



DELIVERABLE D6.1

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

Hydrodynamic and water quality
models



Title
The Vistula Lagoon, the Ria the Aveiro Lagoon, the Mar Menor Lagoon and the Tyligulskyi Lagoon - Hydrodynamic and water quality models
Author(s)
See contributions to report chapters
Report No.
LAGOONS Report No. D6.1
This report should be cited as:
LAGOONS. 2012. Hydrodynamic and water quality models. LAGOONS Report D6.1. 71 pp.
Organisation name of lead contractor for this deliverable
Institute of Hydro-Engineering of the Polish Academy of Sciences - IBW PAN
No. of pages
71
Due date of deliverable:
30 November 2012
Actual date of deliverable:
17 December 2012 ¹
Dissemination level ¹
PU
Key words
Coastal lagoon, hydrodynamic model, water quality model, climate change
<Other>

Title of project: *Integrated water resources and coastal zone management in European lagoons in the context of climate change*

Instrument:

Contract number: 283157

Start date of project: October 2012

Duration: 36 months

Disclaimer

The information provided and the opinions given in this publication are not necessarily those of the authors or the EC. The authors and publisher assume no liability for any loss resulting from the use of this report.

¹ PU Public

PP Restricted to other programme participants (including the Commission Services)

RE Restricted to a group specified by the consortium (including the Commission Services)

CO Confidential, only for members of the consortium (including the Commission Services)

Contents

Quantitative lagoons modelling - general introduction	3
1. Introduction	3
2. Short summaries of the models	5
Chapter 1	
The Vistula Lagoon - Hydrodynamic and water quality models	8
1. Introduction	8
2. Hydrodynamic models	10
2.1 General description of Delft3D-FLOW	10
2.2 Processes modelled in the lagoon	10
2.3 Model set up	12
2.4 General description of Mike modelling suite	14
2.5 Model set up (for the Vistula lagoon of the Baltic Sea)	14
2.6 Problems and future actions	17
3. Ecological model	17
3.1 General description of the model	17
3.2 Processes modelled in the lagoon	17
3.2.1 The processes of the Vistula Lagoon Delft3D-WAQ model	17
3.2.2 State variables	19
3.3 Model set up	20
3.3.1 Spatial and temporal resolution	20
3.3.2 Forcing functions for Delft3D Water Quality model	21
3.4 Problems and future actions	22
References	22
Chapter 2	
The Ria de Aveiro Lagoon - Hydrodynamic and water quality models	24
1. Introduction	24
2. Hydrodynamic model	24
2.1 General description of the model	24
2.2 Processes modelled in the lagoon	26
2.3 Model set up	27
2.4 Problems and future actions	28
3. Ecological model	29
3.1 General description of the model	29
3.2 Processes modelled in the lagoon	30
3.3 Model set up	30
3.4 Problems and future actions	30
References	31
Chapter 3	
The Mar Menor Lagoon - Hydrodynamic and water quality models	33
1. Introduction	33
1.1 Description of the study area	33
1.2 Main ecological and environmental problems	35
1.3 Selection of the mathematical models	37

2. Hydrodynamic model	39
2.1 General description of the model	39
2.2 Processes modelled in the lagoon	40
2.3 Model set up	40
2.4 Problems and future actions	42
3. Ecological model	44
3.1 General description of the model	44
3.2 Processes modelled in the lagoon	45
3.3 Model set up	45
3.4 Problems and future actions	46
References	47

Chapter 4

The Tyligulskyi Lagoon - Hydrodynamic and water quality models	48
1. Introduction	48
2. Hydrodynamic model	49
2.1 General description of the model	49
2.2 Processes modelled in the lagoon	51
2.3 Model set up	53
2.4 Problems and future actions	55
3. Ecological model	57
3.1 General description of the model	57
3.2 Processes modelled in the lagoon	58
3.3 Model set up	61
3.4 Problems and future actions	67
References	69

Quantitative lagoons modelling - general introduction

Małgorzata Bielecka¹ and Ana I. Lillebø²

¹*Institute of Hydro-Engineering of the Polish Academy of Sciences, Poland;* ²*University of Aveiro, Portugal*

1. Introduction

The environmental issue of concern of the LAGOONS project is the anthropogenic - including possible climate change impacts - deterioration of surface water ecosystems, from river basin to coastal zones, with particular emphasis on transitional water bodies – coastal lagoons. In this context, work package 6 titled ‘**Quantitative lagoons modelling (climate and hydrobiogeochemistry)**’ is a very important part of the LAGOONS project and is interconnected with all other project work packages.

Although there is a lot of uncertainties regarding the future state of coastal ecosystems, modelling has been recognised as a useful tool for estimating and simulating likely states of the water quality status in the context of the Water Framework Directive (WFD). The aim of the modelling effort within LAGOONS is to simulate the four lagoons’ responses to climate change and land use change scenarios. The modelling of the catchment uses SWIM model, a continuous-time and spatially semi-distributed model, integrating hydrological processes, vegetation growth, nutrient cycling, and sediment transport at the river basin scale. The modelling of the lagoons’ hydrodynamic and ecological parameters is performed by different models adapted to specific conditions of each of the lagoons. For the climate change scenarios different sets of existing regional climate scenarios, namely from the ENSAMBLES project, will be used. In management terms, LAGOONS will contribute to the decision-support methodologies for a coordinated approach to the WFD, the Marine Strategy Framework Directive (MSFD) and the Integrated Coastal Zone Management (ICZM). In addition, LAGOONS will propose actions to tackle bottlenecks in the context of climate change. The use of modelling tools to assess the spatial impacts in the context of EU policies pose some additional challenges, namely due to the gaps in data sets and the lack of effective information-sharing systems.

In order to analyse future possible trends and conditions in coastal lagoons, LAGOONS project will combine the knowledge elaborated by different scientific disciplines, integrated with local knowledge and the views of stakeholders, in order to produce integrated, participatory scenarios. This scenario approach will combine qualitative-quantitative scenarios, supplemented with the science based modelling inputs, namely from WP5 and WP6. The main objective of this work package is to evaluate and estimate the lagoons responses (water dynamics, water quality, and biota) to different climate scenarios based on results of climate and land based river discharges and nutrient inputs modelling performed in WP5. Drainage basin modelling (WP5) delivers necessary information on discharges from the watershed to the lagoons based on different climate change scenarios adopted in the project. These two science based modelling WPs are also closely linked to WP2, WP3 and WP4. The

data and information gathered (qualitative and quantitative) in WP2 on environmental, socio-economic and institutional and policy related issues will be further discussed with stakeholders through the processes in WP4. This extensive overview of natural and socioeconomic situation in each of the lagoons allows for formulation of methodologies (WP3) and implementation of appropriate methods and tools in order to provide answers on the lagoons' response to changing climate. As the stakeholders participation plays a key role in the project it is also reflected in the activities within the WP6. Work package 4 ensures stakeholders participation in the process of defining key environmental problems in each of the lagoons and formulation of stakeholders' expectations from the project. The stakeholders are being informed about the expected and achieved results of WP6, e.g. on the lagoons' response to different climate based scenarios and participate in discussion of the project results. The results of the qualitative scenarios produced in WP4 will be used as inputs into quantitative models in WP5 (drainage basin) and WP6 (lagoons) and will in a similar way be used to modify the qualitative scenarios, and to develop qualitative/normative scenarios that will provide policy recommendations in WP7. This approach combines knowledge and insights from a range of natural sciences, working together to adjust and apply dynamic models of drainage basins for a range of scenarios with quantitative models of lagoons. Conclusions and all analysis are provided to WP7 where relevant strategies are proposed to prevent possible negative impacts of climate change on the state of the lagoons and the coastal zone. Figure 1 illustrates the interdependencies between all work packages.

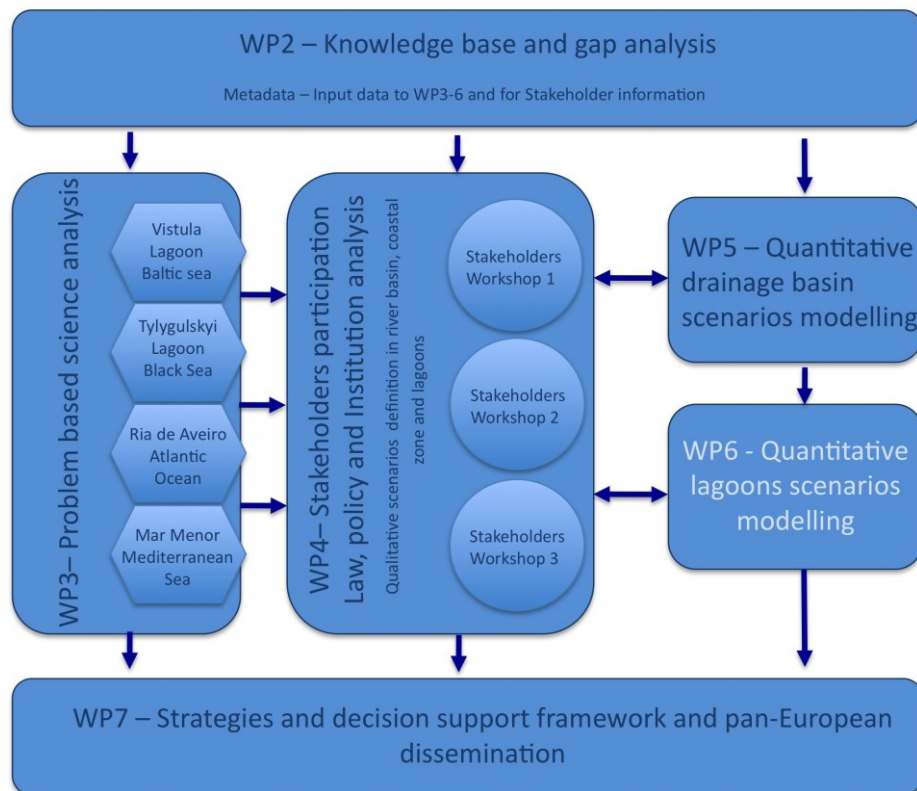


Figure 1 – Schematic representation of the interdependencies between LAGOONS work packages.

Methods and tools used for assessment of the lagoons' response to climate change will be utilized in building the decision support framework in WP7. LAGOONS will then develop

strategies and decision support frameworks for pan-European dissemination and application. To fulfil these objectives, four case study lagoons have been selected to represent a set of "hotspot" coastal lagoons with a wide and balanced geographical distribution and different characteristics. More details on physiogeographical conditions of each case study area are available in LAGOONS project webpage (<http://lagoons.web.ua.pt/> - LAGOONS Report D2.1a, b, c and d). In this report the description of the hydrodynamic and water quality models to be used in each case study area will be presented in a separate chapter as follow: Chapter 1 - Vistula Lagoon in the Baltic Sea (transboundary Poland/Russia); Chapter 2 - Ria de Aveiro Lagoon in the Atlantic Ocean (Portugal); Chapter 3 - Tylygulskiy Lagoon in the Black Sea (Ukraine); Chapter 4 - Mar Menor in the Mediterranean Sea (Spain).

2. Short summaries of the models

(With the contribution from the authors of each case study area chapter)

In case of the **Vistula Lagoon** (Poland/Russia) the modelling approach is focused on representation of the major features of the Vistula Lagoon, both from the hydrodynamic and ecological point of view. In order to represent properly main hydrological and ecological problems in the Vistula Lagoon, as well as account for Polish – Russian cooperation, selection of the models was based on the efficiency of representing analysed problems and also accessibility and their present usage by partners involved in the modelling process. Therefore, two sets of hydrodynamic and ecological models for the Vistula Lagoon are proposed. They are modifications and developments of the models worked out in the FP5 MANTRA-East project. Polish partners (IBW PAN and NMFRI) will use a DELFT 3D suite, which is successfully operated by them in the Vistula Lagoon. It will be applied to answer general questions related to climate change impacts, with respect to the whole of the lagoon (Polish and Russian parts). First set of the models is based on the Delft3D software (Deltares, NL), both hydrodynamic and ecological modules. For representation of hydrodynamic conditions the area of lagoon is covered by a fine grid (4418 cells) in horizontal and discretized by 10 layers in vertical directions. For modelling of ecological processes it is proposed to apply the aggregated grid, both horizontally (100 grid cells) and vertically (8 layers).

The proposed hydrodynamic model will be applied to represent temporal and spatial variability of currents, salinity, water levels, whereas the ecological model will represent cycles of nitrogen, phosphorus, silicate, carbon and oxygen in water column and sediment.

The second set of the models is a development of the Mike modelling system (also used in MANTRA-East project in 2D version). The Mike modelling system, traditionally operated in Kaliningrad region and installed at end-users institutions, will be used 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.

To answer the question concerning saltwedge intrusions upstream the Pregola River, MIKE 3 FM (3 dimensional hydrodynamic model) will be used. Years with general strongest wind influence, especially from western or south-western directions during autumn period, will be selected for simulations and comparison with the "average" year.

Parameters of saltwedge intrusion upstream the Pregola River are very sensitive to river runoff magnitude. The ecohydrological river basin model SWIM (Soil and Water Integrated Model), applied in WP5 to all river catchments analysed in the project, will be used to study the peculiarities of seasonal variations of the Pregola River runoff at the downstream part of the river. Namely, an input of very catchment area around the proper Pregola River stream

(the last 30 km, downstream the Town of Gvardeysk), which is usually not included in catchment simulations, and the division of the runoff of the Pregola River catchment into two branches (the proper Pregola and Deima) at the Town of Gvardeysk, will be studied.

The DELFT 3D hydrodynamic and water quality models, as well as Mike modelling system are set up for a whole of the lagoon (both Polish and Russian sides) and ready to proceed with calibration, validation and scenario calculations. It should also be mentioned that both sets of models will be using the same data sets collected and exchanged by Polish and Russian partners.

In case of the **Ria de Aveiro** the proposed approach consisted of applying Mohid, a three-dimensional marine model that was previously calibrated and validated for the lagoon. In addition, several research projects on-going in the Ria de Aveiro are based on the Mohid application. However, initial tests in the model design phase showed that a configuration with all the hydrodynamic and biogeochemical features was unable to represent a full hydrological year within a reasonable time. So, a new coupled hydrodynamic and water quality model is being built for Ria de Aveiro to improve on previous implementations. This new model (the Delft3D-Flow package) allows for the simulation of hydrodynamic and biogeochemical quantities at the tidal, fortnightly, seasonal and event scales. Currently the hydrodynamics and the transport of salt and heat have been setup and mostly calibrated and validated whilst the modelling of biogeochemical quantities is still in the initial stages of design.

In case of the **Tylygulskiy Lagoon** (Ukraine) development of a plan for hydroecological management in the lagoon, taking into account changes in the anthropogenic influence and climate conditions, presupposes use of mathematical modelling methods for quantitative assessment of probable consequences and environmental efficiency of various managerial solutions for different scenarios which are being developed within the framework of WP4 in the project.

For the Tylygulskiy Lagoon, a modified version of MECCA (Model for Estuarine and Coastal Circulation Assessment), a three-dimensional numerical non-stationary hydrothermodynamic model, is employed (Hess, 1989, 2000). The model is implemented in the σ vertical coordinates and allows calculating the water dynamics and substance distribution in the water areas on an integrated spatial grid. It is also possible for one horizontal direction that some zones of the water areas have smaller (subgrid) sizes comparing to the computational grid mesh (e.g. the artificial canal connecting the sea and lagoon).

The information required for the model to be put to use, the results obtained during adaptation of the model to the conditions in the lagoon and the potential problems in the course of its further use for the purposes of climate scenario modelling are given description. The data on changes in the thermohaline structure of the lagoonal waters received under climate scenario modelling along with the results of biotesting its water quality under diverse temperature and salinity characteristics of the waters to be obtained during implementation of WP5 tasks, will make it possible to draw conclusions on the probable influence of the climate change on water quality in the Tylygulskiy Lagoon.

Estimates of the effect which morphometric characteristics of the artificial canal, connecting the Tylygulskiy Lagoon with the Black Sea, exert on the intensity of water exchange through the canal and water renewal by sea waters in various lagoonal areas are obtained by means of the hydrothermodynamic model.

The main environmental problem of the Tylygulskiy Lagoon is water eutrophication and development of oxygen deficit (hypoxia) in water in the summer period, which results in the

death of hydrobionts, causes unfavourable conditions for fishing, aquaculture, recreation and tourism. The water eutrophication model for the Tyligulskyi Lagoon, which represents the afore mentioned hydrothermodynamic model supplemented by a biogeochemical unit, will be used for finding possible ways of solution to this problem (development of hydroecology management plans). The mathematical structure of the biogeochemical unit is based on a symbiosis of the known models for water quality (RCA - HydroQual, 2004, CE - QUAL - ICM, 1995, WASP5, 1993), pursuant to the volume of available information on variability of chemical and biological characteristics of the hydroecological regime in the lagoon. Since macrophytes are widespread in the spacious areas of the bottom in the shallow northern part of the lagoon, they were also included into the structure of a biogeochemical unit of the water eutrophication model for the lagoon as an additional variable.

Available information, which is used for calibration and verification of the water eutrophication model for the Tyligulskyi Lagoon, is given description. The problems which became evident during calibration of the biogeochemical unit of the model and ways for their solution are indicated. Issues of the use of water eutrophication model under climate scenario modelling are given consideration.

In case of the **Mar Menor** (Spain) new hydrodynamic and ecological models have been developed in the framework of the LAGOONS project. The application of the MOHID water modelling system to this case study area is providing an exceptional opportunity to describe the functioning of the lagoon and identify the most important features that determine lagoonal response to terrestrial inputs of nutrients.

The quantification and evaluation of the different processes related to the solute transport and the main biogeochemical cycles provided by the hydrodynamic and ecological models constitute very useful tools for the assessment of the recent eutrophication problem in the Mar Menor as a consequence of human activities in the area and permit the identification of future environmental problems in the lagoon under a wide range of possible socio-economic and climatic scenarios.

Chapter 1

The Vistula Lagoon

Hydrodynamic and water quality models

Mariusz Zalewski¹, Małgorzata Robakiewicz², Małgorzata Bielecka², Boris Chubarenko³

¹*National Marine Fisheries Research Institute, Poland*

²*Institute of Hydro-Engineering of the Polish Academy of Sciences, Poland*

³*Atlantic Branch of P. P. Shirshov Institute of Oceanology of Russian Academy of Sciences, Russia*

1. Introduction

The Vistula Lagoon is a water body shared by Poland and Russia, located in the South Baltic Sea, and separated from the Gulf of Gdansk by the Vistula Spit and its extension on the Russian side called the Baltiyskaya Kosa.

It is a shallow coastal ecosystem with an average depth of 2.7m and the maximum natural depth of 5.2m close to the Baltiysk Strait. The lagoon exchanges water with the Gulf of Gdansk through the Baltiysk Strait (Fig. 2.1), which has a width of approximately 400m, a length of 2km and an average depth of 8.8 m (Łomniewski, 1958; Chubarenko and Chubarenko, 2002).

A navigation canal leads from the Baltiysk Strait up to the harbour of Kaliningrad. This narrow canal plays an important role in transporting sea water from the Baltic Sea into the lagoon.

With respect to salinity, the Vistula Lagoon is considered a transitional area. Average salinity for the eastern part of the lagoon (spring-autumn) is 2.5-4.3 PSU, for the central part 3.9-5.0 PSU, and for the southern part 1.0-3.4 PSU. At the Baltiysk Strait salinity may reach up to 7 PSU.

Average retention time of water inside the lagoon, due to the river drain, is about 6-7 months. More than 20 rivers discharge directly into the Vistula Lagoon; the most important ones are: Pregola, Elbląg, Pasłęka, Nogat, Prokhladnaya, Mamonovka, Bauda, Primorskaya and Szkarpa (Fig. 2.1). The main part of the annual freshwater inflow (41%) is coming from Pregola River (Łazarenko and Majewski, 1975).

Usually, the Vistula Lagoon is covered by ice during several months in winter. Due to recent climate changes this period gets shorter. This implies great changes in ecosystem functioning.

Eutrophication is one of the major issues in the lagoon. Vistula Lagoon is especially vulnerable to eutrophication due to the large drainage area and limited water exchange with the Baltic Sea.

The horizontal distribution of water quality parameters in Vistula Lagoon is strongly influenced by hydrological and meteorological factors. Of these, the exchange of water masses between the Gulf of Gdansk and the lagoon constitutes one of the most important factors. As a consequence, the

lagoon area close to the Baltiysk Strait is ventilated by permanent inflow of marine waters and the concentrations of nutrients in this area are lower in comparison to those in remote parts of the lagoon. Moreover wind is the most important factor in water circulation of the lagoon, with vertical and horizontal mixing at time scales of hours and days. The lagoon's main axis is in the direction of predominant winds (S to W winds; Łazarenko and Majewski, 1975; Witek at. all, 2010). Vistula Lagoon in comparison to other shallow water bodies located along south Baltic Sea coast appears as a relatively large, saline, moderately eutrophied and productive ecosystem, affected by anthropogenous pressure (Witek at. all, 2010).

The modelling approach proposed in the LAGOONS is based on experience gained within a MANTRA-East project and develops tools used in that project. Therefore two sets of models are applied: DELFT 3D suite which will be used to answer general questions related to climate change impacts, with respect to the whole of the lagoon (Polish and Russian parts) and Mike modelling system, including MIKE 3 FM and SWIM models, which will be used 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. All models will be set up, calibrated and validated against the same data sets collected and exchanged by Polish and Russian partners.

2. Hydrodynamic models

2.1 General description of Delft3D-FLOW

The Vistula Lagoon model is set-up based on Delft3D-FLOW software suite (license Deltres – Delft Hydraulics, the Netherlands).

The hydrodynamic module of Delft3D simulates two-dimensional (depth-averaged) or three-dimensional unsteady flow and transport phenomena resulting from meteorological phenomena, tides, including the effect of density differences due to a non-uniform temperature and salinity distribution.

In the Delft3D-FLOW the non-linear shallow water equations are solved. These equations are derived from the three-dimensional Navier-Stokes equations for incompressible free surface flow. In the vertical direction Delft3D-FLOW applies a so-called σ co-ordinates system. The system of equations consists of the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. These equations are formulated in orthogonal curvilinear coordinates or in the spherical coordinates. The flow can be forced by tide at the open boundary, wind stress at the free surface, pressure gradients or density gradients. Source and sink terms are included in the equations to model the discharge and withdrawal of water.

This well documented software (Delft3D-FLOW, 2010) was used in many practical applications all over the world. The Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) has been using this software since 1993 when the first 3D model of the Gulf of Gdańsk was set-up. Since then a number of applications have been prepared, calibrated and validated, e.g. Pomeranian Bay - Szczecin Lagoon, Świna Strait, Puck Bay, Vistula River mouth, Tam Giang - Cau Hai Lagoon, Admiralty Bay. Vistula Lagoon was also modelled using Delft3D-FLOW within the MANTRA-East project (Bielecka and Kaźmierski, 2003), however it is anticipated that in the new model set-up modelling results will improve with respect to their accuracy.

The present model set-up for the Vistula Lagoon varies from the version applied in the MANTRA-East project. The main difference is related to differences in horizontal discretization; the proposed grid is now better adjusted to local bathymetry (see Fig. 2.2). This change resulted in increased number of computational cells in the horizontal plane (about 50%). From the point of view of the calculation time this increase is not critical; the efficiency of processors for the last few years increased considerably.

2.2 Processes modelled in the lagoon

Hydrodynamic conditions in the Vistula Lagoon are wind and density driven. Several rivers discharge into this lagoon, which is exchanging its waters with the south Baltic Sea through the Baltiysk Strait (Fig. 2.1). Marine inflow constitutes 80% of the total ingoing water balance, while the rivers' inflow is of 17%.

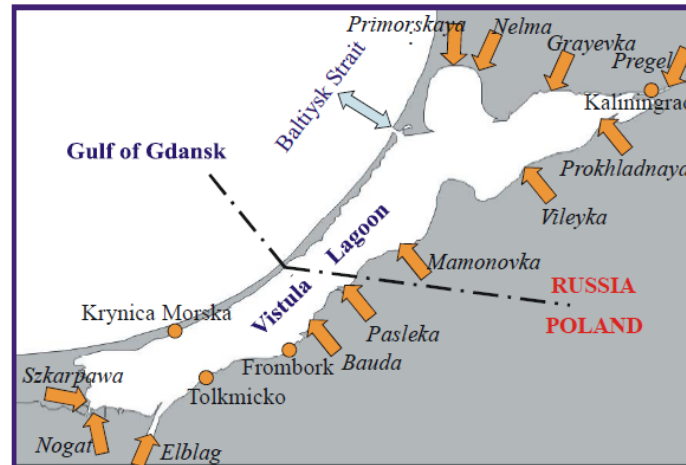


Fig. 2.1. The Vistula Lagoon and its discharges.

