibrated separately:

1. for the deep southern and the central parts of the lagoon without an equation of biomass dynamics for the bottom macrophytes taken account of;
2. for the shallow northern part of the lagoon with the equation of biomass dynamics for the bottom macrophytes taken account of.

To account for the inflow of biogenic and organic substances into the lagoon from the external sources, a relation of the following form (Ivanov, Tuchkovenko, 2008) is used in the 1D model version:

$$Q_i = \sum_k \frac{q_k}{W_{tot}} (C - C_{ki}),$$

where: Q_i – the inflow of substance i from external sources (the Tyligul River and the connecting canal to the sea); q_k – the discharge of source k, m^3·s^{-1}; C_{ki}, C – concentration of the modelled substance i in the water of source k and in the water of the studied water area, respectively; W_{tot} – the total volume of water in a dilution zone (see Section 3.1). It was assumed that a primary dilution occurs within the limits of upper 1.5-meter layer.

The 1D version was calibrated in three stages. As the first step, the parameters of equations for the biomass dynamics of phytoplankton (B_{Ph}), bottom macrophytes (B_{mPh}), organic

phosphorus (P_{org}) and nitrogen (N_{org}), and dissolved oxygen (O_2) were calibrated. The seasonal dynamics of other variables in the model was assigned from the observational data.

As the second step, the parameters of equations for the mineral forms of nitrogen (NH_4^+, $NO_2^- + NO_3^-$) and phosphorus (PO_4^{3-}) were calibrated; moreover, the equation parameters for organic nitrogen (N_{org}) and phosphorus (P_{org}) were corrected.

The results of calibration of the biogeochemical unit parameters for the ecological model of the Tyligulskyi Liman Lagoon in the 1D variant are given in Fig. 5.1.

As the third stage of the ecological model calibration, the equation parameters for the biogeochemical unit of the model, which had been determined with the use of the 1D model variant, were used in the 3D version.

Modelling of seasonal dynamics for environmental variables of the model in the 3D variant was performed under the hydrometeorological conditions of 2010, in a vegetation season from the last ten-day period in April through October, in view of the lack of observational data for the rest of these months. Based on the results of the 3D modelling, certain values of parameters for the equations of the biogeochemical unit, having been assigned in the 1D version, were specified.

Selected results of the calculations obtained with the use of the 3D model version are given in Fig. 5.2 and 5.3.

5. Problems and recommendations

The main problems that arose at the stage of calibration and validation are related to the ecological model.

Unfortunately, the data on hydrobiological and hydrochemical observations are distributed extremely irregularly by months and along the lagoonal water area. As an example, the characteristics for the distribution of the observations of phytoplankton biomass by months and years are given in Table 5.1. The majority of hydrochemical observations are carried out in the summer months. In certain months, the observations were either not conducted at all or sporadic. In addition, the data from hydrochemical and hydrobiological observations are often inconsistent in time and space. The predominant number of observations was made in the southern part of the lagoon. Therefore, the annual variability of the modelled hydrochemical and hydrobiological characteristics, as reproduced from the observational data for the period of 2001-2010, is only a rough approximation to the real average long-term variability. This fact considerably reduces the accuracy of calibration for biogeochemical unit parameters of the model.

In the course of calibration of the biogeochemical unit, since there were only sporadic observational data available on water transparency in the lagoon, the annual changes of water transparency were specified hypothetically, in accordance with the available information.

