Hydrodynamic modelling of the Curonian Lagoon, Lithuania

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Introduction

The purpose of this research originated from the need to protect and manage the Curonian Lagoon, an environment that is the object of many environmental and economical interests.

The Curonian Lagoon, also known as the Kuršių Marios, is a complex ecosystem with many interacting processes. It is an open system, influenced by the exchange of the fresh Nemunas river water and saline water of the Baltic sea. Water salinity in the northern part of the lagoon may fluctuate between 0.1-7 psu and rappresentatives of marine, brackish and fresh-water species live there. The Kuršių Marios lies along the Baltic coast of Lithuania and the Kaliningrad oblast (province) of Russia. The total area of the Lagoon is approximately 1600 km^2. Total volume of water of the Lagoon is approximately 6.2 km^3, and the average depth, about 3.8 m. It is separated from the Baltic by a narrow ($\sim$ 1-3 km) sandy spit, the Curonian Spit. The border between the two countries divides the lagoon into a smaller, northern part in Lithuania (413 km^2) and a bigger southern part in Russia. The largest city of the region, the industrial town of Klaipėda (1993 population 206.400), lies at the northern end of the Lagoon just north of its only connection with the Baltic, the narrow Klaipėda Strait. The area of land draining into the Curonian Lagoon covers 100.458 km^2, of which 48 % lies in Byelorussia, 46 % in Lithuania, and 6 % in the Kaliningrad oblast, with a total population of about 5 million inhabitants. The Lagoon has been heavily polluted from a combination of shipping, military and industrial sources. Pathogenic organisms characteristic of untreated sewage loads are also abundant. Concentrations of petrochemicals and heavy metals in lagoon waters have been very high. Not surprisingly, fishing and bathing in the lagoon have declined significantly in modern times.

Despite its importance, the Curonian lagoon, by a hydrodynamic point of view has not been properly studied in the past. Only in the earlier time hydrodynamic model was applied to the lagoon in order to describe the water circulation pattern.

The scientific hydrodynamic investigation of the Curonian lagoon started in the fisrt half the last century. Measured variation of the physical and chemical parameters or measured water current were used to describe the water circulation pattern. These studies pointed out the relationship between the wind and the current velocities and indivduated a cyclonic behavior of the surface water current in the central and southern part of the lagoon. This cyclonic circulation pattern has been therefore confirmed in the 1959 by the application of a reduced physical model of the Curonian lagoon. Only in the last years some hydrodynamic models have been applied to the Curonian lagoon. U. Raudsepp and T. Kuts applied a 2D finite difference hydrodynamic model to simulated the circulation pattern under steady wind blowing from eight different directions. In this study the influence of the rivers was not taken into account, but anyway they showed the presence of some two-gyre circulation system in the southern part of the lagoon In the 2003, L. Davuliene and G. Trinkunas using a 3D finite difference baroclinic circulation model to studied the dominant currents and the dispersion of a passive tracer in the Curonian lagoon and in the Lithuanian marine water under differente forcing. The authors showed that the two-gyre circulation structure in the southern part of the lagoon develops under any wind direction except for the eastern and western winds. Moreover they pointed out the strong influence of the Nemunas river on the water circulation of the northern part of the lagoon.

In this study the hydrodynamic circulation of the Curonian Lagoon will be investigated with a framework of numerical models. These models consist of a two-dimensional finite element hydrodynamic model, a radiational transfer module of heat at the water surface and a transport diffusion model. The models have been calibrated for the Curonian lagoon comparing the simulation results against experimental water level, salinity and water temperature data. Moreover the water residence time has been investigated to study the renewal capacity of the lagoon under the action of different forcings. Similar models has been developed and applied, with sucess in some italian lagoons, like the ones in Venice, Taranto, Orbetello and Cabras.

1 The hydrodynamic model

The hydrodynamic model used in this work is a two-dimensional finite element model developed at the CNR-ISMAR of Venice (Umgiesser, 1997; Umgiesser and Bergamasco, 1995) and successfully applied to the Venice lagoon. The finite element method gives the possibility to follow faithfully the morphology and the bathymetry of the system and to better represent the zones where hydrodynamic activity is more interesting and important, like the Nemunas delta and the Klaipėda strait. The model uses finite elements for spatial integration and a semi-implicit algorithm for integration in time. The terms treated implicitly are the divergence terms in the continuity equation and the Coriolis term, the pressure gradient and the bottom friction in the momentum equation; all other terms are treated explicitly.