More details on physiogeographical conditions of the Vistula Lagoon have been presented in Deliverable D2.1a of the LAGOONS project, titled "The Vistula Lagoon – Current knowledge base and knowledge gaps" (LAGOONS, 2012).

The ideal hydrodynamic model of the Vistula Lagoon should represent all phenomena observed in nature as good as possible, i.e. good representation of the following phenomena is expected:

- water level variations in time and space;
- water velocity variations in time and space;
- salinity and temperature variations in time and space, including influence of discharges;
- water exchange between lagoon and the sea.

To enable reaching such a perfect situation the mathematical formulations taking into account the following physical phenomena should be included:

- time and space varying wind shear-stress at the water surface;
- time varying sources (river discharges);
- time varying water level at the open boundary;
- space varying shear-stress at the bottom;
- transport of salt and heat;
- water with variable density;
- turbulence induced mass and momentum fluxes;
- heat exchange through the free surface;
- evaporation and precipitation;
- the effect of Earth's rotation.

However there are general limitations that make modelling with such an accuracy not possible. The basic one is insufficient accuracy of data to represent the forcing functions (e.g. space varying wind field over the lagoon, meteorological data to represent heat exchange with the appropriate accuracy). Moreover to represent all physical phenomena mentioned above it will be necessary to introduce very fine discretisation in space and time (small time step), and leading to time consuming calculations.

In the Lagoons project the hydrodynamic model plays different role. Its basic role is to support the water quality model with flow and salinity patterns varying in time and space. The expectations

from the water quality modelling are limited to general changes rather than to local phenomena. There are two reasons for this; the first – chemical and biological processes have different time of reaction, and the second – at present data availability for water quality modelling is quite limited. As a consequence the proposed set-up presented below is a compromise between technical possibilities and project requirements.

2.3 Model set up

In the hydrodynamic model the area of the Vistula Lagoon is represented by curvilinear orthogonal grid (MxN) in horizontal plane using 94 x 47 grid cells (Fig. 2.2), and 11 layers using σ -coordinates (Table 2.1). The grid sizes vary in M-direction (i.e. along the main axis of the lagoon) in the range of 360-1300 meters, in N-direction (i.e. perpendicular to the main axis) - 390-980 meters, with the aspect ratio M/N in the range of 1 - 2.18. The time step proposed for calculations is equal to 1 minute.

The area of lagoon is connected with the Baltic Sea by Baltiysk Strait (named “balt” in Fig. 2.2), where the open boundary is introduced. The shape and structure of the grids is well suited to the bathymetry of the water body (see in Fig. 2.2). In the model 9 discharges are incorporated. Due to data limitations it was decided that transport of salt will be included, while the heat transport will not. In addition spatially uniform wind will be used for calibration, verification and scenario calculations as non-uniform data with the appropriate accuracy are not available for the region. To carry out calculations initial conditions covering spatially varying salinity and water levels will be applied. The methodology of preparing the initial conditions will be presented in detail jointly with the calibration results.

Table 2.1 Vertical distribution of layers in the Vistula Lagoon using σ -coordinates.

Layer	depth [%]	layer	depth [%]
1	5	8	9
2	9	9	7
3	12	10	4
4-6	14	11	2
7	10		

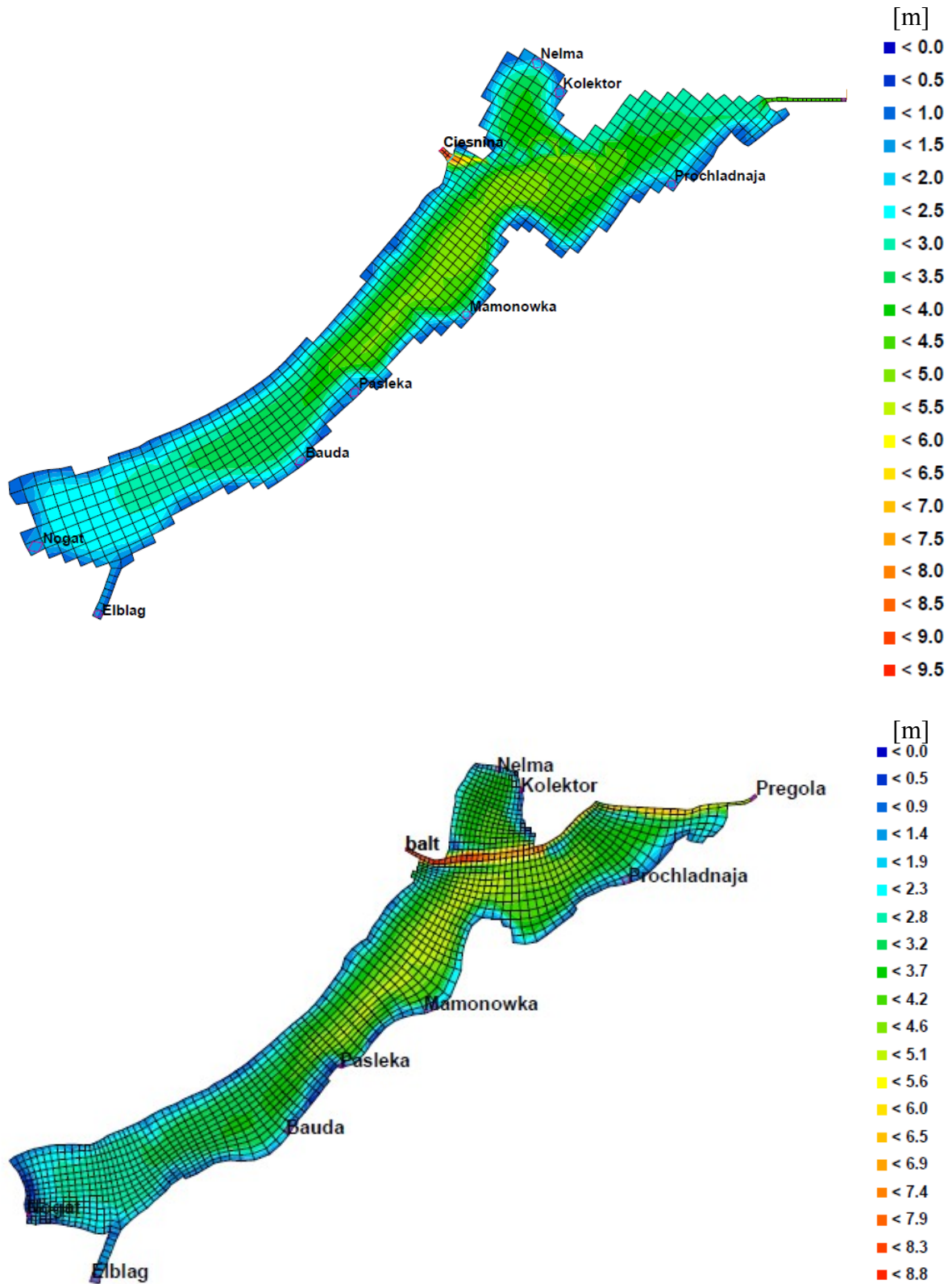


Fig.2.2 Horizontal discretization of the Vistula Lagoon and its bathymetry, top – grid in MANTRA-East project; bottom – presently proposed grid.

2.4 General description of Mike modelling suite

MIKE21-FlowModel (DHI Water & Environment, (<http://www.dhi.dk>) is a professional engineering software package containing a comprehensive modelling system for 2D free-surface flows, applicable to the simulation of hydraulic and related phenomena in lakes, estuaries, bays, coastal areas and seas where stratification can be neglected. The hydrodynamic (HD) module is the basic module in the MIKE 21 Flow Model. It provides the hydrodynamic basis for the computations performed in the Environmental Hydraulics modules. The hydrodynamic module simulates water level variations and flows in response to a variety of forcing functions in lakes, estuaries and coastal regions. The effects and facilities include: bottom shear stress; wind shear stress; barometric pressure gradients; Coriolis force; momentum dispersion; sources and sinks; evaporation; flooding and drying; wave radiation stresses.

2.5 Model set up (for the Vistula lagoon of the Baltic Sea)

MIKE 21 will be used for investigation of long-term dynamics of hydrological characteristics of the Vistula Lagoon (the Baltic Sea) to calculate saltwedge problem. It was previously used and calibrated for the Vistula Lagoon within Mantra-East project, as well as a project carried out in 1994.

Information about bathymetry for this grid was assumed from navigation maps and last measurements, both Russian and Polish (Chubarenko, 1996; Chubarenko, 1997). Numerical regular rectangular grid of 500×212 meshes in horizontal ($200\text{m} \times 200\text{m}$) (Figure 2.3) was used. Integration time step was of 25 s, what kept the Courant number close to 1. Allowances were made for the Coriolis force (54.5°N).

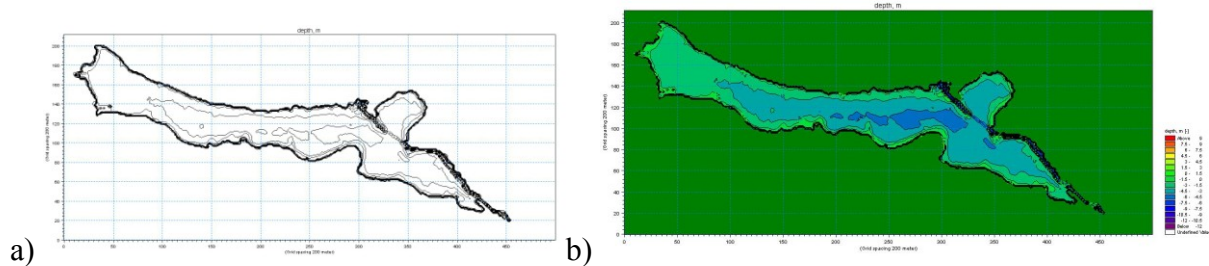


Figure 2.3. Bathymetry and rectangular grid 500×212 in horizontal dimension ($200\text{m} \times 200\text{m}$).

Tab. 2.2 Parameters of Mike 21 grid made for the Vistula Lagoon

Grid x-step,	Grid y-step,	Grid size	Origin of the grid		Orient. of the grid	Coordinates of open boundary
m	m		λ	φ	α	(x,y)
200	200	0...499 - 0...211	54.0628	19.6412	310.96	(299; 145) - (300; 145)

Open boundary was placed in the Baltiysk Strait. The river runoff to the Vistula Lagoon was formed from the seven rivers (Pregola, Momonovka, Nelma, Bauda, Elblag, Nogat, Pasleka).

Tab.2.3. The list of rivers discharging to the Vistula Lagoon (included in the model)

Country	Name of the river	Coordinates of the the grid points	
		x	y
RU	Pregola	451	22
RU	Momonovka	223	96
RU	Nelma	357	150
PO	Bauda	137	99
PO	Elblag	33	130
PO	Nogat	26	160
PO	Pasleka	167	104

The presented set-up is now ready for calibration and is based on the set up from MANTRA-East project. However, in a different set-up (1 km x 1 km) this model has already been calibrated (Chubarenko, 1996; Chubarenko, 1997).

MIKE 21/3 Coupled Model FM (MIKE 21/3, 2005) developed in Danish Hydraulic Institute will be used for simulations of vertical distribution of current fields in the Vistula Lagoon and Pregola River.

The model is based on the solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of hydrostatic pressure (MIKE Sci. Doc., 2005).

Current fields will be simulated using grid with flexible meshes, covering Vistula Lagoon and the part of Pregola River (Figure 2.4).

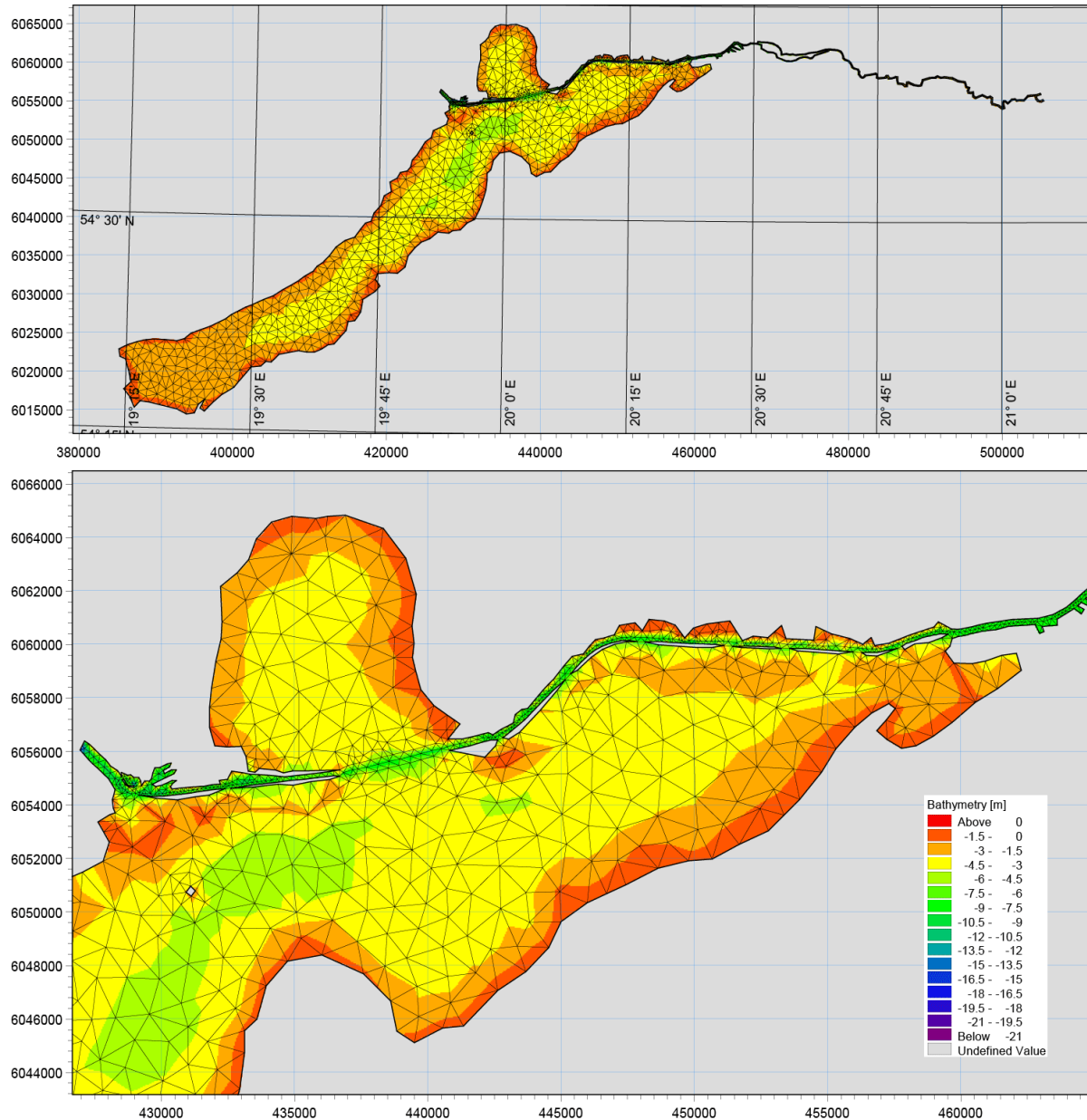


Figure 2.4. Computational domain for MIKE3 FM. Vistula lagoon and the part of the downstream of the Pregola River; (a) total system, (b) zoom of the northern part of the Vistula Lagoon with Kaliningrad Marine Canal area.

Mesh size for the internal part of the lagoon will be about 1 km, and in Kaliningrad Marine Canal and the Pregola River – about 50-100 m.

Baltiysk Strait will be the only open boundary for the computational domain.

It is assumed that wind measured in Baltiysk could be uniformly applied for the entire area of simulations. The Pregola River and other rivers, as well as two major sources of pollutions (Kaliningrad collector and outlet from new Kaliningrad Waste Water Treatment Plant) will be included in the study.

In order to investigate in detail the problem of salt intrusions upstream the Pregola River, SWIM model, applied in the LAGOONS project for other catchments, will be used. Details of this model will be presented in deliverable D5.1.

2.6 Problems and future actions

At present the hydrodynamic Delft 3D and Mike models are ready for calibration and validation. For calibration purposes data from years 1998-2000 collected within MANTRA-East project will be used, while for validation data from 2009 gathered in the Lagoons project are planned to be used. When calibration/validation procedure will be finished, scenario calculations will start. Procedure to transfer hydrodynamic results from Delft 3D – HD model to the Delft 3D water quality model was tested. As water quality model will use more general grid an aggregation concept was worked out (see Chapter 3) and tested.

The SWIM model set-up is developed within the WP5 and will be further applied for the Pregola River in the context of the saltwedge intrusions.

3. Ecological model

3.1 General description of the model

Delft3D-WAQ is a 3-dimensional water quality part of the Delft3D software developed by Delft Hydraulics, The Netherlands (WL | Delft Hydraulics, 2001). Delft3D software solves the advection-diffusion-reaction equation for a wide range of chemical and biological state variables. The Delft3D-WAQ module is supplied with hydrodynamic data from Delft3D-FLOW module (see Chapter 2 - Hydrodynamic model) using the coupling procedure.

We have modified our first modelling assumptions which were made during the MANTRA-East project and the outcome provides better understanding of the Vistula Lagoon ecosystem functioning. Based on modelling it was possible to quantify roughly main fluxes of substances (inflow, outflow, mineralization, release from sediments, oxygen consumption, nitrification, denitrification, nitrogen fixation, net accumulation etc.; Witek et al., 2010).

3.2 Processes modelled in the lagoon

3.2.1 The processes of the Vistula Lagoon Delft3D-WAQ model

In the Vistula Lagoon model the following processes will be included:

- Algae growth, respiration and mortality (representing natural mortality and zooplankton grazing);
- Mineralization of particulate and dissolved organic matter;
- Sedimentation and resuspension of algae and particulate matter;
- Adsorption and desorption of phosphorus onto inorganic matter;
- Nitrification;
- Denitrification;
- Reaeration of oxygen.

Growth and mortality of algae - growth of algae is determined by light and nutrient availability. Mortality of algae depends on the temperature and thus in summer months is much higher. Under natural conditions, mortality of algae depends also on zooplankton grazing. However, zooplankton activity is not implemented in the model. Therefore, mortality

due to grazing is approximated by increased value of temperature factor. Sedimenting algae are also present in the bottom sediment and can be resuspended (Fig. 3.1). However, mortality of algae in the sediment is much higher than in the water column.

Mineralization is formulated as a function of mineralization rate and temperature. There is a critical temperature below which mineralization is zero. Each element (C, N, P, Si) in a given substance may have individual mineralization rate and individual temperature coefficient.

Sedimentation depends on sinking velocity and wind mixing. Sedimentation takes place when wind velocity drops below a critical value. Each substance (algal groups, detritus, inorganic matter) may have individual sedimentation velocity and individual critical value of wind velocity.

Resuspension depends on resuspension rate and wind mixing. Resuspension takes place only when wind velocity exceeds a critical value. All resuspending materials have the same resuspension rate and a critical wind velocity.

Nitrification of N-NH_4 occurs only in the water column. Nitrification is a function of nitrification rate, temperature and oxygen concentration. There is a critical temperature and a critical oxygen concentration below which nitrification is zero.

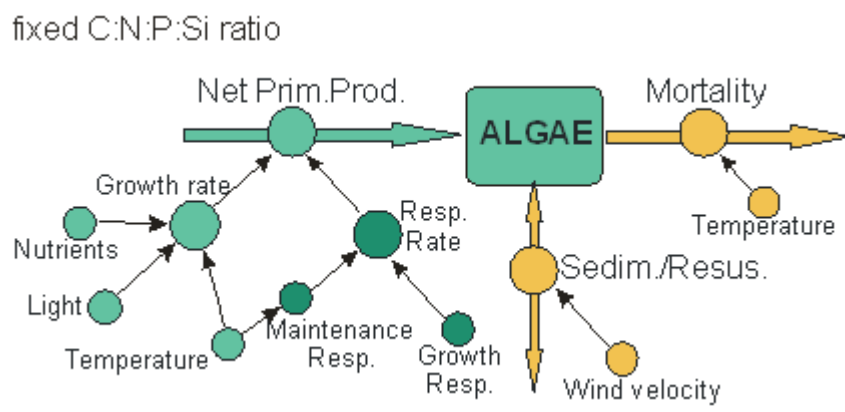


Fig. 3.1 Growth and mortality of algae in the Delft3D-WAQ model.

Denitrification of N-NO_3 occurs only in the bottom sediment. Denitrification in the sediment consumes N-NO_3 from the water column (near-bottom layer). Denitrification depends on denitrification rate and temperature. There is a critical temperature below which denitrification is zero. There is no dependence on oxygen concentration, assuming that at certain depth in sediment conditions are anoxic.

Adsorption of inorganic phosphorus onto inorganic matter occurs only in water column. It is a reversible process, dependent on relative concentrations of dissolved (P-PO_4) and adsorbed (AAP) phosphorus concentrations. The formulation is based on maximum adsorption capacity, equilibrium constant and adsorption rate constant. Adsorption/ desorption in water column is independent of water temperature. Adsorbed phosphorus can sediment with inorganic matter. In bottom sediment, desorption of adsorbed phosphorus may take place. This process is dependent on desorption rate and temperature. Below a critical temperature no phosphorus desorption occurs.

Reaeration of water column is controlled by a difference between the saturation content of oxygen and dissolved oxygen in the water column. Reaeration can have a positive or a negative value and depends on wind velocity.

3.2.2 State variables

The model of the Vistula Lagoon covers cycles of nitrogen, phosphorus, silicate, carbon and oxygen in water column and sediment. An example of the nitrogen cycle is shown in Figure 3.2. There is no zooplankton as a state variable in the model. Zooplankton grazing pressure on phytoplankton is expressed only by algal mortality. The following state variables were considered in the model:

- Two phytoplankton groups, expressed in carbon units: one representing diatoms which take up silicate - Algae (1) and the second representing all other groups of algae - Algae (2);
- Nutrients in dissolved form – accessible for algal uptake: N-NO_3 , N-NH_4 , P-PO_4 , dissolved silicate - Si(OH)_4 ;
- Nutrients and carbon in particulate organic matter: DetN, DetP, DetSi, DetC;
- Nutrients and carbon in organic matter in sediment: DetNS1, DetPS1, DetSiS1, DetCS1;
- Dissolved organic matter - refractory fractions containing carbon and all nutrients: DOP, DON, DOSi, DOC. Refractory dissolved organic matter fractions are present only in the water column not in sediment;
- Suspended inorganic matter IM1 and inorganic matter in sediment IM1S1;
- Phosphorus bound with inorganic matter in water column AAP and in sediment AAPS1;
- Dissolved oxygen in water OXY.

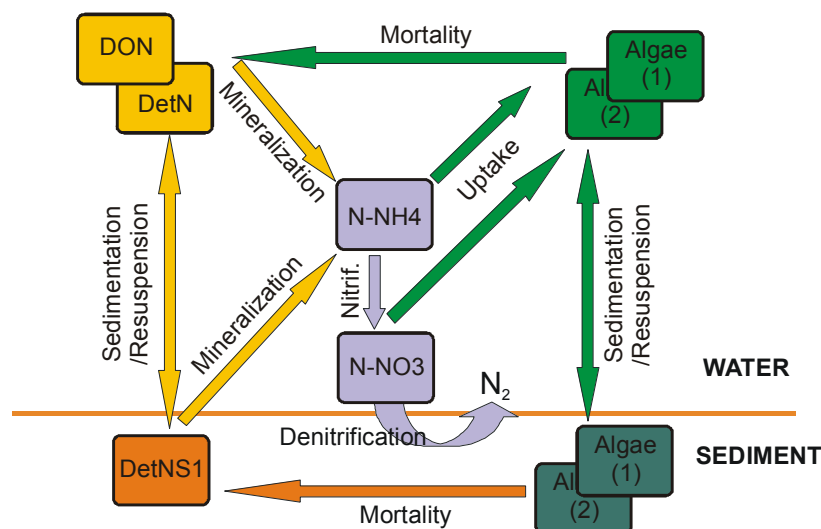


Fig. 3.2 Nitrogen cycle in the Delft3D-WAQ model

3.3 Model set up

3.3.1 Spatial and temporal resolution

The water quality module Delft3D-WAQ covers a greater number of modelled processes as compared to the hydrodynamic module Delft3D-FLOW. In order to shorten simulation time, the model grid used in hydrodynamic module, was aggregated. Horizontal grid presented in Chapter 2 (Hydrodynamic model) was limited to 100 grid cells, while in vertical 8 layers (instead 11) were introduced. Also a calculation time step was increased to 10 minutes. The aggregation of hydrodynamic grid was made in such a manner as to follow the main trends in bathymetry of the Vistula Lagoon (Fig.3.3; Table 3.1).