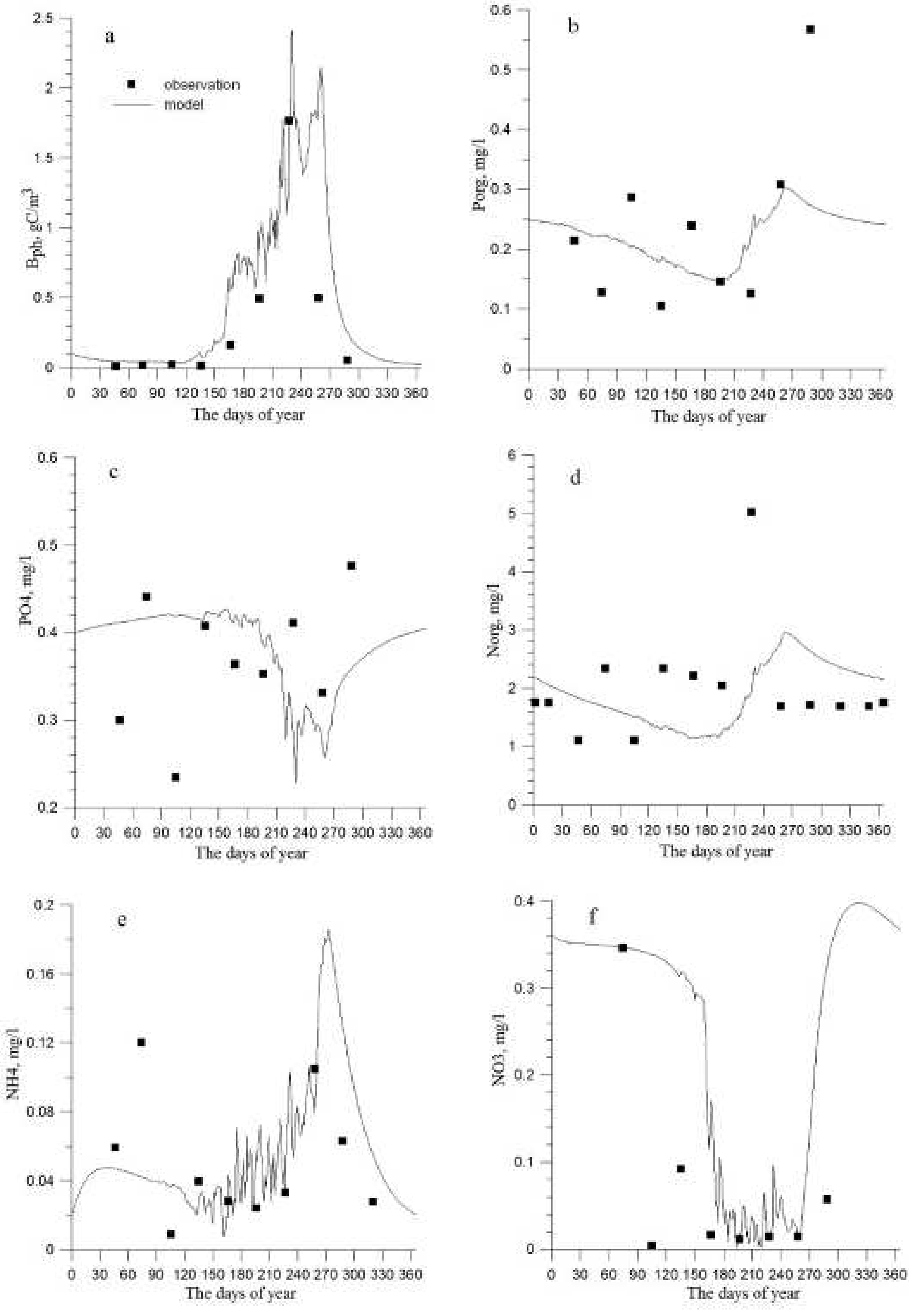


Fig. 5.1. The results of calibration and verification of the biogeochemical unit of the ecological model (variability of the bio-chemical parameters).