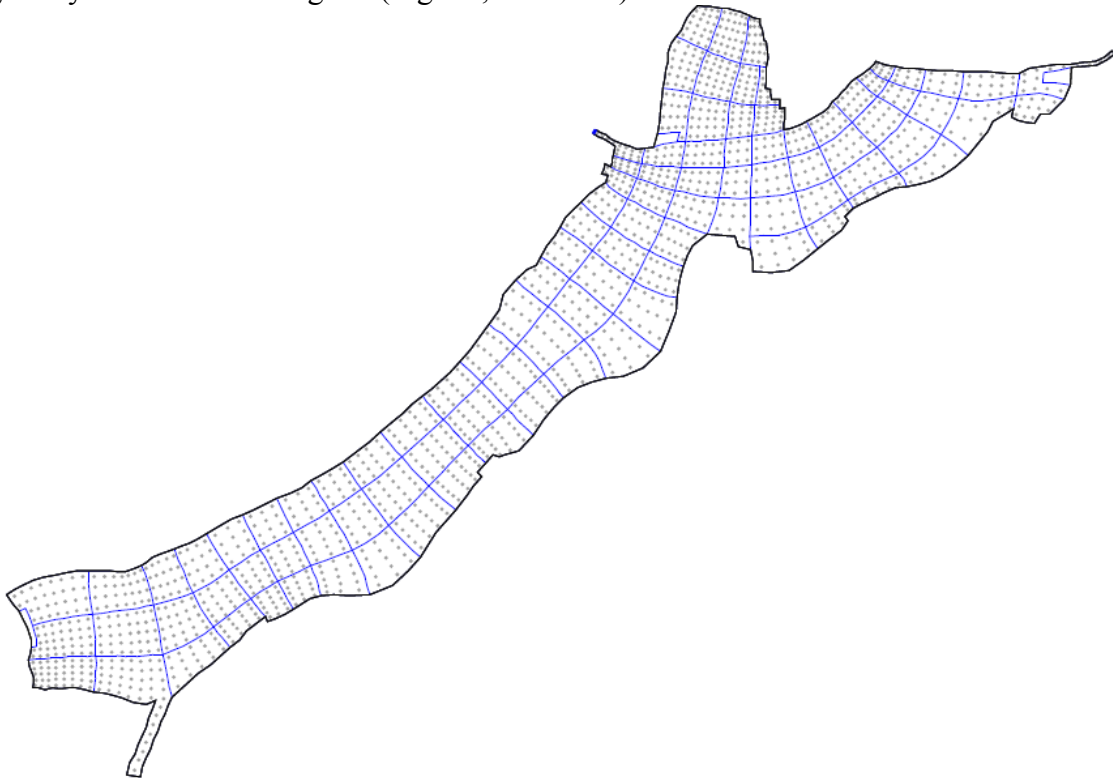


Fig. 3.3 Spatial resolution of the water quality grid.

Table 3.1. Vertical distribution of layers in Vistula Lagoon in hydrodynamic module (Delft3D-FLOW) and water quality module (Delft3D-WAQ).

Delft3D-FLOW		Delft3D-WAQ	
layer from the surface		layer from the surface	
number of the layer	% of total depth	number of the layer	% of total depth
1	5	1	14
2	9		
3	12	2	26
4	14		
5	14	3	28
6	14		
7	10	4	10
8	9	5	9
9	7	6	7
10	4	7	4
11	2	8	2

3.3.2 Forcing functions for Delft3D Water Quality model

All data used for preparation the water quality model and the first calculation steps/ simulations were collected during the MANTRA-East project. The following forcing functions were regarded in the model:

- Daily averaged water temperature values;
- Ice conditions: data on ice cover in the Lagoon;
- Light conditions: daily values of irradiance;
- Wind: daily wind speed values;
- Nutrient discharges from rivers: daily linearly interpolated values were applied in the model. Some parameters were not measured on regular basis within the monitoring program therefore they required interpolation or extrapolation on the basis of data existing for other rivers (Fig. 3.4);
- Atmospheric deposition of nutrients and inorganic matter: only nitrogen and inorganic matter deposition are taken into account in the model;
- Nutrient inflow from the Baltic Sea: water exchange with the Baltic Sea was calculated by the Delft3D-FLOW module. Concentrations of substances in the inflowing sea water were estimated on the basis of data extracted from the Baltic Environmental Database (Fig. 3.4; BED - Wulff et al. 1996).

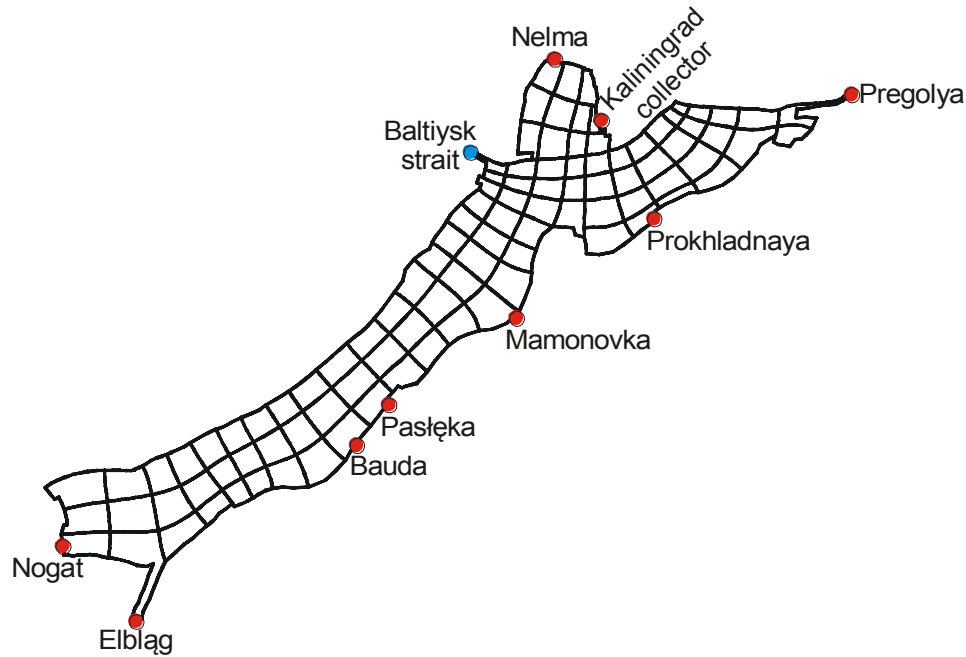


Fig. 3.4 Location of the nutrient discharges (red points) and open boundary (blue point) in the Vistula Lagoon Delft3D-WAQ model

3.4 Problems and future actions

The water quality model of the Vistula Lagoon is ready to proceed to next actions using the new hydrodynamic grid, which will encompass:

- Preparation and execution of calibration runs based on data set from time period 1998-2000;
- Preparation and execution of the year 2009 validation (simulation);
- The above steps will facilitate future scenario calculations.

Since some parameters have not been monitored on regular basis over the last years, the gaps in filed data required interpolation or extrapolation on the basis of data existing for other rivers. The interpolation or extrapolation has to be done as well for other time periods. There were a number of parameters for which measured data were not available at all. Concentrations of these substances were estimated indirectly (for example: DetC and DOC – from COD-Cr, phytoplankton C, N, P, Si – from chlorophyll and stoichiometric proportions, IM – from total suspended matter etc). Also deposition of inorganic matter was approximated based on measurements at the south Baltic Sea coast (Pęcherzewski, 1991).

References

- Bielecka M., Kaźmierski J., 2003. A 3D mathematical model of Vistula Lagoon hydrodynamics - General assumptions and results of preliminary calculations. [In:] Proceedings of the 7th International Specialised Conference on Diffuse Pollution and

- Basin Managements and 36th Scientific Meeting of the Estuarine and Coastal Sciences Association (ECSA). Ed. M. Bruen, Dublin: University College, 2003, Vol. 3, s. 6.140-6.145.
- Chubarenko B.V., Chubarenko I.P., 2002. General water dynamics of the Vistula Lagoon. *Environmental and Chemical Physics*, 24 (4): 213-217.
- Chubarenko I.P., 1996. Calibration of the hydrodynamic and advection-dispersion modules of the numerical model MIKE21 and calculations of the annual dynamics of fields of salinity in the Vistula Lagoon. Research Report on International Russian-Polish-Danish project "Vistula Lagoon". ABIORAS, heads - V.T.Paka, B.V.Chubarenko. - Volume 4. - Kaliningrad, 1996. - 135 p.: Чубаренко И.П. Калибрация гидродинамического и адвекционно-дисперсионного модулей численной модели MIKE21 и расчёты годовой динамики полей солёности в Вислинской лагуны. Отчет о НИР по международному российско-польско-датскому проекту «Вислинская лагуна». АО ИОРАН; руководители – В.Т.Пака, Б.В.Чубаренко. – Том 4. – Калининград, 1996. – 135 с.
- Chubarenko I.P., 1997. Using a complex model MIKE21 for modeling of hydrological regime of the Vistula Lagoon / I.P. Chubarenko, M.Ya.Kolosentseva // *Ecological problems of the Kaliningrad region: a collection of scientific papers* / KSU., Kaliningrad, 1997. - P. 80-83.
- Delft3D-FLOW, 2010. Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments. Deltares, User Manual. v.3.14, Delft, the Netherlands.
- DHI Water & Environment - <http://www.dhi.dk>
- LAGOONS, 2012. The Vistula Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1a. 99pp.
- Lindström, G., Pers, C.P., Rosberg, R., Strömqvist, J., Arheimer, B., 2010. Development and test of the HYPE (Hydrological Predictions for the Environment) model – A water quality model for different spatial scales. *Hydrology Research* 41.3-4:295-319.
- Łazarienko N.N., Majewski A. (eds.), 1975. Hydrometeorologiczny ustrój Zalewu Wiślanego [The hydrometeorological system of the Vistula Lagoon]. Wydawnictwo Komunikacji i Łączności, Warszawa, 518 (in Polish).
- Łomniewski K., 1958. Zalew Wiślany [The Vistula Lagoon]. *Prace Geograficzne*, Polska Akademia Nauk, Instytut Geografii, PWN Warszawa 15, 106 (in Polish).
- MIKE 21/3 Coupled Model FM., 2005. User Guide, DHI Software, 43.
- MIKE 21 & MIKE 3 Flow Model FM Hydrodynamic and Transport Module. 2005. Scientific Documentation, DHI Software, 48.
- Pęcherzewski, K., 1991. Substances deposited from the atmosphere to the Southern Baltic waters. *Akademia Rolnicza in Szczecin*, pp. 40 (in Polish).
- Witek, Z., Zalewski, M., Wielgat-Rychert, M., 2010. Nutrient stocks and fluxes in the Vistula Lagoon at the end of the twentieth century, Pomeranian Academy in Słupsk, Sea Fisheries Institute in Gdynia, Słupsk-Gdynia 2010, 186pp.
- WL | Delft Hydraulics, 2001. User Manual Delft3D WAQ. Delft, The Netherlands.
- Wulff, F., A. Sokolov, O. Andrejev, M. Rodriguez-Medina, 1996. The Data Assimilation System and the Baltic Environmental Database. <http://nest.su.se/das/>

Chapter 2

The Ria de Aveiro Lagoon Hydrodynamic and water quality models

João D. Lencart e Silva, Nuno Vaz and João M. Dias

University of Aveiro, Portugal

1. Introduction

The Ria de Aveiro (Figure 1) consists of four main channels, which radiate from the mouth with several branches, islands and mudflats. More details on physiogeographical conditions of the Ria de Aveiro are available in LAGOONS project webpage (<http://lagoons.web.ua.pt/> - LAGOONS Report D2.1b).

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). The total fluvial discharge into the lagoon during a tidal cycle is about $1.8 \times 10^6 \text{ m}^3$, while the tidal prism is $137 \times 10^6 \text{ m}^3$ for maximum spring tide, and $35 \times 10^6 \text{ m}^3$ 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 torrential 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 shallow depth and to the tidal wave amplitude the intertidal area is a significant part of the total area being studied.

2. Hydrodynamic model

2.1 General description of the model

Originally, the MOHID modelling package was targeted as the candidate platform for the modelling of the Ria de Aveiro in the context of this project. However, initial tests in the model design phase showed that a configuration with all the hydrodynamic and biogeochemical features was unable to represent a full hydrological year within a reasonable

time. The time needed for the calculations depends directly from the number of calculation points. To decrease computation time with the same hardware, the number of calculation points must decrease. Decreasing calculation time to allow the representation of the seasonal cycle demanded a different approach using curvilinear grids which increase spatial resolution where it is needed and reduce it elsewhere. Several curvilinear grids were tested with MOHID and Delft3D-Flow and it was found the previous package was not robust enough for the use of such grids in Ria de Aveiro. Hence, the Delft3D-Flow package was chosen for the modelling of the hydrodynamics, given that its ability to support curvilinear grids allows the timely calculation of the several model configurations needed for the calibration, validation and scenario simulation with the necessary resolution in the relevant areas.

Delft3D-Flow is a three-dimensional, finite differences hydrodynamic and transport model which simulates a full range of flow and transport phenomena 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 (Bos et al. 1996, WL|DelftHydraulics 1996, Nicholson et al. 1997, 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.

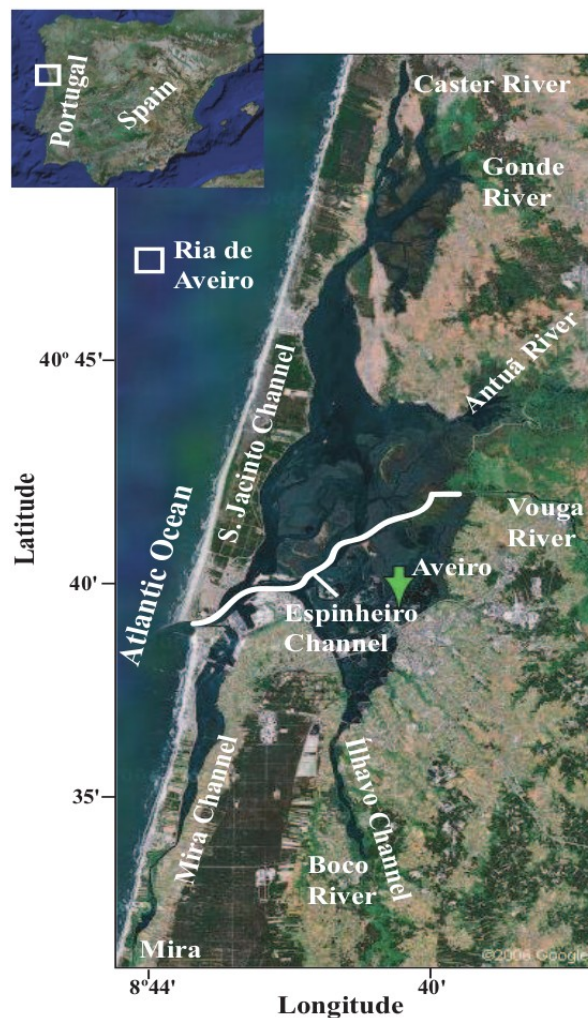


Figure 1- Ria de Aveiro and tributary rivers (Vaz 2007).

The Delft3D-Flow platform has been used previously in estuarine and ROFI conditions e.g. in Tomales Bay California (Harcourt-Baldwin and Diedericks 2006), the Rhine ROFI (de Boer et al. 2008), the Ria de Muros in North-West Spain (Carballo et al. 2009) and Maputo Bay (Lencart e Silva et al. 2010). In addition to Maputo Bay, the UAVR team has experience using Delft3D-Flow in Ria Formosa Lagoon Portugal, Langebaan Lagoon South Africa and Xiangshan Bay China (Ferreira et al. 2008).

The modelling of the Ria de Aveiro presented here by the UAVR team combines the experience of using Delft3D-Flow in other systems with the solid modelling expertise of the Ria de Aveiro using other models such as SYMSIS2D, MOHID, ELCIRC, SELF3D in the past 15 years in more than 20 research and consultancy projects.

2.2 Processes modelled in the lagoon

In order to model the hydrodynamics and transport at the tidal, fortnightly, season and event scales two main processes need to be represented:

- i) Propagation of the tidal wave inside the lagoon;
- ii) The density field resulting from the temperature and salinity fields.

To a lesser extent the wind-driven circulation assumes some importance in the central part of the lagoon (Lopes and Dias 2007).

The propagation of the tide was modelled by imposing the main 19 astronomic constituents at the open boundary and calibrating its propagation through the adjustment of the bottom roughness. This parameter assumes the Manning formulation of the Chezy coefficient. To represent accurately the propagation of the tide in the lagoon, the model was given the ability to simulate wet and drying of the intertidal areas.

In the present application, the model can compute the 2-dimensional depth-average hydrodynamic solution or a 3-dimensional solution using terrain-following σ -layer vertical grid. In 3-dimensional space, vertical mixing is computed using a κ - ϵ turbulence closure model.

To reproduce wind driven circulation, spatially-constant momentum flux of wind is prescribed.

To model the time and space distribution of temperature, the transport model calculates advection and diffusion of heat in the lagoon and the heat model calculates the heat flux between the lagoon and the atmosphere. The heat model uses air temperature, the combined net (short wave) solar and net (long wave) atmospheric radiation, relative humidity and wind speed to calculate heat losses due to evaporation, back radiation and convection. Boundary conditions for temperature are prescribed at the oceanic open boundary and at the input points of freshwater from the catchment.

The transport of salt within the modelling domain is computed taking into account the input of freshwater from the catchment and the salinity prescribed at the oceanic open boundary. Precipitation and evaporation are not taken into account in the mass balance.

2.3 Model set up

To depict accurately the flow both in the tidal channels and in the intertidal flats a great emphasis was placed on the construction of the numerical grid. In this way the grid must have the following properties:

- i) To cover all of the area of interest;
- ii) To represent the main hydrodynamic features of the lagoon;
- iii) To be numerically robust by complying with the CFL criterion;
- iv) To prevent spurious propagation of open boundary effects inside the area of interest;
- v) To do all of the above with the minimum number of calculation points in order to allow a timely calculation of all the hydrodynamic and biogeochemical variables.

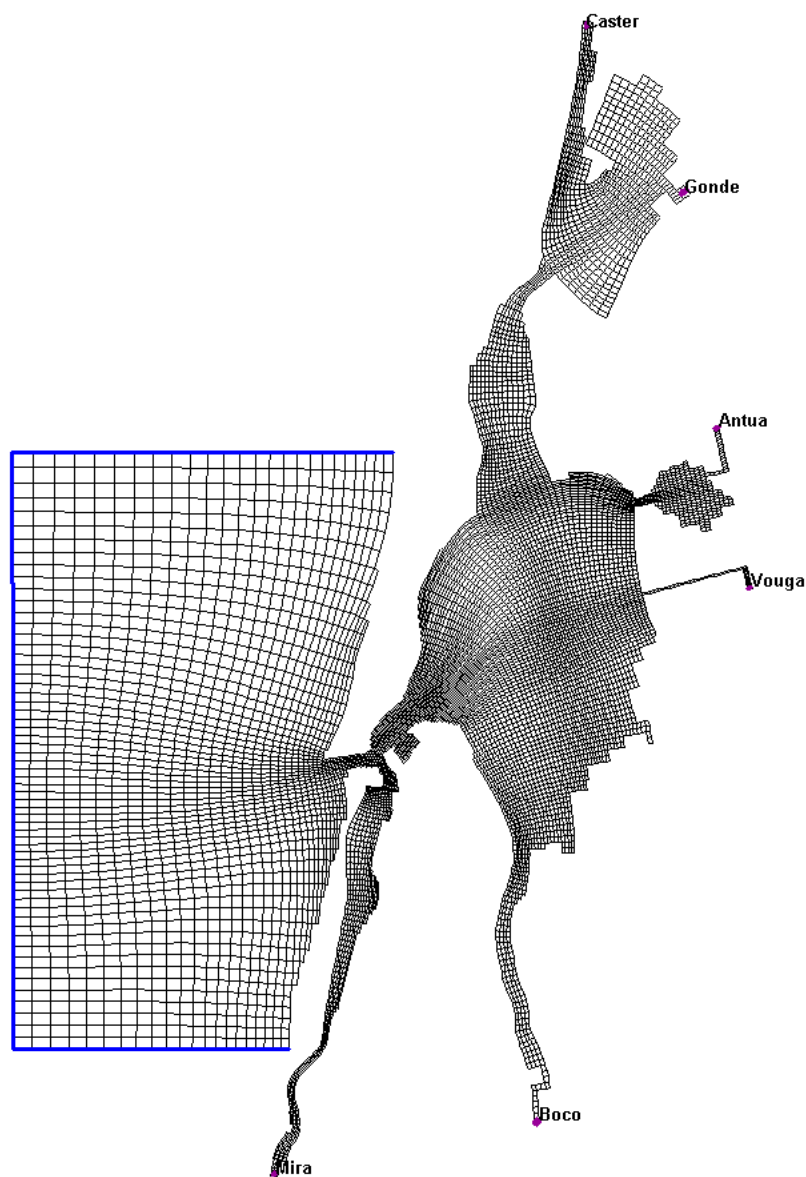


Figure 2 - Computational grid Delft3D-FLOW and Delft3D-WAQ for Ria de Aveiro.

In order to comply with all of the above, a curvilinear orthogonal grid was developed in Cartesian coordinates (Figure 2). This grid has a total of 9828 calculation grid points with an open boundary at the shelf in the segments represented in blue in Figure 2. A total of 6 freshwater points were defined as outflows representing the Vouga, Antuã, Boco, Caster, Gonde and the system of streams discharging water at head of the Mira Channel. 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.

The bathymetry of the Ria de Aveiro used in this work results from the interpolation to the numerical grid of a set of surveys from 2011, 2003 and 1987-88. The interpolation was a piecewise, exclusive process starting with the most recent survey and moving to earlier surveys where later data was unable to provide a solution (Figure 3).

The Ria de Aveiro is for most of the time a vertically well-mixed system allowing for the 2-dimensional depth-average approximation. To test this, some calibrations runs were performed with a vertical dimension using 7 σ -layers uniformly distributed in the water column. Currently the model has a time step of 30 s.

The model starts at high-water with elevation equal to the value at the mouth of the lagoon for that instant. This reduces spin-up time by allowing the reflected tidal waves to reach equilibrium faster during the subsequent ebb tide. The spin-up takes the first 5 days of calculation time for dynamic water level and tidal currents. During this time interval the solution is considered inaccurate and discarded from the results.

Yearly runs start at the beginning of the summer from uniform salinity and temperature equal to the value at the open boundary to allow 3 months of spin-up time, discarding these first 90 days of every run.

2.4 Problems and future actions

The most recent bathymetric surveys of the Ria de Aveiro cover the main navigational channels with very fine resolution. However, the more intricate channels and salt pond areas were last surveyed in 1987 – 1988. In addition to this there is a high uncertainty level as to the position of the top limit of the intertidal. Topographic surveys in dry land inside the Ria are sparse in time and in space, thus posing a relevant uncertainty on the shape of the intertidal slope and of the lagoon's storage volume. This is reflected on the ability of the model to reproduce accurately the shallow water tidal harmonics such as the M4 and MSf.

The calibration of the hydrodynamics is nearly finished and will be the subject of the next report. Currently, the propagation of the tide has been fully calibrated and validated for all of the harmonic constituents forced at the boundary and for additional shallow water constituents, resorting to 15 tidal calibration stations. Salt and heat are calibrated for the seasonal time scale using fortnightly CTD surveys at 32 stations along the Espinheiro Channel. The calibration and verification of salt and heat at the tidal scale is still underway. Future work includes the production of a reference condition and of the scenarios agreed upon by the consortium.

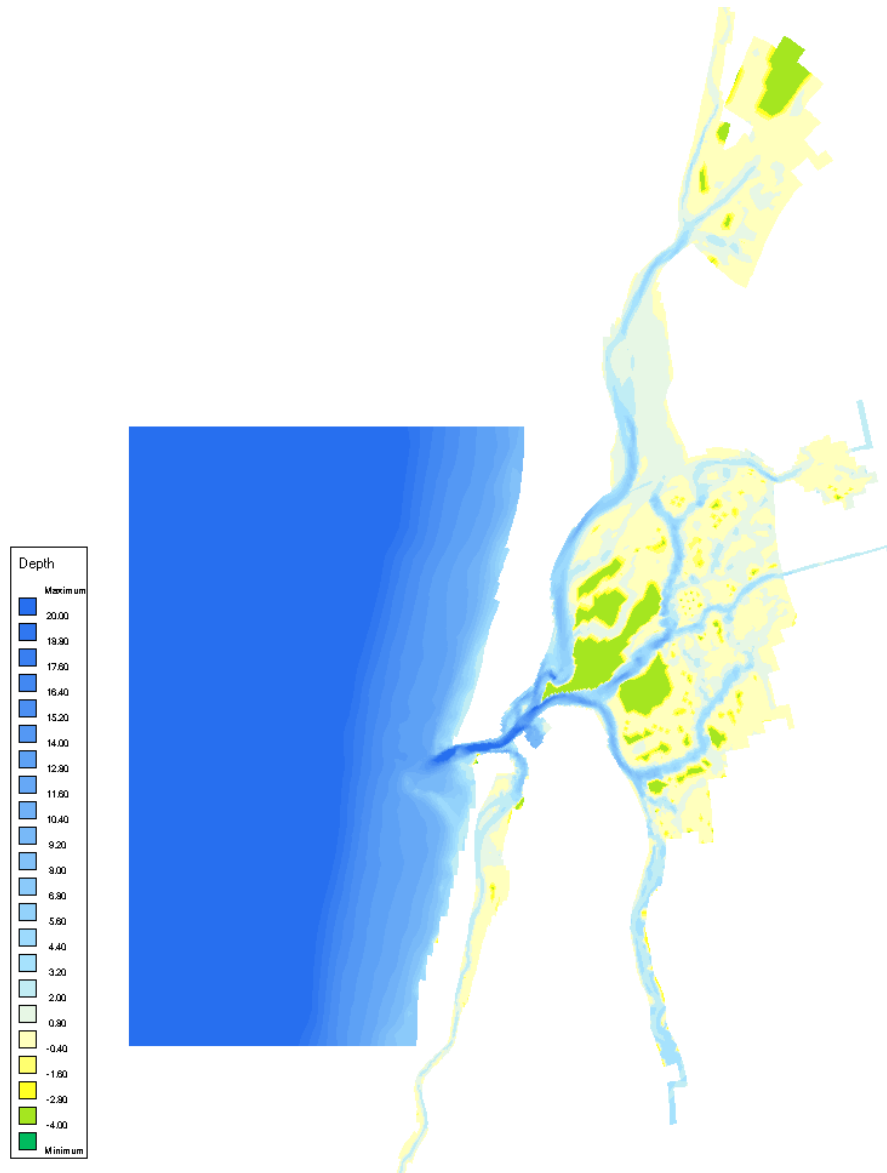


Figure 3- Bathymetry for Ria de Aveiro.

3. Ecological model

3.1 General description of the model

The Delft3D-WAQ model solves the advection-diffusion-reaction equations to calculate the space and time variation of biogeochemical and water quality state variables and derived quantities.

In the current implementation Delft3D-WAQ uses hydrodynamic quantities calculated by Delft3D-Flow to parameterise its advection-diffusion numeric scheme. Temperature and Salinity are also taken from Delft3D-Flow. Quantities calculated by Flow are communicated to WAQ using a spatial and time coupling algorithm which allows for the change of time step and spatial resolution within WAQ, thus reducing the computational load.

Only limited previous experience existed in the UAVR team Delft3D-WAQ. However, the team has 2 ongoing projects where water quality modelling is being carried out with the MOHID platform in Ria de Aveiro, the Tagus and Douro Estuaries and in the North and Norwest coast of the Iberian Peninsula.

3.2 Processes modelled in the lagoon

The processes modelled in WAQ will result in the calculation of the following quantities: turbidity, nutrient levels, oxygen and phytoplankton. To do this, the biogeochemical cycles of carbon, nitrogen, phosphorus, silicon and oxygen are represented.

Currently the design phase of the WAQ model is underway which means that the list of processes represented in these phase will be revised according to the relevance of each process to the overall model result. In the present version of the model design the following candidate processes are included:

- Algae growth;
- Settling and resuspension of particulate matter and algae;
- Mineralization of particulate and dissolved matter including nitrification, denitrification and oxidative processes for phosphorous and silicon;
- Adsorption of inorganic phosphorous;
- Reaeration of oxygen;

The model will assume a constant C:N:P:Si ratio and approximates planktonic primary production by representing two groups of phytoplankton: i) diatoms; ii) all other algae. The nutrients will be represented both in their dissolved and particulate organic forms. Suspended inorganic matter will be modelled including the fraction already inside the lagoon and the fraction imported from the catchment.

3.3 Model set up

During this early design phase, the WAQ model is assuming the same configuration as the FLOW model without any spatial upscaling. In the initial test runs the time step was set to 30 minutes. The FLOW results for heat, salt and hydrodynamic properties are used as forcing functions of the WAQ model. Nutrients and fine sediments from the catchment are included as discharges at the same points included in FLOW. At this phase, wind effects are included in the velocities sourced from FLOW.

3.4 Problems and future actions

The modelling of WAQ is still in the initial stages of the design phase. In the future a stable list of processes will be reached and the calibration of the parameters will start using 2003 - 2004 monthly surveys of the modelled quantities at 8 stations.

Once the model has been calibrated and validated against the data coming from the LAGOONS 2012 surveys a reference condition and a set of scenarios will be produced.

References

- Bos KJ, Roelvink JA, Dingemans MW. 1996. Modelling the impact of detached breakwaters on the coast. Proceedings of the 25th International Conference on Coastal Engineering, Orlando, USA. New York: American Society of Civil Engineers. pp 2022–2035.
- Carballo R, Iglesias G, Castro A. 2009. Residual circulation in the Ria de Muros (NW Spain): a 3D numerical model study. *Journal of Marine Systems* 75: 116–130.
- de Boer GB, Pietrzak JD, Winterwerp JC. 2008. Using the potential energy anomaly equation to investigate tidal straining and advection of stratification in a region of freshwater influence. *Ocean Modelling* 22: 1–11.
- Dias, J.M.; Lopes, J.F., Dekeyser, I., 2000. Tidal propagation in Ria de Aveiro Lagoon, Portugal. *Phys Chem Earth (B)* 25 (4), 369-374
- Ferreira J. G., Andersson H. C., Corner R. A., Desmit X., Fang Q., de Goede E. D., Groom S. B., Gu H., Gustafsson B.G., Hawkins A. J. S., Hutson R., Jiao H., Lan D., Lencart-Silva J., Li R., Liu X., Luo Q., Musango J.K., Nobre A.M., Nunes J.P., Pascoe P.L., Smits J.G.C, Stigebrandt A., Telfer T.C., de Wit M.P., Yan X., Zhang X.L., Zhang Z., Zhu M.Y., Zhu C.B., Bricker S.B., Xiao Y., Xu S., Nauen C., Scalet M.(2008) SPEAR. Sustainable Options for People, Catchment and Aquatic Resources. Lisboa. IMAR-Institute of Marine Research. 184. Pp
- Harcourt-Baldwin JL, Diedericks GPJ. 2006. Numerical modelling and analysis of temperature controlled density currents in Tomales Bay, California. *Estuarine, Coastal and Shelf Science* 66: 417–428.
- LAGOONS. 2012. The Ria de Aveiro Lagoon – Current knowledge base and knowledge gaps. LAGOONS Report D2.1b. 52pp. (available on <http://lagoons.web.ua.pt/>).
- Lencart e Silva J.D., Simpson J.H., Hogueane A.M., Harcourt-Baldwin J-L. (2010) Buoyancy-stirring interactions in a subtropical embayment: A synthesis of measurements and model simulations in Maputo Bay. *African Journal of Marine Science*. 32, 1, 97-107.
- Lesser GR, Roelvink JA, van Kester J, Stelling GS. 2004. Development and validation of a three-dimensional morphological model. *Coastal Engineering* 51: 883–915.
- Lopes J.F., Dias J.M. (2007) Residual circulation and sediments transport in Ria de Aveiro lagoon, Portugal. *Journal of Marine Systems*. 68, 3-4, 507-528.
- Nicholson J, Broker I, Roelvink JA, Price D, Tanguy JM, Moreno L. 1997. Intercomparison of coastal area morphodynamic models. *Coastal Engineering* 31: 97–123.
- Vaz N.A.F.(2007) Estudo dos processos de transporte de calor e de sal no Canal do Espinheiro (Ria de Aveiro) (Study of heat and salt transport processes in the Espinheiro Channel (Ria de Aveiro)) . Departamento de Física. Universidade de Aveiro. Aveiro. Doutoramento. 151pp
- Vaz, N. e Dias, J.M., 2008. Hydrographic characterization of an estuarine tidal channel. *Journal of Marine Systems*, 70 (1–2), 168–181.

Vaz N, Lencart e Silva JD, Dias JM (2012). Salt Fluxes in a Complex River Mouth System of Portugal. PLoS ONE 7(10): e47349. doi:10.1371/journal.pone.0047349.

WLDelftHydraulics. 1996. Delft3D-FLOW user manual version 3.05. Delft: WL Hydraulics.

Chapter 3

The Mar Menor Lagoon Hydrodynamic and water quality models

Javier Lloret

University of Murcia, Spain

1. Introduction

1.1 Description of the study area

The Mar Menor is a hypersaline coastal lagoon located in a semi-arid region of southeast Spain. The lagoon occupies a surface of approximately 135 km² and a total volume of 610x10³ m³ (Arévalo 1988). Maximum depth in the lagoon reaches 6.5 m with an average depth of 3.6 m. According to the geomorphological classification of Kjerfve (1986), the Mar Menor constitutes a restricted littoral lagoon relatively isolated from the adjacent Mediterranean Sea.

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. The enlargement of El Estacio channel led to a substantial increase of water renewal rates from the Mediterranean, as well as subsequent changes in water temperatures and salinities. These changes favoured the colonisation of the lagoon by numerous marine species as lagoonal temperatures and salinities reached less extreme values (Pérez-Ruzafa et al. 1991).

Before the dredging of El Estacio channel salinities in the lagoon reached values of over 52 and temperatures ranged from 6 to over 30° C. Nowadays, salinity ranges from 42 to 47 and temperatures are less extreme ranging from 10° C in winter to almost 30° C during the summer.

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 delimited by a group of mountain ranges (Escalona, Algarrobo, Cartagena) that surround the Campo de Cartagena, an extent plain of about 1,440 km². 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.

Three of these wadis are located on the west margin of the lagoon. Los Alcázares wadi has a diffuse network of channels and reaches the Mar Menor at the town of Los Alcázares. El Albuñón wadi constitutes the largest watercourse and drains the adjacent agricultural area Campo de Cartagena. Miranda wadi presents two main channels that converge diffusely in El Carmoli salt marsh. The other three wadis that reach the lagoon are El Beal, Ponce and Carrasquilla wadis. These originate in the mountains located south of the Mar Menor lagoon, and, during episodic rain events, carry metal wastes and mineral deposits from the mining areas located there (Figure 1).

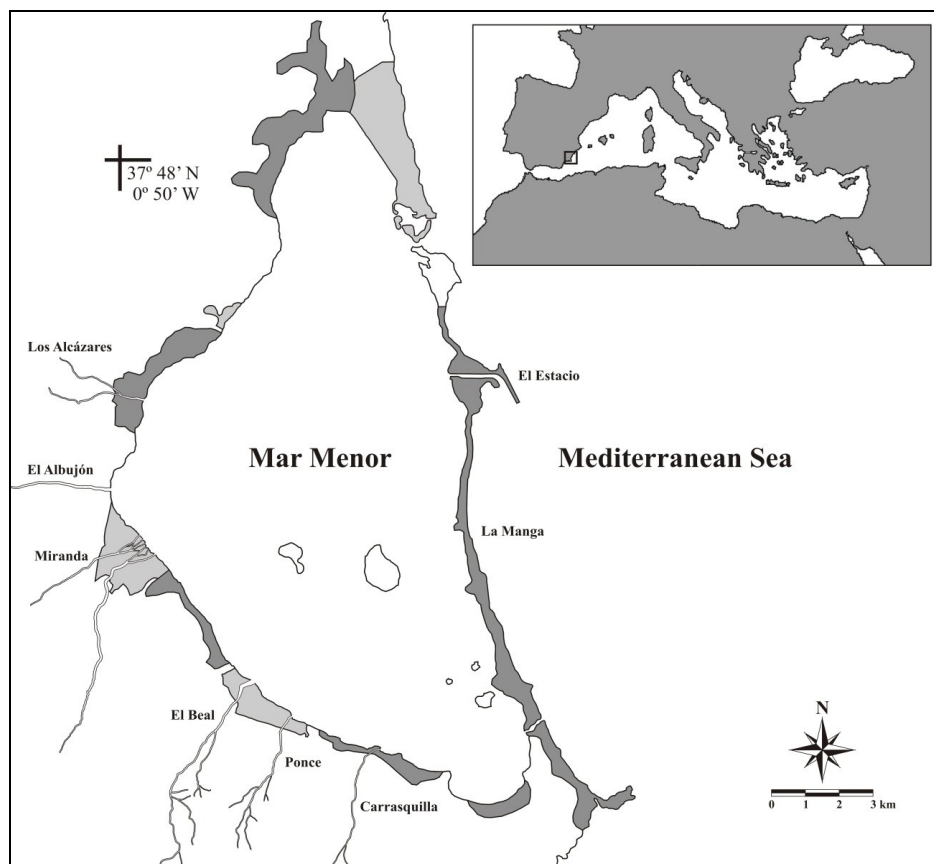


Figure 1. Map of the Mar Menor coastal lagoon showing the location of the main urban areas (dark grey), salt marshes (light grey) and watercourses.

El Albuñón 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.

The area presents a subdesertic Mediterranean climate, characterised by warm and dry weather conditions. Mean annual temperatures range from 17 to 21° C. Winters are mild, with temperatures around 10-13° C. Summer temperatures reach values above 25° C.

The area is characterised by scarce precipitation ($<300 \text{ mm yr}^{-1}$), which mainly occurs during storm events in autumn and winter. Precipitation is almost null during July and August, when maximum evaporation rates are observed.

Wind regimes in the area are dominated by the first and second quadrants with a marked seasonal pattern. Winds from the west dominate during the autumn and winter, while those from the northeast and southeast dominate during the spring and summer.

1.2 Main ecological and environmental problems

Historically, external nutrient inputs to the Mar Menor were mainly via groundwater and atmospheric deposition, in part due to the high ratio of sediment surface area to water volume and lack of major watercourses. However, as in many other Mediterranean coastal zones, the area surrounding the Mar Menor has experienced an intensification of agricultural practises and marked increase in tourist activities that have resulted in increased nutrient inputs to the lagoon.

The distinctive environment of the lagoon has long been attractive for visitors, with the first tourist settlements dating from the first half of the 19th century. However, a surge in touristic activities has taken place in the area since the early 1970s, characterised by intense urban development along the lagoon perimeter to accommodate the growing seasonal population. The marked seasonality of tourism in the area (July to September) is evident when comparing the numbers of the permanent local population of about 45,000 inhabitants to the tourist population that reaches about 450,000 during summer months.

In mid 1980s, sewage from main urban areas began to be treated with the construction of water treatment facilities. However, overflows of water collectors and discharges of untreated or insufficiently treated effluents can be observed in the area, especially after storms and during the peak summer tourist season. Urban discharges are considered as the main source of phosphorus entering the lagoon (Pérez-Ruzafa et al., 2005; Garcia-Pintado et al., 2007).

Around the same time, water derived from the Tajo-Segura river diversion, generated a profound transformation of the agricultural practises in the adjacent agricultural area, Campo de Cartagena, that changed from extensive dry crop farming of cereals, olives, almonds and carob beans to intensively irrigated crops (Figure 2). At the present, Campo de Cartagena is one of the most productive and profitable agricultural areas in Europe, and the use of water, fertilisers and pesticides has increased dramatically.

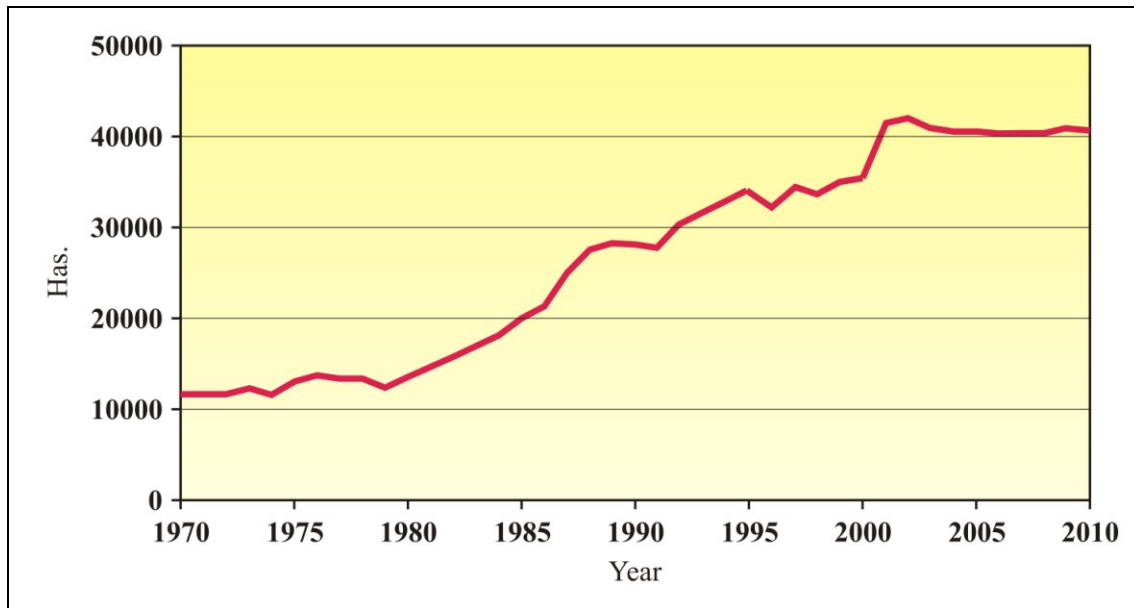


Figure 2. Evolution of the area occupied by intensively irrigated crops (Has.) in the adjacent agricultural area Campo de Cartagena from 1970 to 2010 (Redrawn from Martínez et al, 2007 and completed with data available at www.carm.es).

Due to increased agricultural water usage and decreased groundwater exploitation, phreatic levels have risen. As a result, some watercourses, such as El Albuñón wadi, now maintain a regular flux that is fed by ground water with high nitrate levels.

As a consequence of increased inputs, the waters of the Mar Menor have experienced rising nutrient levels that have led to planktonic changes in the lagoon (Gilabert, 2001, Pérez-Ruzafa et al., 2005). These changes have also favoured the proliferation of the jellyfish species *Cotylorhiza tuberculata* and *Rhizostoma pulmo*, with severe consequences for touristic activities in the area (Pérez-Ruzafa et al., 2002). Furthermore, modified light conditions of the lagoon waters might have favoured the expansion of the macroalga *Caulerpa prolifera* on the bottoms of the lagoon and the confinement of the traditional phanerogam *Cymodocea nodosa* to small patches in shallow areas. These changes have caused a progressive deterioration of the sediments through the accumulation of organic matter and subsequent appearance of anoxic conditions and the production of toxic acid volatile sulphides, all of which have diminished the water quality in several zones of the Mar Menor lagoon (muddy bottoms, bad smell, etc.). In addition, the local fishing industry is negatively affected by decreased populations of commercial fish, as these species, mainly Sparidae and Mugilidae, prefer feeding on patches of the phanerogam or unvegetated bottoms, which are now covered by a dense and continuous bed of the macroalga (Verdiell-Cubedo et al., 2007).

Although these changes have been reported, more severe eutrophication events have not occurred, such as phytoplankton blooms, floating macroalgae proliferations or dystrophic events, despite the fact that the magnitude of inputs is of the same order as that found in other coastal lagoons where eutrophication processes have been reported. This fact highlights the existence of certain biotic feedbacks that may be helping to reduce the level of nutrients in the water column and thus favouring the environmental quality of the lagoon.

Several recent studies demonstrated the role of *C. prolifera* and its associated benthic communities in the processing of nutrients in the Mar Menor and its importance for the maintenance of the lagoon's relatively high ecological status through nutrient sequestration from the water column and its retention in the sediments (Lloret et al. 2008, Lloret and Marin 2009, Lloret and Marin 2011). However, the functioning of this important ecosystem service has also demonstrated to be extremely vulnerable to the expected consequences of climate change in the area (Lloret et al. 2008). Increased temperatures and reduced light availability in the bottoms of the lagoon were identified as the major threats for the survival of benthic communities in the Mar Menor and the services they provide.

1.3 Selection of the mathematical models

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 and oil transformation). The turbulence module uses the well-known GOTM (General Ocean Turbulence Model – [http://www.gotm.net/turbulence model](http://www.gotm.net/turbulence%20model)).

The philosophy of the new MOHID model (Miranda et al. 2000), further on simple designated MOHID, permits to use the model in any dimension (one-dimensional, two-dimensional or three-dimensional). The whole model is programmed in ANSI FORTRAN 95, using the objected orientated philosophy. The subdivision of the program into modules, like the information flux between these modules was object of a study by the MOHID authors.

Currently, the model MOHID is composed by over 40 modules which complete over 150 thousand code lines. Each module is responsible to manage a certain kind of information. The main modules to be used in the Mar Menor case study are listed in Table 1.

Another important feature of MOHID is the possibility to run nested models. This feature enables the user to study local areas, obtaining the boundary conditions from the “father” model. The number of nested models is just limited by the available computer power.

The MOHID model has been applied to several coastal and estuarine areas and it has showed its ability to simulate complex features of the flows. Several different coastal areas have been modelled with MOHID in the framework of research and consulting projects.

Table 1. Principal modules of the model MOHID used in the Mar Menor case study.

<i>Module Name</i>	<i>Module Description</i>
Model	Manages the information flux between the hydrodynamic module and the two transport modules and the communication between nested models
Hydrodynamic	Full 3D dimensional baroclinic hydrodynamic free surface model. Computes the water level, velocities and water fluxes
Water Properties	Eulerian transport model. Manages the evolution of the water properties (temperature, salinity, oxygen, etc.) using an Eulerian approach
Lagrangian	Lagrangian transport model. Manages the evolution of the same properties as the water properties module using a Lagrangian approach. Can also be used to simulate oil dispersion
Water Quality	Zero-dimensional water quality model. Simulates the oxygen, nitrogen and phosphorus cycles. Used by the Eulerian and the Lagrangian transport modules. Based on a model initially developed by EPA (Bowie, <i>et. al.</i> , 1985)
Turbulence	One-dimensional turbulence model. Uses the formulation from the GOTM model
Geometry	Stores and updates the information about the finite volumes
Surface	Boundary conditions at the top of the water column
Bottom	Boundary conditions at the bottom of the water column
Open Boundary	Boundary conditions at the frontier with the open sea
Discharges	River or Anthropogenic Water Discharges
Light Extinction	Computes the effect of different particulate properties on water column transparency
Benthos	Simulates the oxygen, nitrogen and phosphorus cycles at the bottom
Macroalgae	Simulates the growth and nutrient uptake/release of macroalgae attached to the bottom
Hydrodynamic File	Auxiliary module to store the hydrodynamic solution in an external file for posterior usage

The bathymetry of the study area constitutes the base for the water modelling upon which the hydrodynamic, as well as the properties transport and water quality models, are to be applied. For the case of the Mar Menor Lagoon a digital bathymetry was created by georeferencing available bathymetric data (Figure 3).

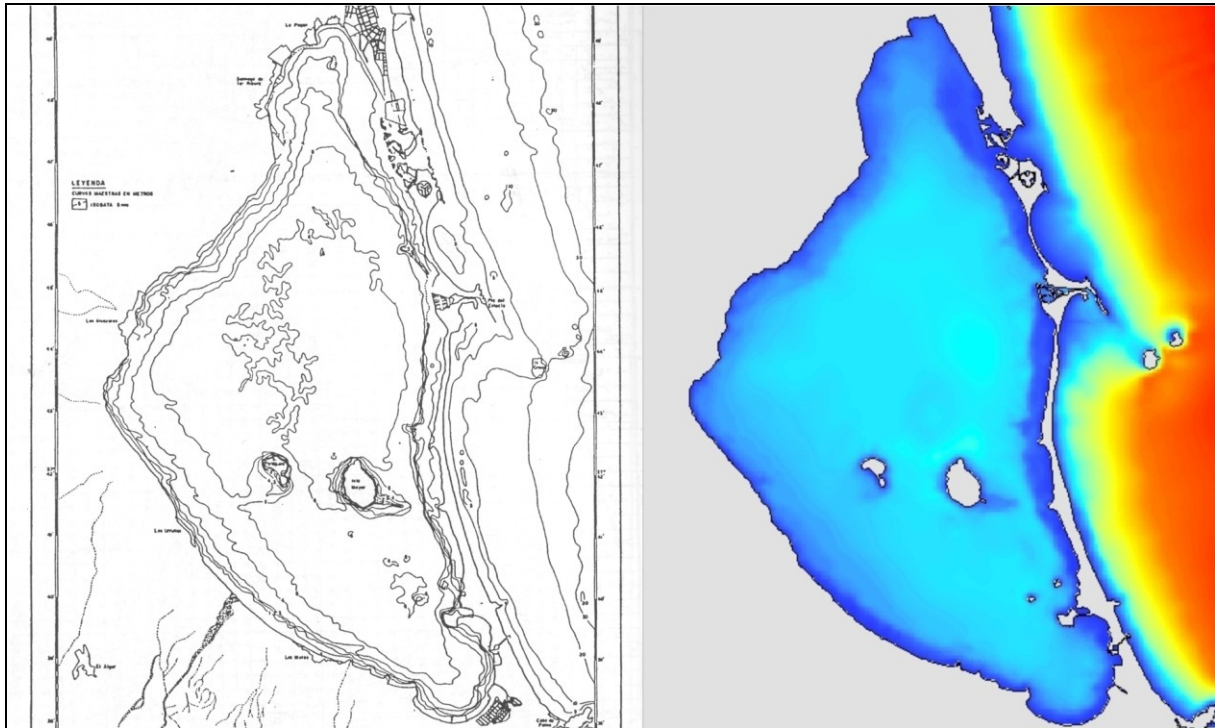


Figure 3. Digitalization of bathymetric data in the Mar Menor Lagoon.