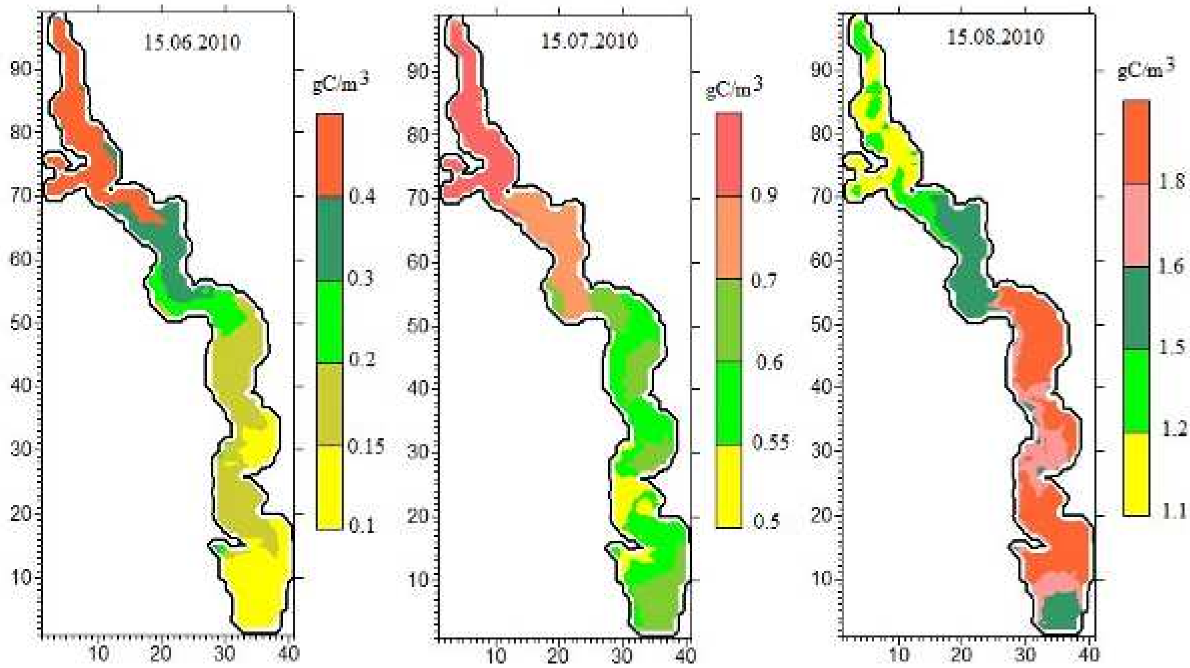


Fig. 5.2. Variability in the spatial distribution of phytoplankton biomass, gC/m^3, in the photic layer in May-August 2010, obtained from the simulations.

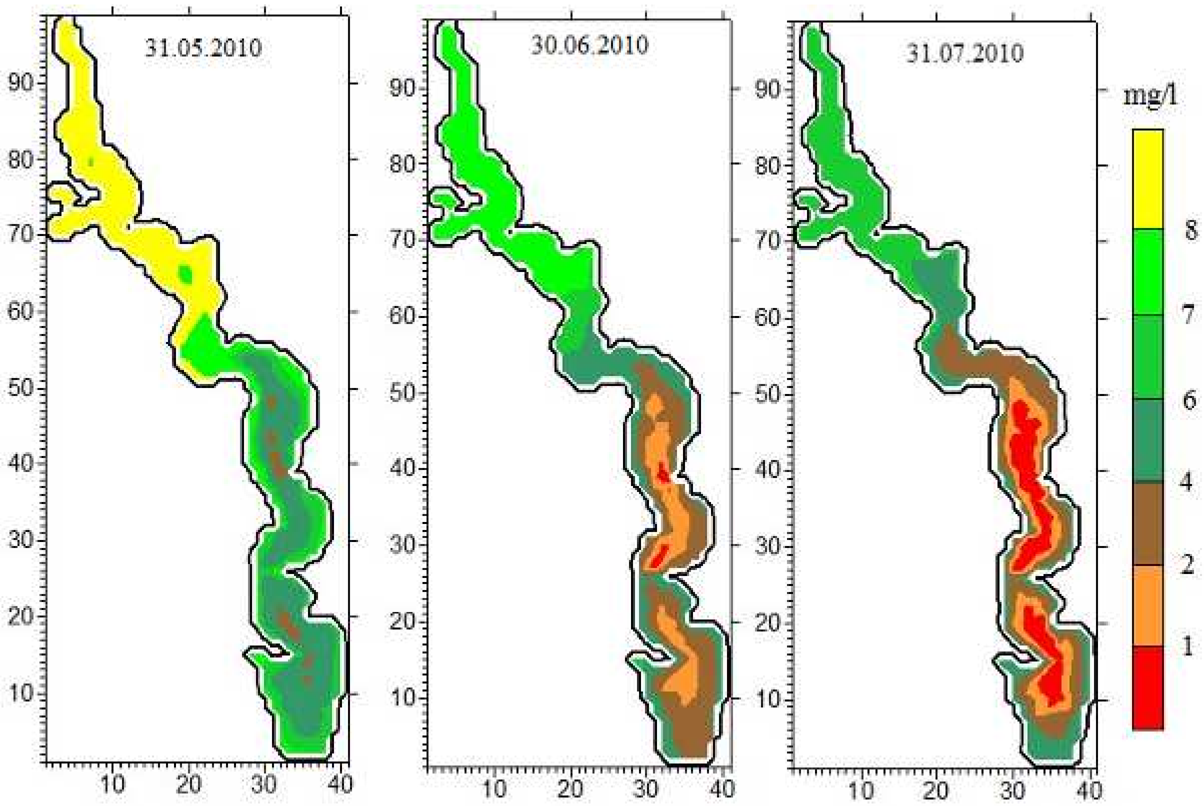


Fig. 5.3. Variability in the spatial distribution of dissolved oxygen, mg/l, in the benthic layer in May-August 2010, obtained from the simulations.

Table 5.1. Characteristics for the distribution of phytoplankton observations by months and years.