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.

2. Hydrodynamic model

2.1 General description of the model

The model solves the three-dimensional incompressible primitive equations. Hydrostatic equilibrium is assumed as well as Boussinesq and Reynolds approximations. All the equations have been derived taking into account these approximations. The temporal evolution of velocities is the balance of advective transports, Coriolis force, pressure gradient and turbulent diffusion. The vertical velocity is calculated from the incompressible continuity equation. The density is obtained from the salinity and from the temperature, which are transported by the water properties module. A complete list of all the equations and approximations of the hydrodynamic module can be found at www.mohid.com.

As mentioned before, the high residence time of the waters in the Mar Menor lagoon is mainly due to the scarce water exchange with the adjacent Mediterranean Sea, which mainly occurs through El Estacio channel, and the extremely low volume discharges of freshwater from El Albuñón wadi. Due to this restricted water exchange, its shallow depth and its location between land and sea, the Mar Menor, as many other coastal lagoons, is considered as a very vulnerable area to land-derived impact of pollutants. In this sense, the study of the hydrodynamics in the lagoon, the calculation of water exchange rates with the Mediterranean

and the characterization of water circulation patterns within the system is of extreme relevance for the evaluation of present and future environmental problems in the area.

2.2 Processes modelled in the lagoon

The hydrodynamic model to be 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.

Through its application in the Mar Menor we will be 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 will also be modeled.

The hydrodynamic model incorporates the influence of various forces: Coriolis, tide potential, baroclinic pressure gradient, atmosphere forcing (wind stress and pressure), horizontal advection and diffusion of momentum, barotropic pressure gradient and bottom friction. A complete list of all the equations and approximations of each term included in the forces discretization can be found at www.mohid.com.

In the Mar Menor, the hydrodynamic model is mainly defined by a set of atmospheric parameters (atmospheric pressure, wind, relative humidity, solar radiation, air temperatures), tidal components (represented by tidal harmonics) and freshwater discharges through El Albuñón wadi.

The hydrodynamic model will allow us to fully describe and quantify the velocity field in the Mar Menor, information that is basic for the study of the dispersion of substances in the lagoon, and for the determination of particulate material deposition and erosion rates.

The heat and salt fluxes are basic to determine the evolution of water temperatures and salinities in the lagoon. Both properties constitute key variables not only for the determination of water density and its influence on hydrodynamics and mixing properties of the water, but also for the biogeochemical cycles of nutrients and the growth and survival of biota in the lagoon.

The calculation of water residence time in the Mar Menor is 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. The calculation of water residence time in the lagoon is based on the dispersion of lagrangian particles. MOHID's Lagrangian module uses the concept of tracer. The most important property of a tracer is its position. In our case the tracer is the water mass (or volume), which is to be transported in and out of the lagoon. By monitoring the distribution and volume of lagrangian particles inside monitoring boxes defined in the lagoon one might be able to determine water residence time in the Mar Menor.

2.3 Model set up

The hydrodynamic model is 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 (Figure 4).

The temporal discretization is carried out by means of a semi-implicit ADI (Alternate Direction Implicit) algorithm. This algorithm computes alternatively one component of horizontal velocity implicitly while the other is calculated explicitly. The resulting equation system is tridiagonal and can be solved in an efficient and quick manner, preserving the stability advantages of implicit methods without the drawbacks of computational expensiveness and associate phase errors.

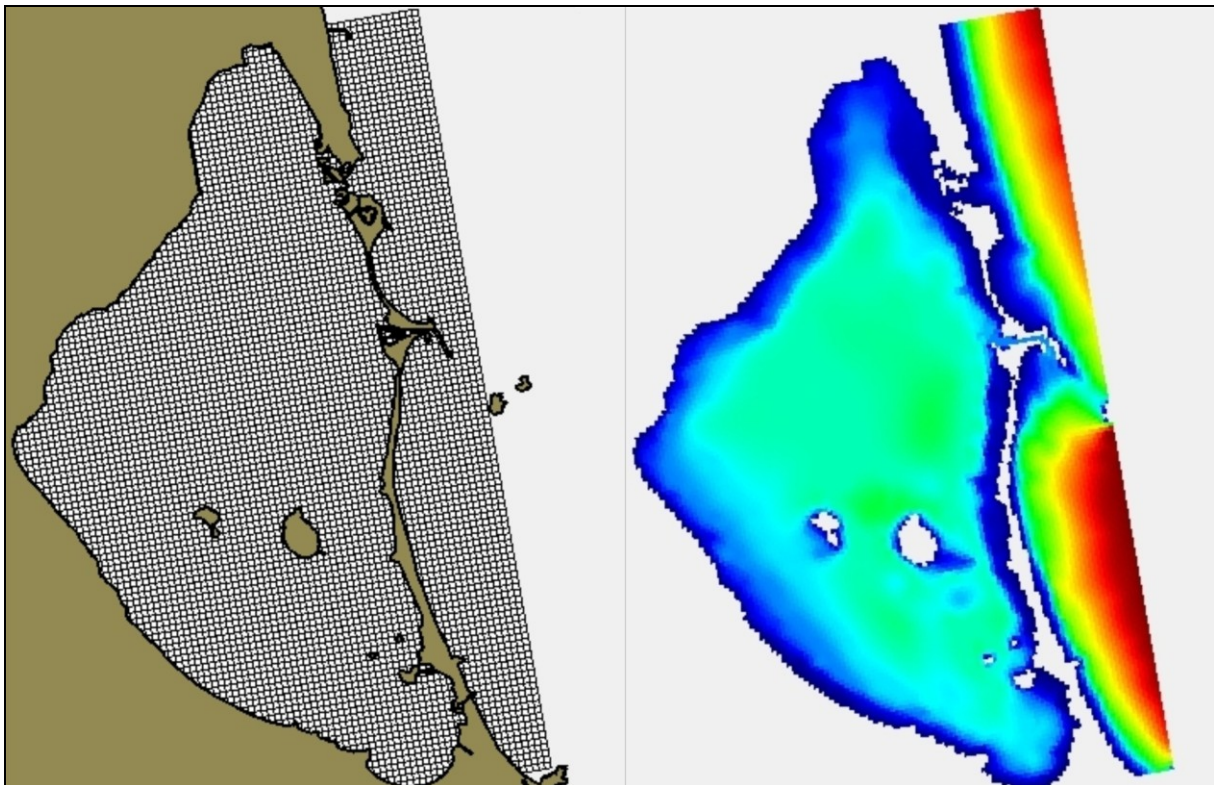


Figure 4. Applied 175 x 175 m grid (left) and resultant finite volume elements or cells with depth data (right).

As boundary conditions for the hydrodynamic model a free surface is assumed. All advective fluxes across the surface are assumed to be null.

Also at the bottom, and as a bottom boundary condition, advective fluxes are imposed as null and diffusive flux of momentum is estimated by means of a bottom stress that is calculated by a non-slip method with a quadratic law that depends on the near-bottom velocity.

For the lateral closed boundaries the domain is limited by land. The lateral boundary layer is solved, so an impermeable, free slip condition can be used.

The open boundary condition arises from the necessity of confining the domain to our study area. The values of the variables must be introduced there to guarantee that the information about what is happening outside the domain will enter the domain in a way that the solution

inside the domain is not corrupted. Also, waves generated inside the domain should be allowed to go out.

As initial conditions for the hydrodynamic model several data sources have been used. Tidal components were obtained from Arevalo (1988), who calculated tidal harmonics in the area close to El Estacio channel. Temperature and salinity values were obtained from different sources. Initial temperatures and salinities inside the lagoon were obtained from data of Pérez-Ruzafa et al. (2005) and Lloret et al. (2006). Temperatures and salinities at the open boundary were obtained from data of IEO (Instituto Español de Oceanografía). Discharges from El Albuñón wadi were extracted from data of García-Pintado et al. (2007) and extrapolated to daily data (Figure 5).

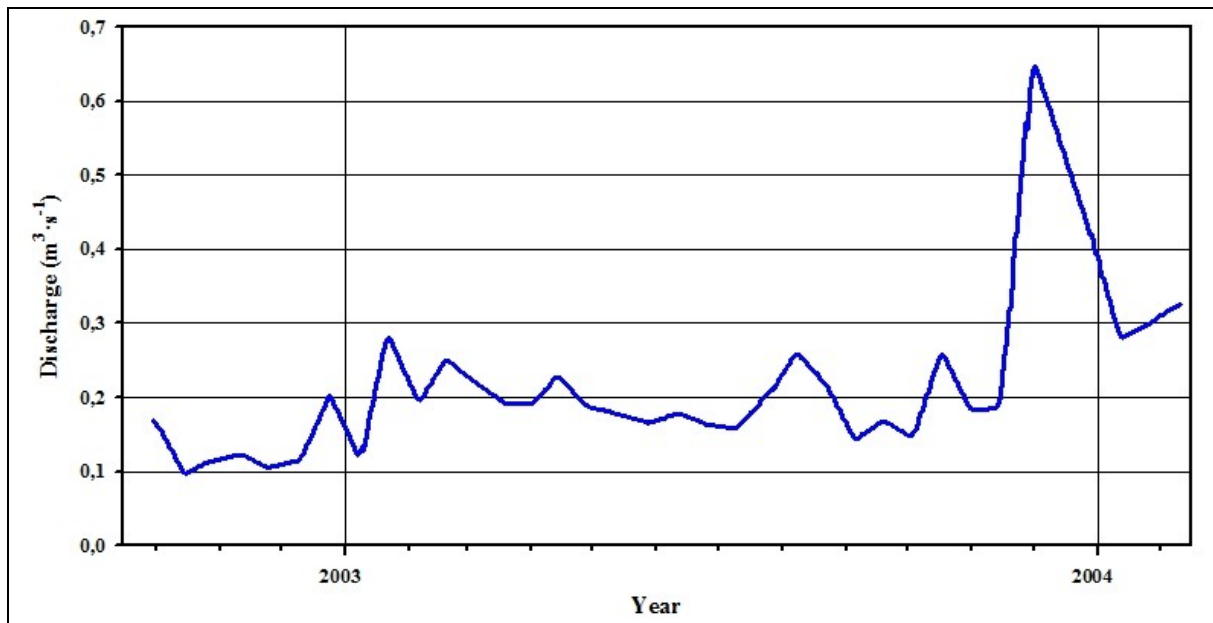


Figure 5. Daily discharge data series extracted and extrapolated from García-Pintado et al. (2007).

2.4 Problems and future actions

One of the major problems found for the setup of the models in the Mar Menor lagoon was the lack of a digital bathymetry in the area. A new digital elevation model of bathymetric data needed to be created from available nautical charts of the Mar Menor, that were digitalized, georeferenced and depths extrapolated to create a raster layer of bathymetry, which was the base for the definition of cells for our model.

Although the problem was solved, the particular characteristics of the lagoon inlets (very narrow and shallow channels) made difficult the definition of cells in the inlets. One possible approach to solve this problem was to re-define our grid to refine spatial resolution at the inlets but this solution was not possible due to the lack of a detailed bathymetry of these channels. The solution was to manually adjust bathymetry in the inlet cells of the original grid (manual calibration) to ensure consistent flows of water through the inlets, even though a more realistic geometry of the channels cannot be used.

Another problem was the lack of data for water discharges from El Albuñón wadi. Due to its temporality and low volume discharge, this watercourse does not have a gauge station that

continuously compiles data. The only data available come from two studies carried out between 2002 and 2004 (Figure 5) compiled by García-Pintado et al. (2007) and Velasco et al. (2006).

Hydrodynamic model calibration is going to be done by comparing the model results with data compiled from SIOM (Oceanographic Information System of the Region of Murcia). SIOM has a network of sampling stations distributed along the coasts of the Region of Murcia. Four of these stations are located in the Mar Menor lagoon and another station in El Estacio channel. Current velocities and direction and temperatures are provided by SIOM's website at <https://caamext.carm.es/siom/> (Figure 6).

The model is going to be validated against an independent series of data from the years 2002-2003 in a total of 11 sampling stations distributed within the lagoon with data compiled by Pérez-Ruzafa et al. (2005) and Lloret et al. (2006). Another data series that is available is the series provided by the 28 stations included in the Mar Menor lagoon Monitoring Network, with data from 2009 (Figure 6).

Once the model has been calibrated and validated against the available data a reference condition and a set of scenarios will be produced.

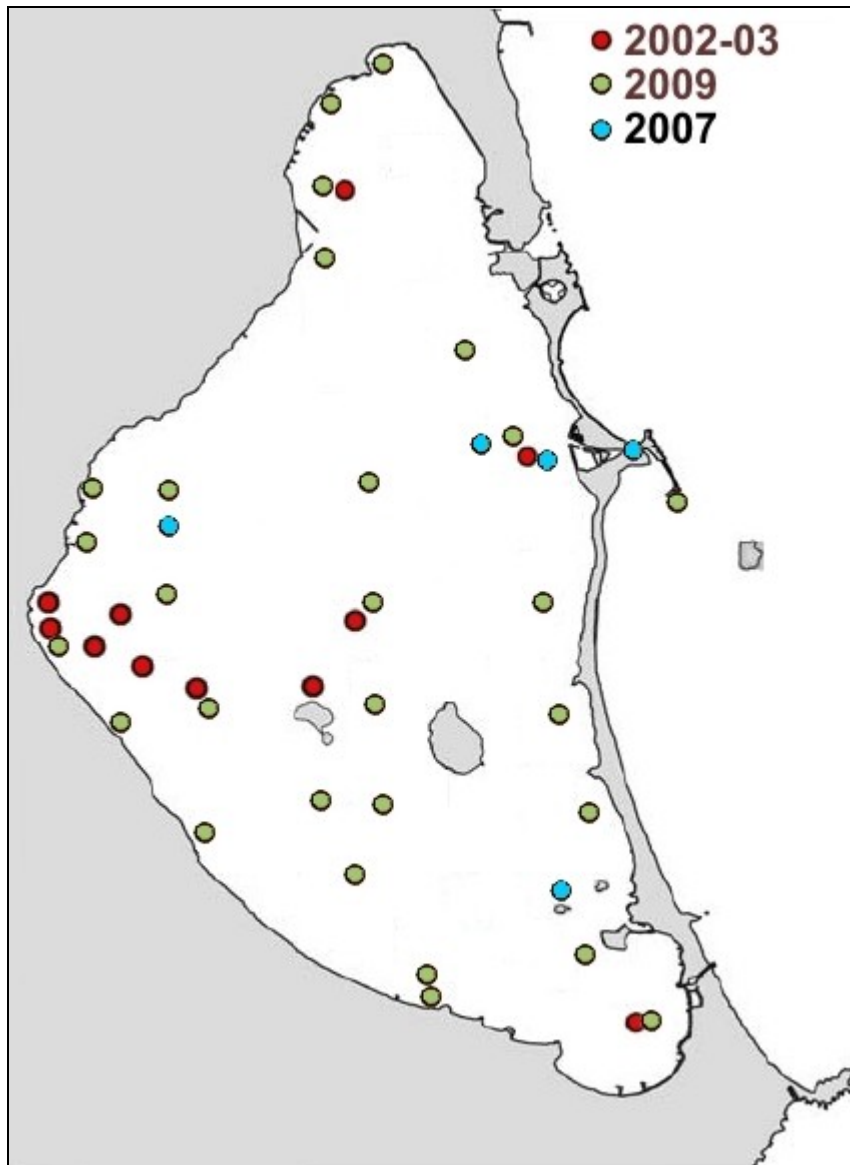


Figure 6. Location of sampling stations from different studies providing data for the hydrodynamic model calibration and validation (Pérez-Ruzafa et al. 2005 and Lloret et al. 2006 in red, SIOM 2007 in blue and Mar Menor Monitoring Network in green)

3. Ecological model

3.1 General description of the model

The ecological model included in MOHID is adapted from Environmental Protection Agency (1985) and constitutes an ecosystem simulation model (sets of conservation equations describing as adequately as possible the functioning and relationships of real ecosystem components).

The general model consists of several state variables including dissolved nutrients, organic matter, phytoplankton, zooplankton and bacteria and processes occurring in the pelagic and benthic phases. However, and due to the complexity of the Mar Menor biogeochemical cycles

and the enormous importance of benthic primary production of the macroalga *Caulerpa prolifera*, another component was included to study the contribution of macroalgae to the nutrient cycles and its influence to the water quality in the lagoon.

The modules included in our ecological model for the Mar Menor lagoon are the Water Quality module, the Benthic module and the Macroalgae module. The MOHID's Water Quality module is the base for the nitrogen, phosphorus and oxygen cycles. The other two modules, Benthic and Macroalgae, study the information flux between the Water Quality module and macroalgal and benthic processes in the lagoon.

The application of the ecological model in the case of the Mar Menor will provide valuable information about the evolution of water quality, the relative importance of the different ecosystem compartments in the nutrient fluxes and the assessment of the recent eutrophication problem in the lagoon.

3.2 Processes modelled in the lagoon

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

- Mineralization of particulate and dissolved organic matter, including nitrification and denitrification, both in the water column and the interface sediment-water.
- Sedimentation and resuspension of phytoplankton and particulate matter.
- Phytoplankton primary production.
- Effect of phytoplankton and particulate matter concentrations on water column light attenuation.
- Macroalgal primary production.

A list of all the equations, assumptions and parameters used for the ecological model can be found at www.mohid.com.

As mentioned before, the complexity of the Mar Menor biogeochemical cycles of nutrients, due to the enormous influence of the *Caulerpa prolifera* bed in nutrient uptake, makes necessary to include this ecosystem compartment in our model. Furthermore, due to the demonstrated role of *Caulerpa prolifera* in the maintenance of relatively low phytoplankton concentrations in the lagoon together with its relative sensitiveness to climate change impacts (mainly the increase of water column light attenuation and extreme temperatures), the evolution of macroalgal biomasses is of extreme importance for the functioning of the lagoon (Lloret et al. 2006, Lloret et al. 2008, Lloret and Marin 2009, Lloret and Marin 2011).

3.3 Model set up

The ecological model uses the same grid applied in the hydrodynamic model, as well as the same boundaries for the advective fluxes of dissolved or particulate properties (surface, bottom, land and open boundary).

Initial concentrations of nutrients, phytoplankton densities and macroalgal biomasses were extrated from Lloret et al. (2006). Discharges of inorganic nutrients from El Albuji3n wadi

were extracted from data of García-Pintado et al. (2007) and extrapolated to daily data (Figure 7).

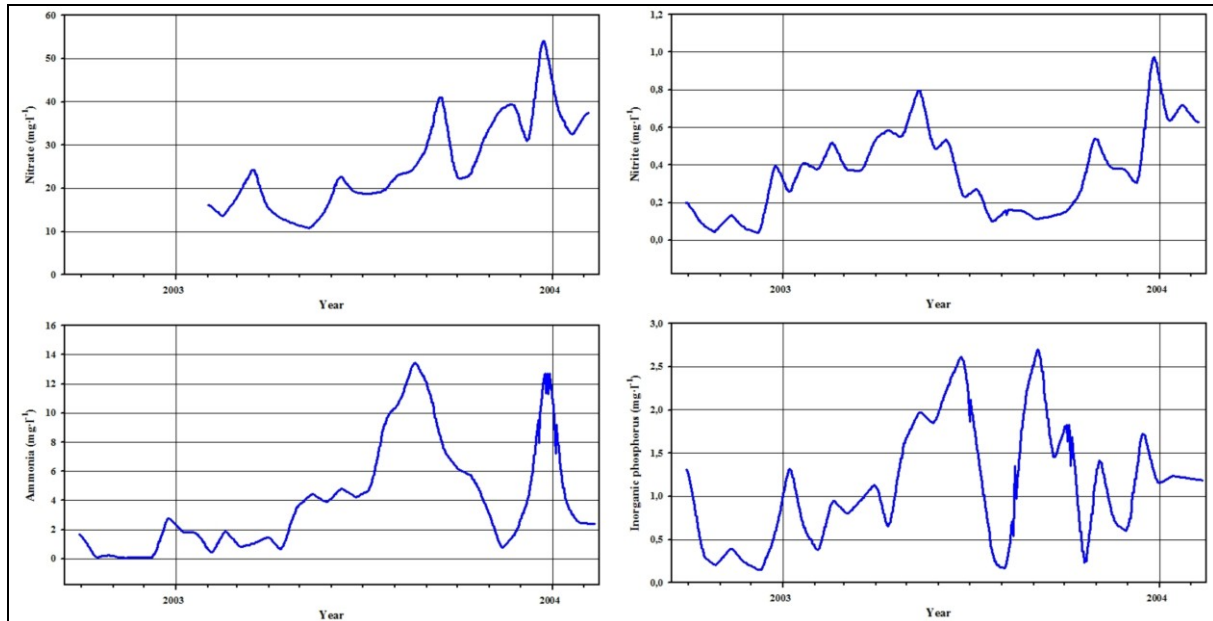


Figure 7. Discharge of inorganic nutrients from El Albujón wadi extracted from García-Pintado (2007).

Parameterization of water column light attenuation was made empirically from lineal adjustments of that parameter against phytoplankton and particulate matter concentrations in the lagoon obtained from field data collected by Lloret et al. (2006).

Parameterization of *Caulerpa prolifera* growth is based on the studies of Terrados (1991) who characterized macroalgal photosynthesis and growth and whose findings were later applied and tested by Lloret et al. (2008) for an empirical production model in the Mar Menor.

3.4 Problems and future actions

One of the main problems found with the ecological model was obviously the cited complexity and the amount of processes considered. Furthermore, the scarce (and at times inexistent) data for some parameters (phytoplankton C:N:P, accurate proportions between the different forms of organic nutrients,...) and also for the definition of some processes (zooplankton ingestion rates, sediment fluxes of nutrients,...) is making the calibration of the ecological model difficult. Some of these parameters have to be extrapolated from other studies and assumed for our model.

Model calibration is going to be made with data from 2002-2003 collected by Pérez-Ruzafa et al (2005) and Lloret et al. (2006) in a total of 11 sampling stations. Data generated from the validation run in 2009 will be compared with the available data from the Mar Menor Monitoring Network with 28 sampling stations (See Figure 6).

Once the model has been calibrated and validated against the available data a reference condition and a set of scenarios will be produced.