Number of obser-vations	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	0	1	3	7	6	11	14	3	6	11	0	0
Years	-	2011	2010	2003 2011	2006 2008	2001 2002 2005 2006	2000 2003 2005 2010 2011	2001 2002 2010	2003 2010	2001 2006 2010	-	-

One of the main problems with the use of a 3D version of the ecological model consists in the fact that the hydrodynamic and bio-chemical model variables are calculated in an integral spatial calculation grid, although with different time steps. For securing numerical stability of the calculation schemes in the period when the canal is operating and very strong currents are formed in it, a very small calculation time step in the hydrodynamic unit (a few seconds) is required. On the other hand, although the calculation time step in the biogeochemical unit of the model is 1 day, the calculations are made in each mesh point of the computational grid. As a result, modelling of the annual cycle with the use of an ecological model lasts 7–9 days of the real time, which significantly limits the number of numerical experiments that could be realized by means of the 3D model version.

The second problem is in the fact that macrophytes are widespread in a narrow coastal strip in the southern and the central parts of the lagoon, which in most cases is smaller than the spatial step of the computational grid (400 m). Therefore, their contribution to the dynamics of the modelled ecosystem components is taken into account only in the shallow northern part of the lagoon, which, together with a very rough assignment of the variability in water transparency, results in deviation of the modelled values of hydrochemical characteristics from the observed ones.

Recommendations.

In mutual judgment of the experts, a primary threat for the ecosystem of the Tyligulskyi Liman Lagoon will be represented in the future not by the water eutrophication, but by a long-term tendency towards an increase in water salinity (Fig. 5.5). The salinity growth will lead to a decrease in biodiversity of the lagoonal ecosystem, loss of the prospects for aquaculture development and significance of the lagoon as a protected natural water body. There are two ways to decrease the rate of salinity growth: (1) to increase the Tyligul River runoff by reduced withdrawal of water for filling numerous ponds and reservoirs in the river catchment area; (2) to provide maximum possible flowage of the lagoon, i.e. the inflow of lagoonal water, together with the salts they contain, into the sea.

For the development of the scenarios for water quality management in the lagoon, with the water salinity as the main environmental issue, a use of the 3D model is inappropriate and impossible in view of the computational limitations.

This problem can be solved with the required accuracy on a long-term temporal scale only by means of a 0-dimensional model for water-salt balance of the lagoon that has been developed and calibrated. The results of the calculations and the validation of the model for the period of 1953 - 2012 are given in Figs 5.4 and 5.5.