References

- Arevalo, L. (1988): "El Mar Menor como sistema forzado por el Mediterraneo. Control hidráulico y agentes fuerza". Boletín del Instituto Español de Oceanografía. 5(1): 63-96.
- García-Pintado, J., Martínez-Mena, M., Barberá, G.G., Albaladejo, J., Castillo, V.M., 2007. Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor, Spain. Science of the Total Environment 373, 220-239.
- Gilabert, J., 2001. Seasonal plankton dynamics in a Mediterranean hypersaline coastal lagoon: the Mar Menor. Journal of Plankton Research 23, 207-217.
- Kjerfve, B. (1986): "Comparative oceanography of coastal lagoons". In: Wolfe, D.A. (ed). Estuarine variability. Academic Press. New York. 63-81.
- Lloret, J., Marín, A., Marín-Guirao, L., Velasco, J. 2005. Changes in macrophytes distribution in a hypersaline lagoon associated to the development of intensively irrigated agriculture. Ocean & Coastal Management, 48: 828-842.
- Lloret, J., Marín, A., Marín-Guirao, L. (2008). Is coastal lagoon eutrophication likely to be aggravated by global climate change? Estuarine, Coastal and Shelf Science 78: 403-412.
- Lloret, J., Marín, A. (2009) The role of benthic macrophytes and their associated macroinvertebrate community in coastal lagoon resistance to eutrophication. Marine Pollution Bulletin 58: 1827-1834.
- Lloret, J., Marín, A. (2011) The contribution of benthic macrofauna to the nutrient filter in coastal lagoons. Marine Pollution Bulletin 62: 2732-2740.
- Martínez, J. Esteve, M.A. Martínez-Paz, J.M. Carreño, F. Robledano, F. Ruiz, M. Alonso, F. (2007). Simulating management options and scenarios to control nutrient load to Mar Menor, Southeast Spain. Transitional Waters Monographs 1: 53-70.
- Miranda, R., Braunschweig, F., Leitao, P., Neves, R., Martins, F., Santos, A., 2000. Mohid 2000, a coastal integrated object oriented model. Hydraulic Engineering Software VIII, WIT Press.
- Pérez-Ruzafa, A., Marcos, C., Ros, J.D., 1991. Environmental and biological changes related to recent human activities in the Mar Menor (SE of Spain). Marine Pollution Bulletin 23, 747-751.
- Pérez-Ruzafa, A., Gilabert, J., Gutiérrez, J.M., Fernández, A.I., Marcos, C., Sabah, S., 2002. Evidence of a planktonic food web response to changes in nutrient input dynamics in the Mar Menor coastal lagoon, Spain. Hydrobiologia, 475/476, 359-369.
- Pérez-Ruzafa, A., Fernández, A.I., Marcos, C., Gilabert, J., Quispe, J.I., García-Charton, J.A., 2005. Spatial and temporal variations of hydrological conditions, nutrients and chlorophyll a in a Mediterranean coastal lagoon (Mar Menor, Spain). Hydrobiologia 550, 11-27.
- Velasco, J., Lloret, J., Millán, A., Marín, A., Barahona, J., Abellán, P., Sánchez-Fernández, D., 2006. Nutrient and particulate inputs into the Mar Menor lagoon (SE Spain) from an intensive agricultural watershed. Water Air and Soil Pollution 176, 37-56.
- Verdiell-Cubedo, D., Oliva-Paterna, F. J. and Torralva-Forero, M. (2007). Fish assemblages associated with *Cymodocea nodosa* and *Caulerpa prolifera* meadows in the shallow areas of the Mar Menor coastal lagoon. *Limnetica* 26 (2): 341-350.

Chapter 4

The Tyligulskyi Lagoon Hydrodynamic and water quality models

Yuriy Tuchkovenko, Oksana Tuchkovenko, Oleg Shabliy, Valeriy Khokhlov

Odessa State Environmental University,, Ukraine

1. Introduction

The Tyligulskyi Lagoon is a unique natural system with numerous natural resources, which can be used for social and economic development of the adjacent territories in the Odessa and Mykolaiv regions of Ukraine in the spheres of recreation, ecotourism, health care, aquiculture and regulated fishing. The ecological system of the lagoon has unique conditions for the life of fauna and flora, and the lagoonal water area is of great value for sustenance of the biological balance in the region. The local community, the resource users concerned, representatives of both the local and the regional self-government bodies, and the local authorities stress the necessity for conservation and renewal of natural resources of the Tyligulskyi Lagoon as the principal management task of the lagoon and the adjacent territories. In spite of this, the scientifically substantiated plans for water and environment management of the Tyligulskyi Lagoon have not been developed so far.

Many stakeholders and experts in Environmental Science consider that it is possible to stabilize the hydroecological regime of the Tyligulskyi Lagoon through regulation of two factors of system governance:

- provision of sustained water exchange of the lagoon with the sea through the artificial canal with sluices, development of a schedule for its functioning;
- implementation of a package of nature protection measures for renewal of natural runoff of the Tyligul River and other small rivers in the catchment basin of the lagoon, in particular, through clearing of the beds of small rivers and gullies, liquidation of unused ponds, imposition of restrictions on the number of useable artificial ponds and development of rules for their operation.

However, the consequences of implementation of the stated ways for stabilization of the hydroecological regime in the lagoon are obvious. In particular, water exchange of the lagoon with the sea through the connecting artificial canal, on the one hand, prevents a considerable decline in the water level in the lagoon in the late summer period and shoaling of the shallow areas of the lagoon (the northern part and the submerged ground bridges in the area of spits, which divide the lagoon into parts), contributes to renewal of the polluted waters in the lagoon by relatively pure sea waters, and in the spring period enables the young of saltwater fish to get into the lagoon for feeding, which is conducive to the increase in its fish resources and the development of industrial and amateur fishing. On the other hand, unregulated water exchange with the sea through the connecting canal contributes to

accumulation of salts in the lagoon and supports a long-term tendency to the increase in salinity of its waters. This can result in the gradual transformation of the lagoon into a hyperhaline water body with substantially lesser biodiversity of water flora and fauna, than currently.

Renewal of the natural runoff of fresh waters from the catchment basin of the Tyligulskyi Lagoon requires considerable financial expenditure, including costs on reduction of biogenic runoff into the lagoon, and this, obviously, will give rise to the conflicts of the managing authorities with the local population, the land owners, the pond holders etc. It is necessary to take into account that decrease in the inflow of fresh waters into the lagoon occurs not only as a result of anthropogenic activity, but also due to the climate change. This brings up the issue of efficiency of nature protection measures for renewal of natural runoff of fresh waters into the lagoon under conditions of the expected climate change.

Presently, there is no answer to the question of whether it is possible, with regard to the expected climate change, to avoid or reduce the probability of hypoxia and anoxia development in the benthic layer of the lagoonal waters by means of regulation of water exchange with the sea, enhancement and control of the inflow of fresh waters into the lagoon.

As appears from the above, the stated ways for rehabilitation of the lagoonal ecosystem require assessment of their efficiency based on quantitative indices which can be obtained only by means of mathematical modelling for the scenarios.

2. Hydrodynamic model

A modified version of MECCA (Model for Estuarine and Coastal Circulation Assessment) three-dimensional numerical non-stationary hydrothermodynamic model (Hess, 1985, 1986, 1989, 2000) is used for the Tyligulskyi Lagoon. This model makes it possible to calculate three-dimensional thermohaline structure of the waters, intensity of turbulent exchange, as well as wind (drift and compensative), density, gravity and tidal currents in estuaries, bays, lagoons and on a shallow continental shelf. The characteristic feature of this model is making simultaneous calculations of water dynamics and substance distribution to the area of the adjoint water bodies under both the grid and the subgrid scales. In this case bays, inlets, lagoons and sea shelf areas, spatial dimensions of which substantially exceed a computational grid mesh of the numerical model are considered the water bodies of the grid scale. The subgrid water bodies have the width in one of horizontal directions which is considerably less than the computational grid mesh (e.g., narrow rivers, canals, channels).

The stated characteristic of the model is of especial importance for making proper description of water circulation in a lagoon, where its water exchange with the North-Western part of the Black Sea through a narrow connecting canal is considered.

2.1 General description of the model

The used model is based on the complete system of hydrothermodynamic equations in the Boussinesq approximation and the approximations of incompressibility and hydrostatics. The system includes the equations of motion for the horizontal components of the vector of current velocity, the equations of hydrostatic approximation, the continuity equation, the equation of state, and the equations of conservation of heat and salt.

The model is implemented in curvilinear (in the vertical direction) coordinates (σ -system). On the one hand, this improves the computational properties of the model and, on the other hand, enables one to give a more exact description of the vertical dynamic and thermohaline structures of waters at small depths.

The method used for the solution of the hydrodynamic problem is based on the decomposition of the total current velocity into the velocity averaged over depth (barotropic component) and deviations from this velocity at each depth used for computations (baroclinic component). This operation enables us to use different time steps for the barotropic and baroclinic components of the horizontal current velocity in the numerical solution of the dynamic equations because the first component is connected with the oscillations of the sea level caused by the motion of long gravitational waves and varies more rapidly than the second component.

The vertical turbulent viscosity is described on the basis of the semi-empirical theory of turbulence by using the length of the mixing path. The use of higher-order approximations based on local turbulent kinetic energy balances does not appear to be justified at this time, given the lack of easily-interpretable data on its variability and the computer resources required to implement such approximations. The instantaneous viscosity is formulated as the function of a mixing length, the local vertical velocity shear, and the water column stability (Munk and Anderson, 1948).

The coefficients of horizontal turbulent exchange are found according to the values of the local horizontal shift of the barotropic component of current velocity and the space step of the horizontal finite-difference grid (Tag et al., 1979).

The biogeochemical unit of the model is combined with the hydrodynamic unit into a single model of the water eutrophication model on the basis of the equation of non-conservative transfer of substances. The structure of this equation is similar to structure of the equations of conservation of heat and salt of the hydrodynamic model but differs from these equations by the presence of the gravitational velocity of sedimentation of admixtures and the form of the right-hand side introduced to describe the non-conservative behaviour of substances.

Depending on the type of analyzed substances, the functions of non-conservatism are determined in the biogeochemical unit. For each time step, we solve the system of equations of transfer of non-conservative substances.

The finite-difference approximation of the equations of heat and salt transfer in the original version of the MECCA model is realized by using the traditional algorithms of the numerical solution (by using simple approximations of the derivatives) (Hess, 1989). These algorithms are conservative but do not possess the property of transportivity (monotonicity). In the presence of significant space gradients of modelled elements (in the estuary regions) on the scales comparable with the step of the computational grid, this may lead to the appearance of negative values of concentrations in the process of numerical calculations, which is undesirable in the solution of ecological problems. Therefore, the original numerical schemes of the solution of transfer equations are modified into transportive schemes, i.e., into the FCT (Flux Corrected Transport) scheme (Fletcher, 1988; Boris and Book, 1975) for the horizontal transfer and the TVD (Total Variation Diminishing) scheme (Fletcher, 1988) for the vertical transfer.

In the software realization of the MECCA model corrections to the nonlinear momentum advection terms, suggested by (Brooks, 2008), were taken account of.

The details of numerical realization of the hydrodynamic equations of the model can be found in (Hess, 1989) and the modifications of the transfer equations are discussed in (CIOH, 1999).

The hydrothermodynamic model has been successfully tested at solving the problems of stabilization of the hydroecological regime in Dofinovskyi Lagoon and the Tyzla group of lagoons in the north - western part of the Black Sea by means of regulation of the water exchange with the sea (Tuchkovenko et al., 2008; Ivanov and Tuchkovenko, 2008). As a constituent part of a 3D biogeochemical model of water eutrophication the thermohydrodynamic model was used for calculation of water circulation, transport of pollutant from coastal anthropogenic sources and assessment of the influence of a river runoff and coastal anthropogenic sources on formation of water quality in the Odessa area of the North-Western part of the Black Sea (Tuchkovenko et al., 2011; Ivanov and Tuchkovenko, 2008). Previously the model was used for development of the strategy for hydroecological management of lagoons on the Colombian coast of the Caribbean Sea (Lonin and Tuchkovenko, 2001; Tuchkovenko and Lonin, 2003; Ivanov and Tuchkovenko, 2008).

2.2 Processes modelled in the lagoon

Variability of water level and salinity in the Tyligulskyi Lagoon is determined by the amount of fresh water inflow with the Tyligul River runoff, correlation of the amount of atmospheric precipitation on the lagoon water level and evaporation from it as well as the occurrence of water exchange of the lagoon with the sea through the artificial connecting canal. Since the Tyligulskyi Lagoon is included into the territory of a landscape park, the management of its hydroecological regime can be organized only by means of regulation of fresh water inflow from the Tyligul River and water exchange of the lagoon with the sea through the connecting canal. The estuarine area of the Tyligul River and the connecting canal are located in the opposite parts of the lagoon at a distance of 68 km. Infiltration of sea and river waters into the lagoon water area is conditioned by the peculiarities of water dynamics in the lagoon.

The water area of the Tyligulskyi Lagoon is characterized by ageostrophicity of dynamics and strong influence of the morphological peculiarities of the water area on the water dynamics: bottom relief, configuration and irregularity of the coastal line, availability of shallow spits which divide different, relatively deep (10-15 m) parts of the lagoon water area and considerable oblongness of the lagoon northwards.

The major driving force to cause the motion of waters in the lagoon is the stress of wind friction on the water surface. Due to the emergence of turbulent stress in a liquid, wind can have an impact at a large enough distance from the water surface. Wind flows are subject to the influence of bottom which shows, firstly, in interaction of two turbulent frontier layers: the benthic and the superficial, and, secondly, in formation of water surface slopes, conditioned by the given banks and bottom relief inhomogeneities, which cause development of gradient currents.

Wind originated fluctuations in water level of the sea area which is adjacent to the lagoon and the lagoon itself determine the intensity of water exchange through the artificial connecting canal. Moreover, filling of the lagoon with salt water inflow through the canal depends on seasonal and interannual variability of the runoff of the large rivers, such as the Dnipro and the Pivdennyi Buh, which conditions fluctuations of the sea level in respective time scales.

In the spring-summer period a seasonal pycnocline is formed in the lagoon. In spring its occurrence is caused by the inflow of fresh water into the lagoon from the catchment basin in

spring flood period and by the salt waters which enter through the connecting canal and are desalinated by the flow of the Dniro and the Pivdennyi Bug as well as spring warming up of waters in the superficial layer of the lagoon (Fig. 2.1).



Fig. 2.1 The map of the Tyligulskyi Lagoon, Dniro-Pivdennyi Bug Estuary and sea stations “Odessa-Port” and “Port-Yuzhnyi”

In summer the main factor to sustain the existence of near-surface pycnocline is the strong heating of waters in the surface layer. Under scant winds, which are typical for the summer period, in the depressions of the central part of the lagoon, at the depths of more than 10 m, the benthic cold layer of waters persists as it was observed, for example, in 2010. However, under high storm winds in the summer period the seasonal thermocline turns destructed and the thermohaline structure of waters in the lagoon water area becomes quasihomogeneous (summer of 2012).

On the assumption of the aforesaid, the hydrothermodynamic model described in the previous section will be used for finding solution to the following problems.

- 1) Modelling of spatiotemporal variability of hydrodynamic characteristics (water level, total (wind, density, gradient) currents, intensity of horizontal and vertical turbulence, heat and substance diffusion) in the lagoon water area on the time scales from several months to several years, with water exchange with the sea through the canal, the Tyligul River runoff, the influence of heat exchange with the atmosphere, variability of wind speed and direction, evaporation from the lagoon water level and atmospheric precipitation allowed for.
- 2) Modelling of spatiotemporal variability of the thermohaline structure of waters in the lagoon water area, formation and destruction of a seasonal thermocline in the deeper parts of the lagoon.
- 3) Assessment of influence of water exchange with the sea through the connecting canal on hydrological conditions in the lagoon and water renewal in its various parts. Assessment of

influence of morphometric characteristics of the connecting canal on the intensity of the lagoon water exchange with the sea and dilution of the polluted lagoon waters by relatively pure sea waters.

- 4) Assessment of influence of the Tyligul River runoff on hydrological conditions in the lagoon, formation of pycnocline and intensity of vertical mixing in the spring period.
- 5) Modelling of transfer of non-conservative substance into the lagoon water area, local sources and flows which are calculated in the biogeochemical unit and are defined on the boundary of the computational domain.

The basic data required for hydrothermodynamic modelling in the lagoon include a bathymetric map of the lagoon water area, morphometric characteristics of the connecting canal, as well as the data on time variability of:

- 1) the sea level, salt water temperature and salinity at the open sea boundary of the connecting canal;
- 2) air temperature, wind speed and direction, amount of atmospheric precipitation and evaporation intensity, relative air humidity and cloud amount – for assignment of the conditions at water/air boundary;
- 3) discharges of the Tyligul river, temperature and mineralization of the river waters.
- 4) the temperature of bottom sediments (or benthic layer of the waters) in the deep areas of the water area. With the temporal resolution assigned in the course of calculation the model assimilates the hydrometeorological information referred above. Linear interpolation against time is performed between the entered discrete values.

2.3 Model set up

During adaptation of the thermohydrodynamic model to the conditions of the Tyligulskyi Lagoon and its verification data from occasional field observations of hydrological characteristics of the Tyligulskyi Lagoon waters (temperature, salinity, water level), water exchange through the connecting canal, carried out within the period of 2001-2010, and the data from long-term observations of water level in the Tyligulskyi Lagoon at the hydrometric station in Koblevo urban settlement for the period of 1936 - 1987 were used. Depths in the lagoon were assigned on the basis of the data from the bathymetric survey made in October 2010 under the water level in the lagoon of minus 0.4 m BS (Fig. 2.2).

In the course of calculations the lagoon water area was discretized by a horizontal calculation grid of 44×99 nodes with the mesh cell width of 400 m. 10 calculation levels were used along the vertical in σ -coordinate system. A time step was 3 s for the barotropic constituent of the current velocity and 18 s - for the baroclinic one.

Model calculations were carried out in three stages. The first series of numerical experiments with the model was performed to study the peculiarities of wind circulation of waters in the lagoon under the absence of water exchange with the sea. Calculations of the steady wind flows were carried out under stationary winds of eight basic rhumbs of 5 m/s speed.

In the second series of the numerical experiments spatiotemporal variability of the lagoon water level and thermohaline structure of the waters in the period of early May through late August with the Tyligul River runoff, the difference in monthly amounts of atmospheric

precipitation and evaporation (Table 2.1) taken account of, but under the absence of water exchange with the sea, was modelled. The Tyligul River runoff was assumed to be 0.3 m³/s in May, 0.95 m³/s – in July and 0.05 m³/s – in June and August, which corresponds to the features of runoff formation in the respective period of 2010. Time variability of wind direction and speed, air temperature (with the discreteness of 6 hours), monthly amounts of atmospheric precipitation were assigned on the basis of the data from observations carried out in 2010 at the ‘Port Yuzhnyi’ hydrometeorological station, located 20 kilometres away from the lagoon (Fig. 2.1).

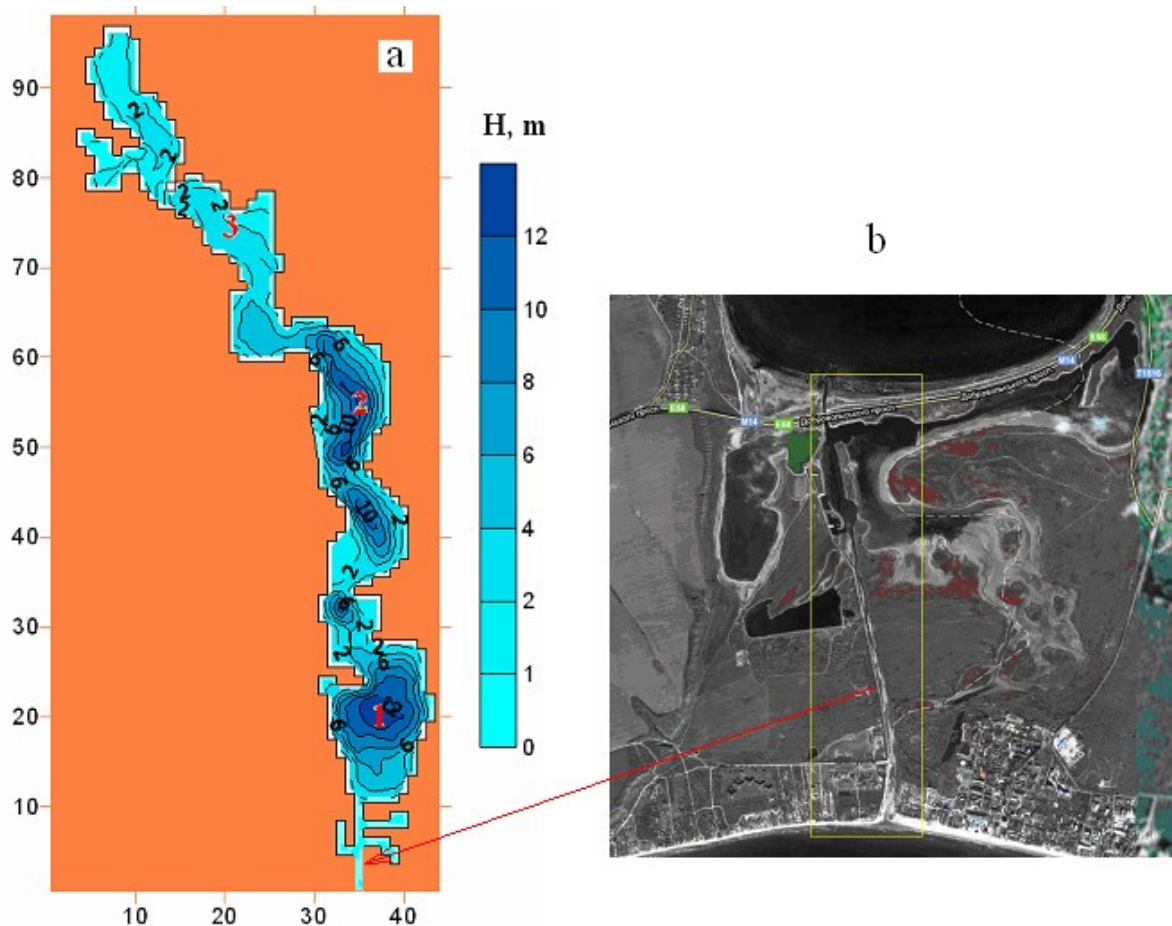


Fig. 2.2. Horizontal calculation grid for the Tyligulskyi Lagoon water area with the depths corresponding to the sea level of minus 0.4 m BS (a)*.

Satellite picture of the coastal area between the southern part of the Tyligulskyi Lagoon and the adjacent water area of the Black Sea (b), where the connecting canal (cropped), as well as a system of salt lakes connected to it, is located.

* Numbers of calculation grid nodes with a horizontal mesh cell width of 400 m are indicated along the reference axes. Tags of 1, 2 and 3 correspond to the numbers of reference points in the lagoon water area for making analysis of the calculation results.

Table 2.1 Long-term monthly average amounts of evaporation and atmospheric precipitation, and the monthly amounts of atmospheric precipitation, measured at the ‘Port Yuzhnyi’ hydrometeorological station in 2010, which are used in model calculations

Months	IV	V	VI	VII	VIII	IX
Atm. precip., mm, 1894-2008	28.1	34.9	47.4	40.2	34.9	35.0
Atm. precip., mm, 2010	45.2	86.2	47.3	113.4	26.7	69.6
Evaporation, mm, 1960-2007	62.0	99.0	124.0	142.0	131.0	91.0

Evaporation from the water surface of the lagoon was assigned on the basis of the average monthly data of observations at the Bolgrad weather-station located in the Odessa region, averaged for the period of 1960-2007 and equated to sea water salinity of 19 ‰. By way of comparison, there presented the long-term average monthly amounts of atmospheric precipitation calculated by the data from the ODESSA-GMO meteorological station for the period of 1894 - 2008. It is evident that, according to the long-term average data, evaporation in the period of May through September exceeds three times the amount of atmospheric precipitation.

In the third series of numerical experiments with the model, water exchange of the lagoon with the sea through the connecting canal, the depth and width of which at the seamark of minus 0.4 m BS were assumed to make 0.5 and 30 m, respectively, was taken account of. As well as in the previous series of experiments, the most critical period of a year for the lagoonal ecosystem, early May through late August, was modelled under hydrometeorological conditions of 2010. Temporal variability of sea water salinity and temperature (average ten-day values) at the open sea boundary of the connecting canal was assigned on the basis of the data from the observations carried out at the ‘Port Yuzhnyi’ marine hydrometeorological station (Fig. 2.1).

The initial seamark was taken equal to minus 0.15 m BS, and the water level in the lagoon equal minus 0.4 m BS. Decline in the lagoon watermark due to the difference between monthly amounts of atmospheric precipitation and evaporation was taken into account. Vertical distribution of water temperature and salinity in the lagoon at the initial time was assigned on the basis of observational data and considered homogeneous on the horizontal plane.

2.4 Problems and future actions

Among the problems related to adaptation and verification of a numerical non-stationary three-dimensional hydrothermodynamic model to the conditions of the Tyligulskyi Lagoon it is possible to distinguish the lack of data on peculiarities of spatial variability of the hydrological characteristics. The major part of available observations was carried out in the coastal shallow-water zone of the lagoon, where the vertical thermohaline structure of waters is quasihomogeneous due to wind mixing. In the course of calibration and verification of model calculations for the deep parts of the water area the observational data from the central

part of the lagoonal water area of 2010 were basically used. The characteristic feature of thermohaline structure of waters of the year's summer consisted in the occurrence of cold and salt waters in the benthic layer of the deep central part of the lagoonal water area. In July-August 2010, under the water temperature in the surface layer of 25-30 °C, the temperature at the depth of 14-15 m did not exceed 8-9 °C. However, the data of hydrological observations performed in 2012 show that under stronger winds in the summer period the vertical thermohaline structure of waters in the lagoon is characterized by considerably smaller vertical gradients of water temperature and salinity. Thus, even in June 2012 the water temperature at the depths of more than 10 m increased up to 20 °C, and in August 2012 bathymetrical distribution of water temperature was practically homogeneous.

Since the occurrence of massive seasonal pycnocline in the summer period results in development of hypoxia and anoxia at the depths below the boundary of upper quasihomogeneous layer, the research into sensitivity of the hydrothermodynamic model to wind conditions becomes particularly significant. The research is still in progress.

In the course of analysis of hydrological data obtained as a result of implementation of occasional observations in the deep parts of the southern and the central parts of the lagoon, accuracy of the bathymetric map, made as a result of measuring works conducted in 2010, raised doubts. Therefore at the end of September a specifying bathymetric survey was made and its results are being currently analysed.

Indeterminateness in the assignment of fluctuations in the sea level at the open sea boundary of the connecting canal should be attributed to a number of major problems related to the necessity of calculations for the chosen climatic scenarios. The above-mentioned results of modelling water level variability in the lagoon in the case of functioning of the connecting canal indicate that the major influence on water renewal in the lagoon is rendered not by the short-period fluctuations in the sea level induced by the wind, but its seasonal fluctuations related to runoff variability of the Dnipro and the Pivdennyi Buh rivers. To take this influence into account at making prognostic calculations it is necessary, firstly, to assess changes in the runoff of the mentioned rivers in view of the climate change, and, secondly, to ascertain an empirical relationship between the fluctuations in the average monthly values of a river runoff and the sea level in the coastal zone in the area of the Tyligulskyi Lagoon.

As the possible scenarios for management of the hydroecological regime of the Tyligulskyi Lagoon it is assumed to consider the following alternatives:

reduction in the number of water bodies in the catchment basin of the Tyligul River to 25, 50 and 75 % of their total number, as well as limitation of the terms for filling water bodies to 1-2 months in the spring flood time, aimed at increase of fresh water inflow into the lagoon;

regulation of functioning of the connecting canal leading to the sea for provision of maximum water renewal of lagoonal waters by sea waters.

Modelling the first of the stated alternatives within the framework of WP6 is possible only on the assumption of its implementation under WP5 scenario tasks for the Tyligulskyi Lagoon.

3. Ecological model

The numerical non-stationary three-dimensional model for water eutrophication, which is developed on the basis of the hydrothermodynamic model, which is given description in the previous section, is used for development of a plan for hydroecological management of the Tyligulskyi Lagoon with the anthropogenic load and the change in climate conditions taken account of. A biogeochemical unit of the water eutrophication model is the system of interdependent differential equations, which describe biogeochemical cycles of biogenic elements, production and destruction of organic matter, oxygen dynamics at a local point of the water environment. Integration of the hydrothermodynamic model with the biogeochemical unit in a unified model for water eutrophication is performed on the basis of application of the equation for non-conservative substance transfer.

The water eutrophication model, with various modifications in the mathematical structure of the biogeochemical unit, was previously used for finding solution to the applied hydroecological tasks related to development of hydroecological management plans for sea water bodies in the Colombian coast of the Caribbean Sea (Tuchkovenko and Lonin, 2003; Ivanov and Tuchkovenko, 2008) and the north-western part of the Black Sea (Tuchkovenko and Savin, 2006; Tuchkovenko et al., 2011).

3.1 General description of the model

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). In the represented version the model was tested in the north-western part of the Black Sea (Tuchkovenko et al. - OSENU, 2011). Inclusion of macrophytes into mathematical structure of the biogeochemical unit of the model is performed on the basis of the principles stated in the paper (Muhammetoglu and Soyupak, 2000).

The biogeochemical unit includes description of dynamics of the following ecological variables at a local point in space: phytoplankton biomass, benthic macrophyte biomass, refractory particulate and dissolved organic phosphorus (RPOP, RDOP), labile particulate and dissolved organic phosphorus (LPOP, LDOP), dissolved inorganic phosphorus (DIP), refractory particulate and dissolved organic nitrogen (RPON, RDON), labile particulate and dissolved organic nitrogen (LPON, LDON), ammonia nitrogen (NH_4), nitrite and nitrate nitrogen ($\text{NO}_2 + \text{NO}_3$), refractory particulate and dissolved parts of the carbonaceous biochemical oxygen demand (RPBOD, RDBOD), labile particulate and dissolved parts of the carbonaceous biochemical oxygen demand (LPBOD, LDBOD), and dissolved oxygen (DO).

A block diagram of relations between the biogeochemical unit variables is presented in Fig. 3.1.

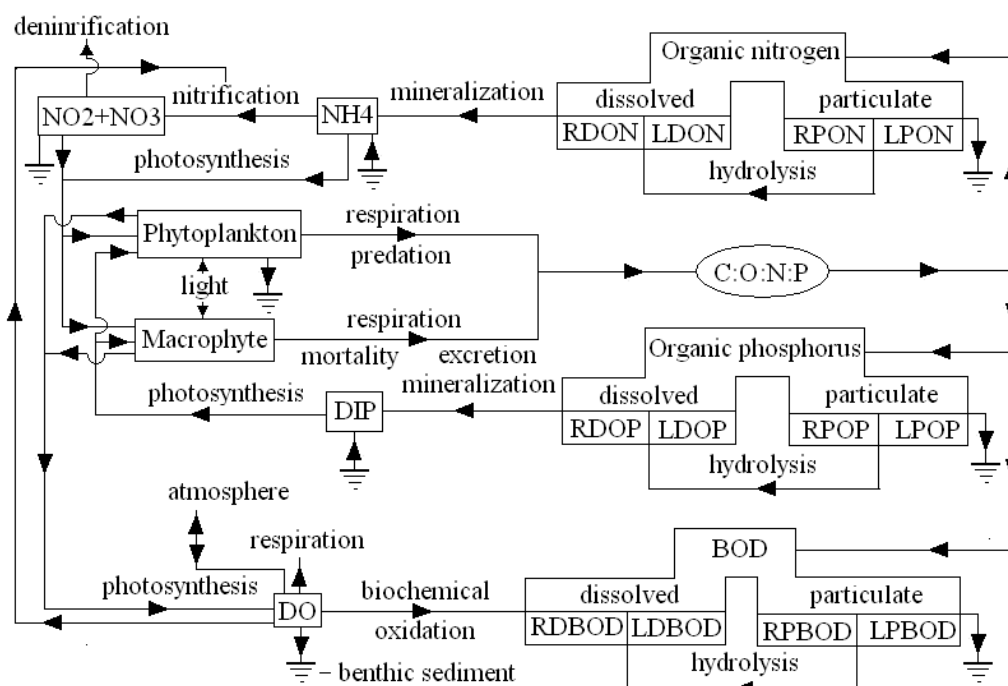


Fig. 3.1 Schematic diagram of the biogeochemical unit for the water eutrophication model of the Tyligulskyi Lagoon and the relationships between its elements

The flows of particulate fractions of organic substances in the benthic sediment are formed by setting their gravitational sedimentation rate in the equation of transfer of non-conservative substances. The unit for calculation of the oxygen demand by the bottom sediments and the flows of nutrients from bottom sediments is based on the principles indicated in (Ambrose et al - WASP5, 1993).

3.2 Processes modelled in the lagoon

The main environmental problem of the Tyligulskyi Lagoon is development of oxygen deficit (hypoxia) in the benthic layer waters of the deep areas in lagoonal water area in the summer period, as well as in the shallow water at night-time under calm and strong heating of the waters (Fig. 3.2). There are registered cases of total lack of oxygen and occurrence of hydrogen sulphide in the waters located deeper than the upper quasihomogeneous mixed layer in the areas, where deep depressions in the relief of the lagoonal bottom are located (Fig. of 3.2a).

Development of oxygen deficit in the water results in the death of hydrobionts and, first of all, fish. There are unfavourable conditions for fishing, aquaculture, recreation and tourism. For example, in summer 2010 in certain areas of the lagoonal coast 20 kg of dead fish per square meter was found for the stated reason. In various parts of the lagoon death of fish was also observed in the summer periods of 1999, 2000, 2001, 2006 and 2007.

The reasons for occurrence of hypoxia in the lagoonal waters in the summer season are as follows:

imbalance of production-and-destruction processes in the ecosystem of the lagoon - an organic matter, which is newly formed by phytoplankton and bottom macrophytes (in the

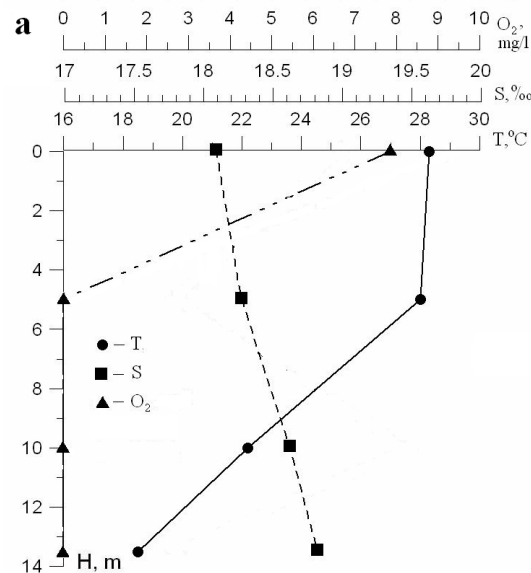
shallow water) in the process of primary production, is not assimilated by the organisms of higher trophic levels in sufficient quantity and, through dying off, provides a favourable basis for development of heterotrophic bacteria. As a result, the time of nutrients turnover in an ecosystem decreases dramatically, and oxygen demand for biochemical oxidation of organic matter in the water and the bottom sediments increases;

weak external water renewal in the lagoon (the total water renewal lasts 5-6 years (Timchenko, 1992) coupled with substantial deficiency of fresh water balance (evaporation from the water level of the lagoon three times exceeds the amount of atmospheric precipitation);

development of seasonal thermocline as a result of spring-summer heating of the waters;

inflow of nutrients with the subsurface runoff into the lagoon and with the bird excrements.

The main reason for occurrence of oxygen deficit in the lagoon is the process of increase in the trophic level of its waters, i.e. the rate of generation of new organic matter in the course of biological production process called eutrophication. Development of the process of water eutrophication in the lagoon is conditioned by high content of nutrients in its waters which enters with the inflow of a lateral surface runoff from the catchment basin of the lagoon, the groundwater runoff, bird excrements, atmospheric precipitation, which have been accumulated in the lagoon for many years under the conditions of weak external water exchange with the sea and substantial deficit of fresh water balance, caused by intensive evaporation from the surface of the lagoon (being 3 times in excess of the atmospheric precipitation, in the summer period).



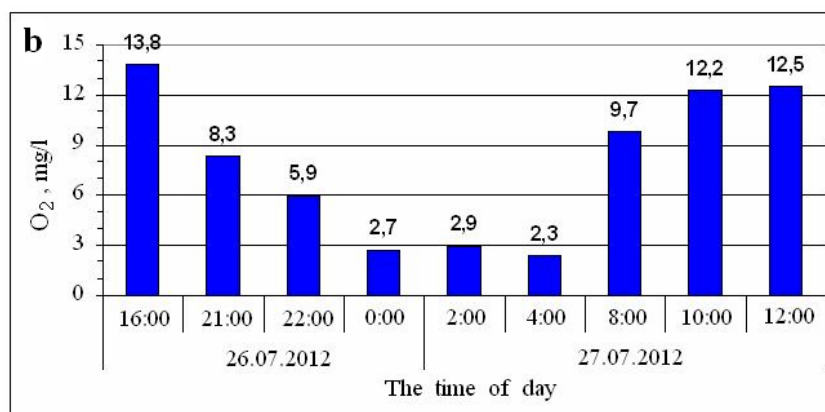


Fig. 3.2 Vertical distribution of water temperature ($^{\circ}\text{C}$), salinity (‰) and the content of dissolved oxygen ($\text{mg}\cdot\text{L}^{-1}$) in the area of one of the deep depressions in the Tyligulskyi Lagoon in August, 2010 (a) and diurnal variation of the content of dissolved oxygen in the water in the coastal shallow water zone in the southern part of the lagoon, August 2012 (b)

The ecosystem of the lagoon is not balanced in the content of basic biogenic elements, nitrogen and phosphorus, because the lagoonal waters are characterized by significant concentrations of phosphates and organic phosphorus, low concentrations of nitrogen mineral forms and high concentrations of organic nitrogen (Zaitsev et al, 2006).

As follows from the previous section, in course of environmental modelling of water eutrophication in the Tyligulskyi Lagoon the following processes in the biogeochemical unit of the model are given consideration:

removal of biogenic elements and primary production of organic matter by phytoplankton and benthic macrophytes under photosynthesis;

production of suspended (particulate) and dissolved nonliving organic substance as waste products of hydrobionts and the process of hydrolysis;

mineralization of nonliving organic matter and regeneration of nutrients;

nitrification and denitrification;

mass transfer of nutrients and oxygen gas exchange with bottom sediments and the atmosphere.

Within the framework of the project the major consideration will be given to research into the impact of climate conditions on production-and-destruction processes in the water ecosystem and the oxygen regime of the waters in the Tyligulskyi Lagoon. Climate conditions are determined by such hydrometeorological characteristics as wind speed and direction, air temperature, atmospheric precipitation, solar radiation flux, lateral fresh water runoff into the lagoon and, foremost, the Tyligul River runoff. Variability of the mentioned characteristics determine hydrological conditions in the lagoon: thermohaline structure, water transparency, strength and stability of a seasonal pycnocline, changes of water level in the lagoon, intensity of three-dimensional spatial advective and turbulent transfer of an substance. The hydrological conditions in the lagoon, in turn, define specific rates of abovementioned biogeochemical processes. For example, it is known that under the change in water temperature of 10°C the rates of biogeochemical processes turn two- or threefold.

The concentration of organic matter (living and nonliving) and the content of dissolved oxygen are used as the main hydroecological indices of water eutrophication level in the lagoon.

Presently, any reliable information on the water pollution with toxic substances in the Tyligulskyi Lagoon, which could be proved by observational data, is lacking, though some specialists express assumptions on the possible washout of the pesticides from the fields sown with rape and the lawn-and-garden sites, which are located up the lagoon coast, into the lagoon with the hill-slope runoff in the period of heavy summer rainfalls.

3.3 Model set up

Under the development of a numerical model for water eutrophication in the Tyligulskyi Lagoon a three-dimensional space, as a rule, is divided into cells (boxes) which correspond to grid boxes of the hydrodynamic unit. It is supposed that the ecosystem elements inside the boxes are linked only by the local matter and energy flows, which are given description in the biogeochemical unit of the model, while transfer of matter and energy between the cells takes place as a result of hydrodynamic (the advective and the turbulent) transfer. Consequently, a hydrodynamic is calculated by a horizontal calculation grid of 44×99 nodes with the mesh cell width of 400 m and the use of 10 calculation levels along the vertical in a σ -system of coordinates. The time step is 3 sec for the barotropic constituent of the current velocities and 18 sec - for the baroclinic one.

A time step in the biogeochemical unit of the model is 1 day (24 hours). In the course of calculations in the biogeochemical unit of the model a transition of depth distribution of the modelled chemico-biological variables from σ - coordinates to z - system and inversely is carried out. In z - system of coordinates the following levels are used: 0; 0.25; 0.5; 0.75; 1.0; 2.0; 3.0; 5.0; 7.5; 10.0; 12.0; 14.0; 16.0 m.

Under the calculations with the use of the model for water eutrophication in the Tyligulskyi Lagoon, the concentrations of the modelled variables in salt (at the open sea boundary of the canal) and river waters (at the point of inflow of the Tyligul River into the lagoon) in the suspended and/or dissolved form, namely: phytoplankton biomass, phosphorus in the mineral and the organic (the particulate, the dissolved) forms, nitrogen in the mineral (ammonium, nitrite + nitrate) and the organic (the particulate, the dissolved) form and the dissolved oxygen are assigned as peripheral boundary conditions.

At the open sea boundary of the connecting canal the time series of sea level, sea water temperature and salinity were assigned according to the data from observations at the 'Port Yuzhnyi' marine hydrometeorological station with the discreteness of 6 hours for the years of 2010 and 2012.

In calibration and verification of the model for water eutrophication in the Tyligulskyi Lagoon the water discharges of the Tyligul River, characteristic for the years with various statistical probability of annual runoff (Table 3.1), as well as the average seasonal values of hydrochemical characteristics of river waters, averaged for the period of 2001-2010 (Fig. 3.3), which were observed with temporal discreteness of once a season at the 'Berezivka' observation post were used.

Table 3.1 Variability of the Tyligul River discharges, m³s⁻¹, in the years with various statistical probability (P) of annual runoff

Years	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2006, P = 47 %	0	0	1.21	2.48	0.82	0	0	0	0	0	0	0
1997, P = 53 %	0	0	0.69	0.78	0.09	0	0	0.66	0.12	0	0.39	1.90
2003, P = 6 %	0	9.76	23.20	7.37	1.29	0.44	0	0	0	0	0	0
2000, P = 94 %	0	0	0.52	0.56	0.17	0	0	0	0	0	0	0.01

Intensity of solar radiation incident on the sea surface, obtained by processing the data of observations carried out in 2003-2007 at the 'Odessa-Port' hydrometeorological station, located 40 kilometres away from the Tyligulskyi Lagoon on the Black Sea coast, is assigned to the upper boundary. It is assumed that photosynthetically active radiation (PAR) makes up 50 % of the total radiant flux.

Parameters of the biogeochemical unit are calibrated under the following scheme.

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

At the second stage the biogeochemical unit parameters are calibrated with the use of a 1-D (by z coordinate) model alternative, in which the terms of motion equations for the horizontal components of the current velocity vector and transfer of non-conservative substances describing a horizontal turbulent exchange and advective transfer are eliminated, and the independence of all functions from horizontal coordinates is assumed. Only a drift constituent of the speed of currents, used for the calculation of vertical turbulent exchange and diffusion coefficients, is taken into account in such problem definition. The main task of calibration consists in attaining maximum possible equivalence between the observational data and the calculations of within-year variation of the modelled variables. This aim was reached by correction of initial values of the constants in the biogeochemical unit, which were assigned on the basis of the literary source data, within the possible limits.

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

for the deep southern and central parts of the lagoon without regard to the equation of biomass dynamics of the benthic macrophytes;

for the shallow northern part of the lagoon with the account of the equation of biomass dynamics of the benthic macrophytes.

For taking account of the inflow of biogenic elements and organic matter into the lagoon from external sources, in the 1D model variant a ratio of the following form (Ivanov, Tuchkovenko, 2008) is used:

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

where Q_i is the inflow of the i substance from the external sources (the Tyligul River or the connecting canal leading to the sea); q_k is the discharge of the k source, $m^3 \cdot s^{-1}$; C_{ki}, C are the concentration of the i modelled substance in the waters of the k source and in the waters of a water area under the study, accordingly; W_{tot} is the total volume of waters in the dilution zone. It was assumed that the initial dilution takes place within the limits of the upper 1-meter layer. The horizontal scale for the dilution zone with regard to the Tyligul River runoff was determined by the boundaries of the northern part of the lagoon, and for the sea waters – by the boundaries of the southern part of the lagoonal water area.

Calibration of the 1D variant is performed in three steps. The first step: the parameters for equations of the dynamics of phytoplankton and benthic macrophyte biomass, RPBOD, LPBOD, RDBOD, LDBOD, O₂ were calibrated. Seasonal dynamics of other variables in the model is assigned by the observational data.

The second step: parameters for the equations of the nitrogen cycle are calibrated and, as the third step, the same was conducted for the phosphorus cycle.

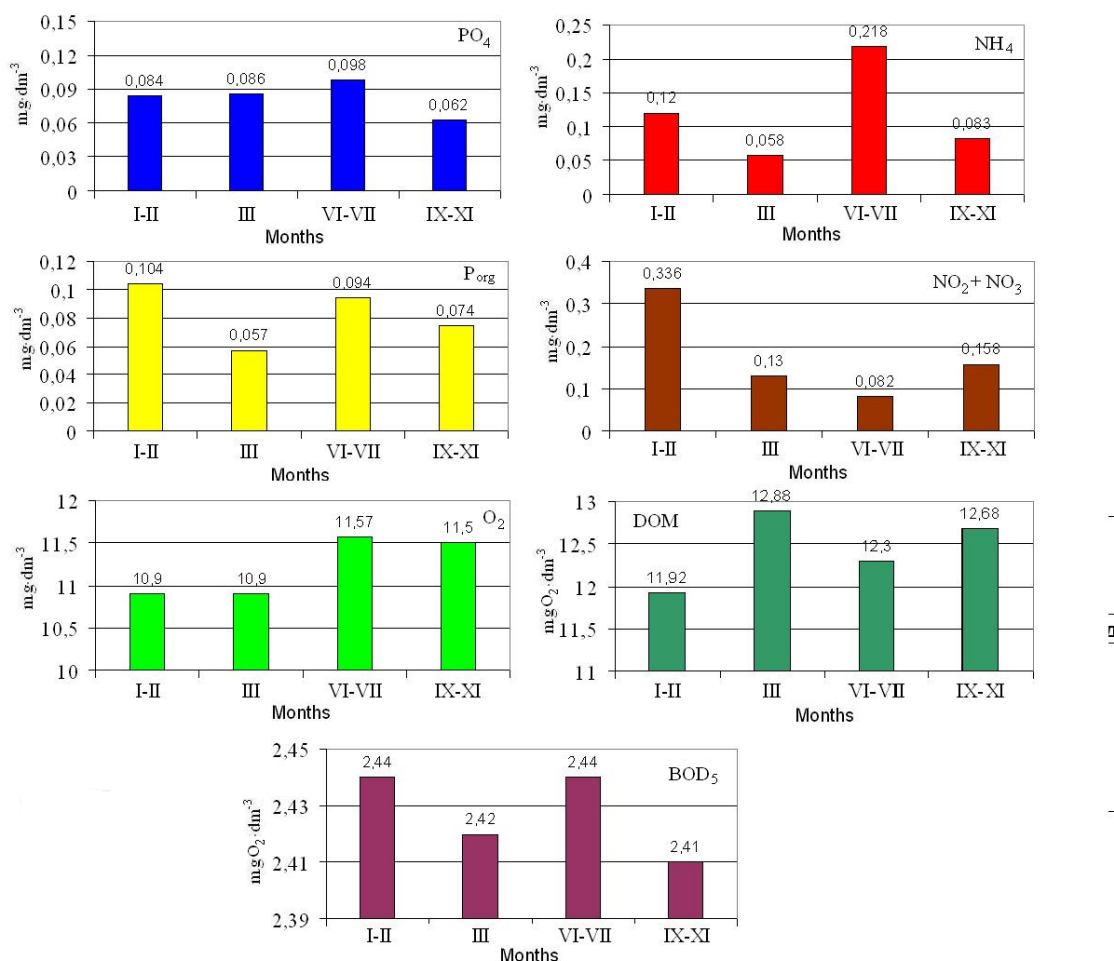


Fig. 3.3 Seasonal variation of hydrochemical characteristics of the Tyligul River waters, according to the data of observations from the 'Berezivka' observation post

Preliminary use of the 1D model alternative is caused by the fact that calibration of the water eutrophication model requires considerably less computing time as opposed to a 3D variant, which makes it possible to carry out a large number of numerical experiments with diverse combination of model parameters and obtain the required type of variability for the modelled variables.

At the third stage of the calibration of the water eutrophication model parameters for the biogeochemical unit of the model equations, which are determined at the second stage, are used in the 3D model version. More precise definition of them is performed in the process of verification and validation of the 3D model alternative.

In the course of calibration of the biogeochemical unit of the model the average monthly values of the following modelled characteristics for the trophic level of the lagoonal waters, which had been calculated for the long-term period of 2001-2010, were used: phytoplankton biomass, benthic macrophyte biomass, organic-N (RPON+LPON+RDON+LDON), ammonium-N (NH_4), nitrite-N + nitrate-N (NO_2+NO_3), organic-P (RPOP+LPOP+RDOP+LDOP), phosphates-P (DIP), dissolved organic matter (DOM= RDBOD + LDBOD), dissolved oxygen (DO).

Within-year variation of phytoplankton biomass and chlorophyll a concentration in the photic layer of the northern and the southern parts of the lagoon, which is used for calibration of the biogeochemical unit of the model, is shown in Fig. 3.4. It is evident that the maximum of phytoplankton biomass in the relatively shallow northern part of the lagoon is observed in June and July, whereas in the southern deep part of the lagoon - in August-September. The reason for this is more rapid heating of waters in the northern part of the lagoon, and the influence of vertical turbulent and diffusive exchange in the deep part of the lagoon. The peak of chlorophyll a concentration in the southern part in April, which does not reveal itself in phytoplankton biomass, is worth special consideration. This peak is determined by an increase in the number of petite phytoplankton cells, which are characterized by higher chlorophyll a / organic carbon ratio in the cells.