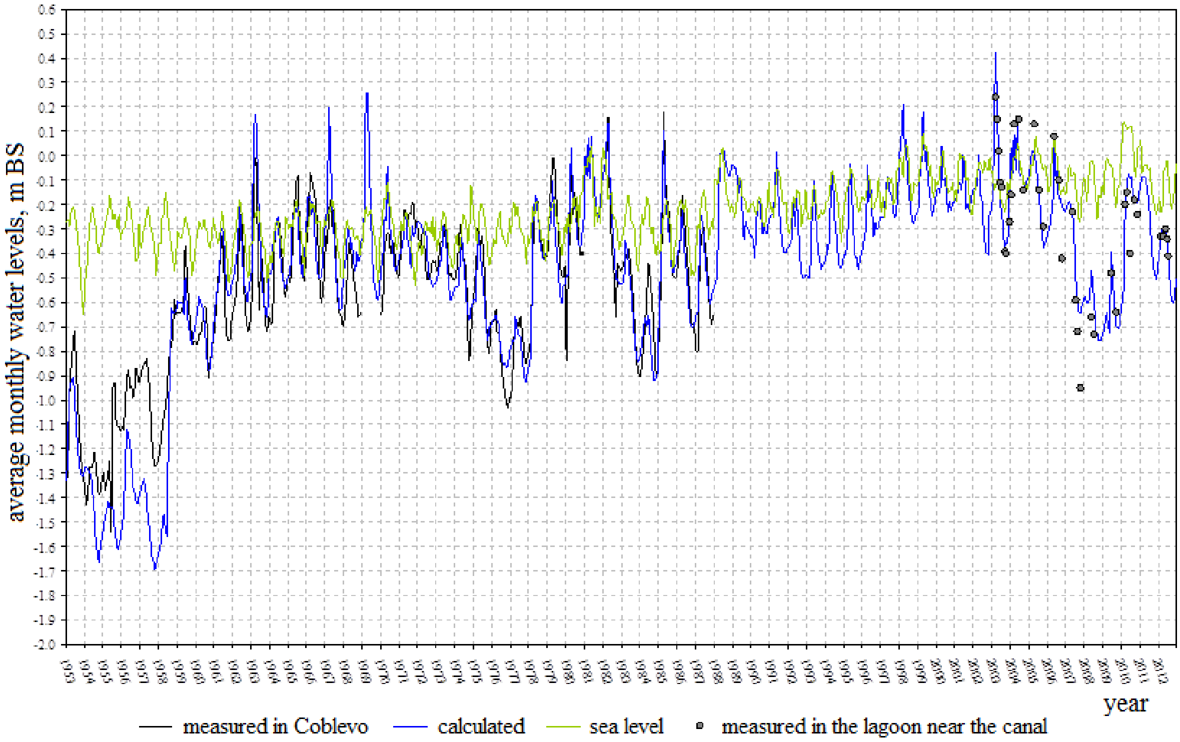


Fig. 5.4. Variability in the average monthly values of water level in the Tyligulskyi Liman Lagoon, calculated by means of the model of water-salt balance for the period of 1953-2012 and determined according to the observational data.

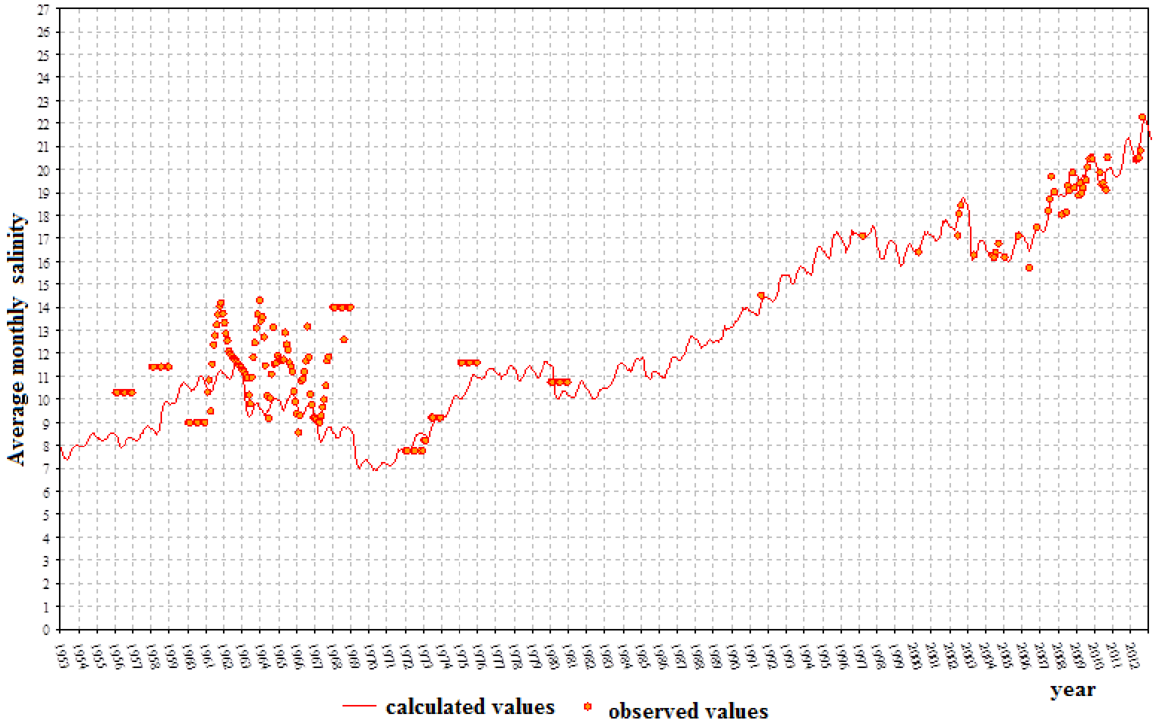


Fig. 5.5. Variability in the average monthly values of water salinity in the Tyligulskyi Liman Lagoon calculated by the model of water-salt balance for the period of 1953-2012.

The results of calculations for the Tyligul River runoff and other small rivers and watercourses, inflowing into the lagoon, in the timespan of 2010–2100, obtained within the framework of WP5, will be used for the scenario modelling of long-term variability in the lagoonal water salinity. In addition, the calculations will be made on the assumption of the reduction in the number of artificial water bodies located in the catchment area of the Tyligulskyi Liman Lagoon by 25, 50 and 75 %, aimed at an increased inflow of fresh water into the lagoon and prevention of its excessive salination.

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