The benthic macrophytes are widespread in the considerable parts of the water area only in the northern shallow part of the lagoon, while in the southern and the central parts they are widespread only in the narrow coastal shallow-water zone (Fig. 3.5), the width of which corresponds to 1-2 steps of the horizontal computational grid for the model (400 m). Seasonal variation of macrophyte biomass in various parts of the lagoon, with its bathymetrical distribution taken account of, is given in Fig. 3.6.

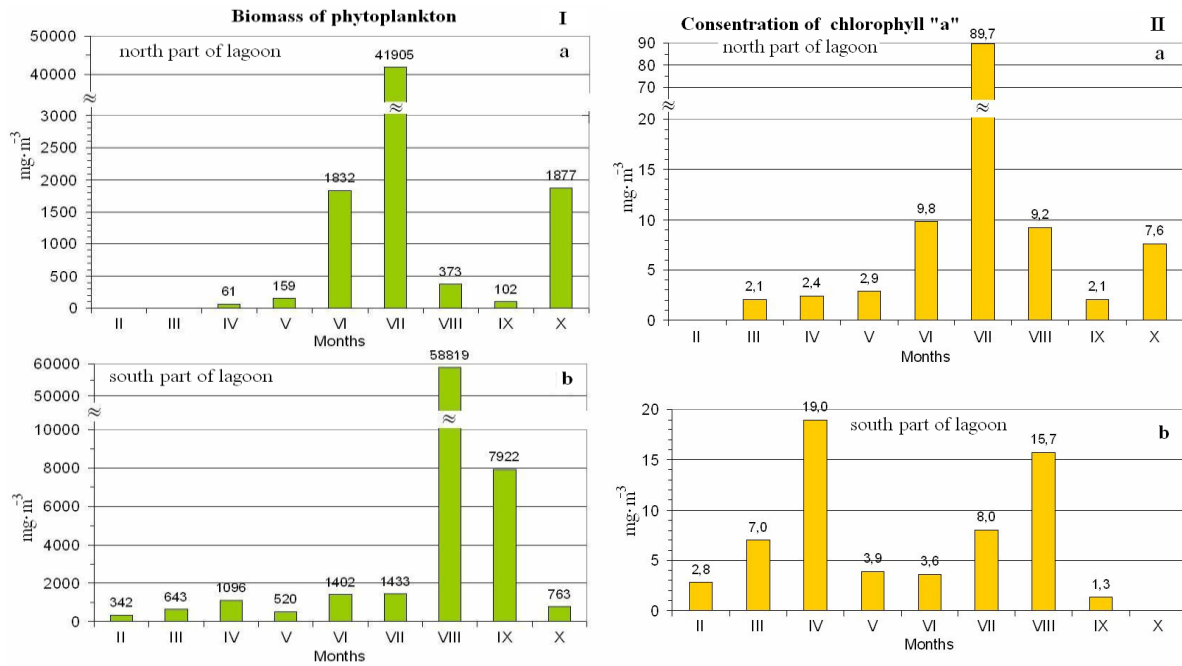


Fig. 3.4 Within-year variability of phytoplankton biomass (I) and concentration of chlorophyll *a* (II) in the photic layer waters of the northern (a) and the southern (b) parts

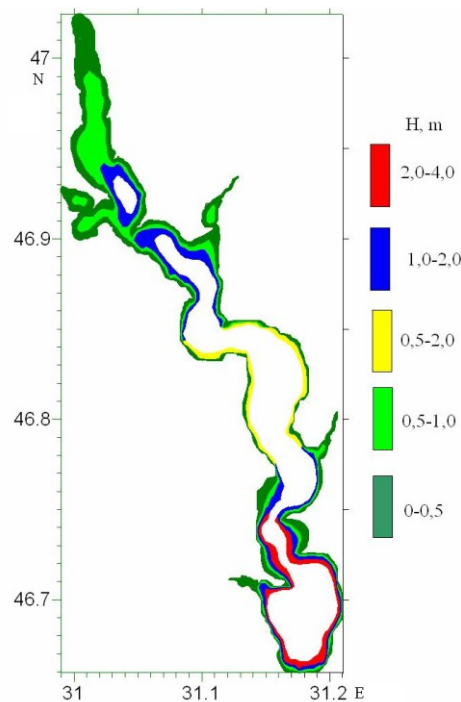


Fig. 3.5 Areas of the depths in the Tyligulskiy Lagoon water area where the benthic macrophytes are widespread

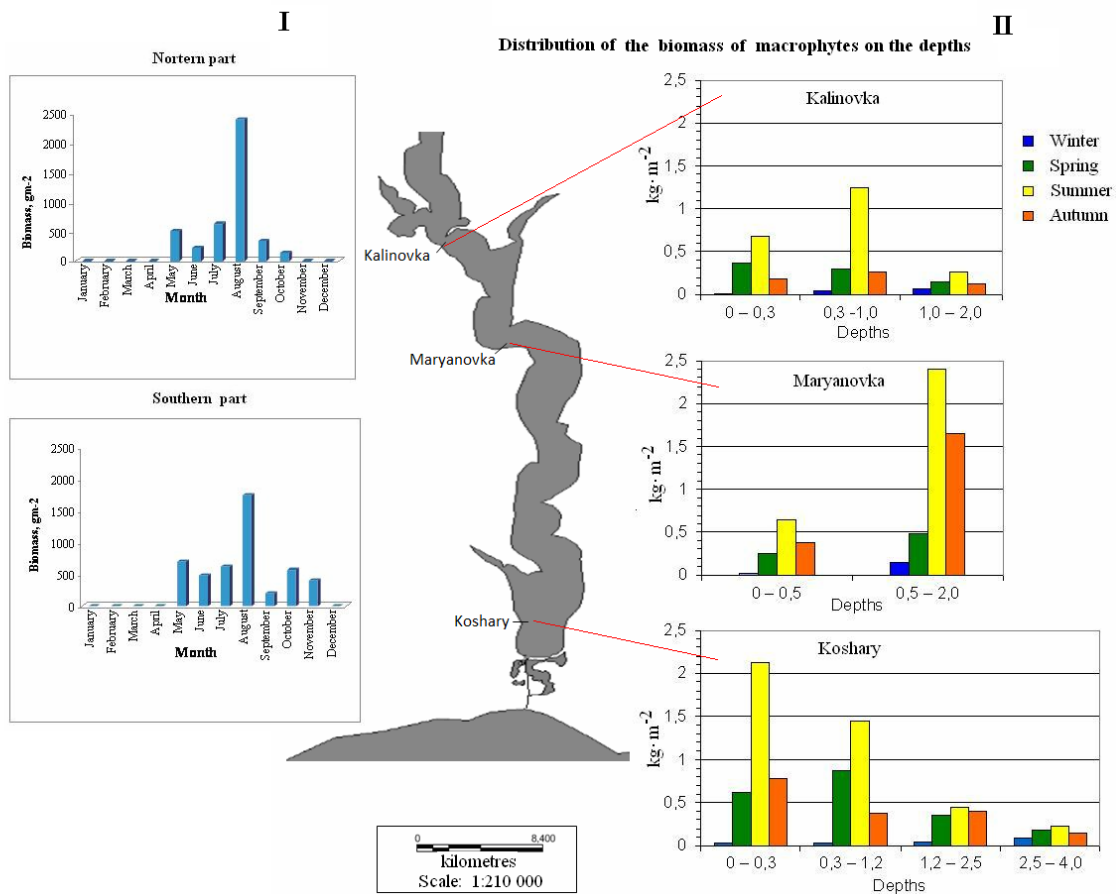


Fig. 3.6 Seasonal variability of average benthic macrophyte biomass in the northern and the southern parts (I) of the Tyligulskyi Lagoon, and at various points in the coastal zone of the lagoon with the bathymetric distribution (II)

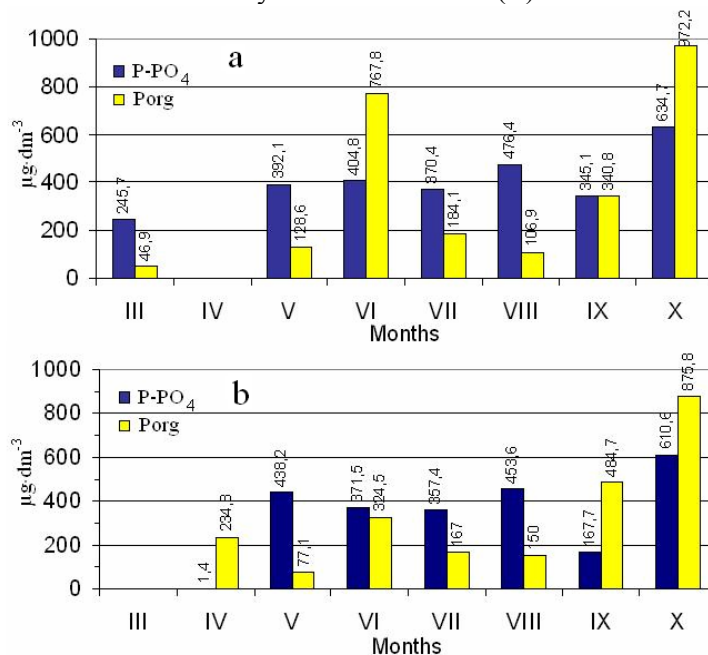


Fig. 3.7 Variability of the average monthly concentrations of mineral and organic forms of phosphorus in the waters of the northern (a) and the southern (b) parts of the lagoon, averaged for the period of 2001-2010

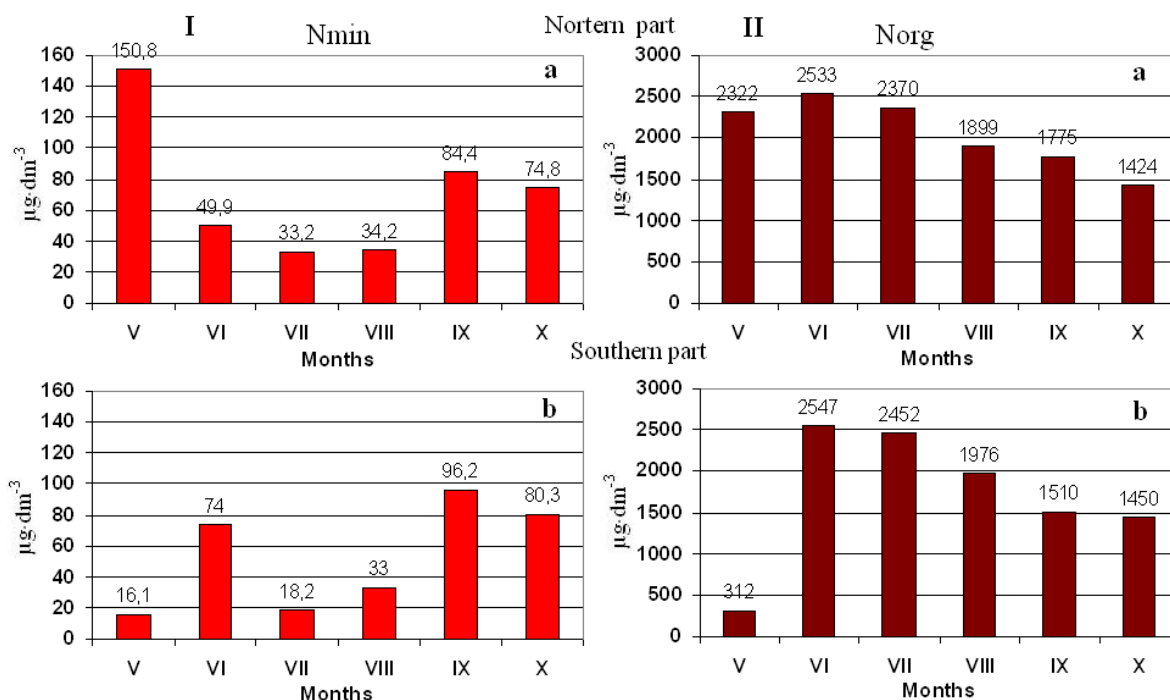


Fig. 3.8 Variability of the average monthly concentrations of mineral (I) and organic nitrogen (II) in the waters of the northern (a) and the southern (b) parts of the lagoon, averaged for the period of 2001-2010

High concentrations of mineral phosphorus, as compared to mineral nitrogen (Fig. 3.7, 3.8), is a characteristic feature of the hydrochemical regime of the lagoonal waters. Thus, the relation between the concentrations of nitrogen and phosphorus in the lagoonal waters equals, on the average, 1:10 for the inorganic forms, 9.5:1 - for the organic forms, and 3:1 - for the total of nitrogen and phosphorus, which is indicative of the high capacity external sources of the inflow of phosphates into the lagoonal waters.

3.4 Problems and future actions

Among the problems related to calibration and verification of the water eutrophication model, the following should be taken special notice of.

The observational data are distributed by the months and the space of the lagoonal water area extremely irregularly. Most of the observational data is obtained in the summer months. Observations in the winter months were not made at all, and in the spring and the autumn ones they were sporadic. Moreover, since the systematic observations were not conducted, the data mismatch in time and space. The largest number of observations has been carried out in the southern part of the lagoon. There are only a few relatively synchronous spatial surveys of the lagoon, and they both were carried out in August. Inspection stations, implemented in the deep parts along the longitudinal axis of the lagoon, are also sporadic and refer to various years. Thus, the annual variation of hydrochemical characteristics recovered by the observational data for the period of 2001-2010 are representative of just a very rough approximation to the real average long-term variability, which substantially decreases the accuracy of calibration of the biogeochemical unit parameters of the model.

There is a lack of observational data on water transparency in the lagoon. All available information on the variability of water transparency is presented in Fig. 3.9. Therefore, under calibration of the biogeochemical unit the annual variation of water transparency in the northern and the southern parts of the lagoon is assigned tentatively, considering the available information.

Information on fraction distribution of the total concentration of organic substance: the dissolved, the particulate, the labile and the refractory fractions are missing. Therefore these correlations were initially established on the basis of information on the ranges of their possible values given in the literary sources (HydroQual, 2004; CE-QUAL-ICM, 1995), and were finally determined in the course of calibration of the model.

For assessment of the content of nonliving organic carbon (or its oxygen equivalent) in the water only one indicator, permanganate oxidability, which was evaluated in the lagoonal waters, is used. This brings about problems of identification for the respective model variables and can affect the adequacy of description of the dissolved oxygen dynamics, a key index for the lagoon, in the model.

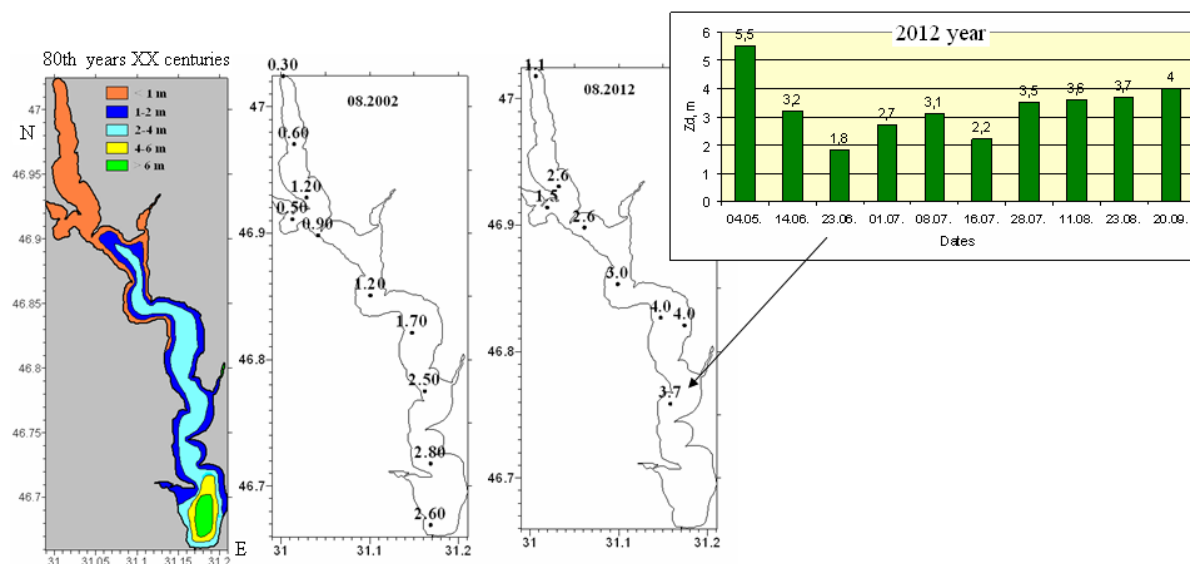


Fig. 3.9 Variability of water transparency, m, in the Tyligulskyi Lagoon water area according to the data (Timchenko, 1990) and the results of observations at an inspection point in August 2002, 2012, and May-September, 2012

At present the sources for heightened phosphorus content in the lagoonal waters are not ascertained. There are only a few well-grounded hypotheses on its inflow with the groundwater's runoff (the estimates of which are unavailable) and as a result of the input of bird excrements, where nitrogen / phosphorus ratio is approximately equal to 1, into the lagoonal waters.

The mentioned problems require consideration of the methods for finding solution to them for modelling which results in prolongation of the process of biogeochemical unit calibration. At the same time, it is obvious that the use of hypothetical assumptions, which are included into a model, makes its predictive capabilities under consideration of future scenarios worse.

Apart from those described in section 2.4, the following variants can be considered as the possible scenarios for management of the eutrophication level and the oxygen regime of waters in the Tyligulskyi Lagoon:

- 1) taking account of perspective plans for land use under WP5, which will entail a change in biogenic runoff of the Tyligul River;
- 2) introduction of restrictions on land use (e.g. their ploughing-up) in the lagoon catchment basin related to its inclusion into ecological corridors of the state and regional value, in accordance with the Law of Ukraine ‘On the State Programme for National Ecological Network Development for the years of 2000-2015’ and the scheme of a regional ecological network in the Odessa region (2011), which will result in the changes of biogenic runoff into the lagoon;
- 3) influence of changes in the hydrological regime conditioned by the climate change on the trophic level of waters and the oxygen regime of the lagoon.

References

- Adobovskii, V.V., Bolshakov, V.N. (2003) *Influence of Abnormal Winter Conditions in 2002-2003 on the Hydrological Regime of the Closed Lagoons in the North-Western Black Sea Region*, Journal of Environmental Safety of Coastal and Shelf Zones and Multiple Use of Shelf Resources. Sevastopol: Marine Hydrophysical Institute, Issue 9, P. 54-58. (In Russian)
- Ambrose R. B., T. A. Wool, and J. L. Martin, *The Water Quality Analysis Simulation Program, WASP5, Part A: Model Documentation*, Environmental Research Laboratory, Athens, Georgia, USA (1993), pp. 49–140.
- Blumberg A.F. (1975) *A numerical investigation into the dynamics of estuarine circulation*. Johns Hopkins University, Chesapeake Bay Institute Tech. Report 91, USA, 110 p.
- Blumberg A.F. (1978) The influence of density variations on estuarine tides and circulations. *Estuarine and Coastal Marine Science*, 6, 209 – 215.
- Boris J.P., and D.L. Book (1975) Flux-corrected transport: generalization of method. *J. Comput. Phys.*, 3, 248 - 283.
- Brooks D.A. (2008) *Corrections to the nonlinear momentum advection terms in Mecca 2.0*. Department of Oceanography. Texas A&M University, 2 pp.
- Cerco C. F. and T. Cole (1995) *User's Guide to the CE-QUAL-ICM three-dimensional eutrophication model (Release version 1.0)*, Waterways Experiment Station, U. S. Army Corps of Engineers (1995).
- CIOH (1999): *Restauracion Ambiental de los Ecosistemas de Influencia del Canal del Dique, Description y Caracterizacion Biotica del Area. Modelación Numérica del canal del Dique, su Sistema Lagunar y las Bahías de Cartagena y Barbacoas: Informe Final*, Universidad del Norte-CIOH, UN, 1999-0010, Cartagena, Colombia.
- Fletcher C. A. J. (1988) *Computational Techniques for Fluid Dynamics*, Vol. 1, *Fundamental and General Techniques*, Vol. 2, *Specific Techniques for Different Flow Categories*, Springer, Berlin.
- Tag P.M., F.W. Murray, and L.R. Koenig (1979) *A comparison of several forms of eddy viscosity parametrization in a two-dimensional long-wave propagation*. U.S. Army Corps of Engineers, Coastal Engineering Research Center Technical Memorandum 32, USA, 29 p.

- Hess K.W. (1985) *Assessment model for estuarine circulation and salinity*. NOAA Technical Memorandum NEDIS AISC 3, National Environmental Satellite, Data, and Information Service, NOAA. USA, 39 p.
- Hess, K.W. (1986) *Numerical model of circulation in Chesapeake Bay and the continental shelf*. NOAA Technical Memorandum NESDIS AISC 6, National Environmental Satellite, Data, and Information Service, NOAA., US A, 47 pp.
- Hess K.W. (1989) *MECCA Programs documentation: Technical Report / NOAA. – NESDIS 46. – Washington, D.C., 97 p.*
- Hess, K.W. (2000) *Mecca2 Program Documentation*. NOAA Technical Report NOS CS 5, Silver Spring, MD, 49 p.
- HydroQual Inc. (2004) User's guide for RCA: release 3.0, Appendix A –HydroQual, Mahwah, New Jersey, P. 3 – 46.
- Ivanov, V.A., Tuchkovenko, Yu. S. (2008). *Applied mathematical water-quality modeling of shelf marine ecosystems*, Sevastopol: Marine Hydrophysical Institute, Odessa State Environmental University, 295 p.
- Lonin, S.A., Tuchkovenko, Y.S. (2001). Water quality modelling for the ecosystem of the Cienaga de Tesca coastal lagoon. *Ecological modeling*, Published by Elsevier Science B.V., Vol. 144, P. 279-293.
- Munk W. H., and E. R. Anderson (1948). Notes on the theory of the thermocline. *J. Mar. Res.*, No. 7, 276–295.
- Muhammetoglu A.(B.), and S. Soyupak (2000) A tree-dimensional water quality-macrophyte interaction model for shallow lakes. *Ecological modeling*, Published by Elsevier Science B.V., Vol. 133, P. 161-180.
- Sobey R.J. (1970). *Finite-difference schemes compared for wave-deformation characteristics in mathematical modeling of two-dimensional long-wave propagation*. U. S. Army Corps of Engineers, Coastal Engineering Research Center Technical Memorandum 32, USA, 29 p.
- Timchenko, V.M. (1990) *Environmental and Hydrological Researches into the Water Bodies in the North-Western Black Sea Region*. Kyiv: 'Naukova Dumka', Institute of Hydrobiology of NAS of Ukraine, 240 p. (In Russian)
- Tuchkovenko, Y.S., Lonin, S.A. (2003). Mathematical Model of the Oxygen Regime of Cartagena Bay. *Ecological modeling*, Published by Elsevier Science B.V., Vol. 165, Issue 1, P. 91-106.
- Tuchkovenko, Yu. S., Savin, P.T. (2006) *Modelling. Current State of an Ecosystem and the Tendencies towards Change: Abiota*. In a monograph 'The North-Western Part of the Black Sea: Biology and Ecology. Kyiv: 'Naukova Dumka', Odessa Branch of the Institute of Biology of the Southern Seas, P.102-124. (In Russian)
- Tuchkovenko, Yu. S., Gopchenko, Ye.D., Adobovskiy, V.V., Bolshakov, V.N. (2008) Regulation of the Hydroecological Regime of Dofinovskyi Liman Lagoon. *Ukrainian Hydrometeorological Journal*, Odessa: Ecology, OSENU, No. 3, P. 124 - 147. (In Russian)
- Tuchkovenko, Yu. S., Ivanov, V.A., Sapko, O. Yu. (2011) *Assessment of the Influence of Coastal Anthropogenic Sources on Water Quality in the Odessa District of the North-Western Part of the Black Sea*. Sevastopol, Marine Hydrophysical Institute, Odessa State Environmental University, 169 p. (In Russian)
- Tuchkovenko, Yu. S., et al (2011) *Research into the Influence of Climate Fluctuations on Hydrological and Hydrochemical Regimes in the North-Western Part of the Black Sea*.

- Technical Report*. Odessa State Environmental University, Odessa, Ukraine, 344 p. (In Russian)
- Wang D.P., and D.W. Kravitz, 1980. A semi-implicit two-dimensional model of estuarine circulation. *J. Phys. Oceanog*, 3, 441 - 454.
- Zaitsev, Yu. P., Aleksandrov, B.G., Minicheva, G.G., Ed. (2006) *The North-Western Part of the Black Sea: Biology and Ecology*. Kyiv: 'Naukova Dumka', Odessa Branch of the Institute of Biology of the Southern Seas, P. 358 - 371. (In Russian)