1.1 The hydrodynamic equations

The model resolves the vertically integrated shallow water equations in their formulations with water levels and transports:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \zeta}{\partial x} + RU + X = 0 \tag{1}$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} + RV + Y = 0 \tag{2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{3}$$

where ζ is the water level, f the Coriolis parameter, u and v the velocities in x and y direction, U and V the vertically-integrated velocities (total or barotropic transports):

$$U = \int_{-h}^{\zeta} u\,dz \qquad V = \int_{-h}^{\zeta} v\,dz$$

with g the gravitational acceleration, $H = h + \zeta$ the total water depth, h the undisturbed water depth, t the time and R the friction coefficient. The terms X, Y contain all other terms like the wind stress, the nonlinear terms and those that need not be treated implicitly in the time discretization.

The friction coefficient has been expressed as:

$$R = \frac{g\sqrt{u^2 + v^2}}{C^2 H}$$

with C the Chezy coefficient. The Chezy term itself is not a constant but varies with the water depth as:

$$C = k_s H^{1/6}$$

where k_s is the Strickler coefficient.

At open boundaries the water level is prescribed. At closed boundaries the normal velocity component is set to zero whereas the tangential velocity is a free parameter. This correspond to a full slip condition.

The semi-implicit scheme combines the advantages of the explicit and the implicit scheme. It is unconditionally stable for any time step Δt chosen and allows the transport variables to be solved explicitly without solving a linear system. Compared to a fully implicit solution of the shallow water equations the dimensions of the matrix are reduced to one third.

The spatial discretization of the unknowns has been carried out with the finite element method, partially modified from the classic formulation. This approach was necessary to avoid high numerical damping and mass conservation problems, due to the combination of the semi-implicit method with the finite element scheme (Galerkin method). With respect to the original formulation, here the water level ζ and the velocities (transports, U and V) are described by using form functions of different order, being the standard linear form function for the water level but stepwise constant form function for the transports. This will result in a grid that resembles more a staggered grid often used in finite difference discretization (Umgiesser and Bergamasco, 1995).

1.2 The transport and diffusion module

For the computation of the transport and diffusion of a passive tracer, as well as temperature and salinity, the model provides also a module that handles these processes. To simulate the behavior of the tracer concentration the model solves the well known advection and diffusion equation, that, in the vertically integrated form, reads

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} = K_H(\frac{\partial^2 S}{\partial^2 x} + \frac{\partial^2 S}{\partial^2 y}) + Q \tag{4}$$

where $S = \int_{-h}^{\zeta} sdz$, u and v the barotropic velocities and K_H is the horizontal eddy diffusivity. The term Q reepresents a source term like a fresh water flux for the salinity or the heat flux through the water surface. Fluxes through the bottom have been neglected here.

The transport and diffusion equation is solved with an explicit time stepping scheme. The advective part uses a upwind discretization to ensure the exact conservation of mass. For very small elements the time step could exceed the time step of the hydrodynamic model, and therefore fractional time steps may be used.

1.3 The water residence times

Commonly for residence time is intended the average period water spends in a particular reservoir. Being the Curonian lagoon a non linear system and subject to matter discharge, we have to use a different approach. We consider as residence times the time necessary for a conservative dissolved substance to reduce its concentration to a factor e^{-1} from its initial value (Cucco and Umgiesser, 2006). Using the transport and diffusion module described in the precendent section, the temporal variation of the concentration C of a dissolved conservative substance for each elements of the lagoon has been determinate.

The time series of the cencentration for every node of the basin have been approximated by a exponential decay equation:

$$C(t) = C_0 e^{-t/\tau} \tag{5}$$

where C_0 is the initial concentration, t the time and τ is the residence time as definite below. As it can be seen, τ is the time it takes to reduce the initial C_0 by a factor e^{-1}. Taking the logarithmic formulation of the decay equation, we get:

$$y(t) = log(c_0/c(t)) = \alpha t \tag{6}$$

with $\alpha = 1/\tau$. In this way the value of α is computed by a simple linear regression problem. Solving it for all the grid points, the residence times distribution can be found.

1.4 The numerical grid

The finite element model has to be supported by a numerical grid. This grid consist of nodes and triangular elements, with variable dimension, that describes the geometrical layout of the basin. Using a finite elements method, that allows the use of elements with variable dimension, it has been possible to describe the area close to the Nemunas Delta and the Klaipėda strait with a higher resolution.

The resulting grid, constructed with an automatic mesh generator, contains of about 2500 nodes and 3800 triangular elements in showed in figure 1. In is easy to see the gradual decreasing of the triangular element dimensions in the area close to the Nemunas delta and in the Klaipėda strait.

To the grid have been added the depth (data where available on a regular grid with mesh of 100 meters) obtaining the bathymetry showed in figure 2.

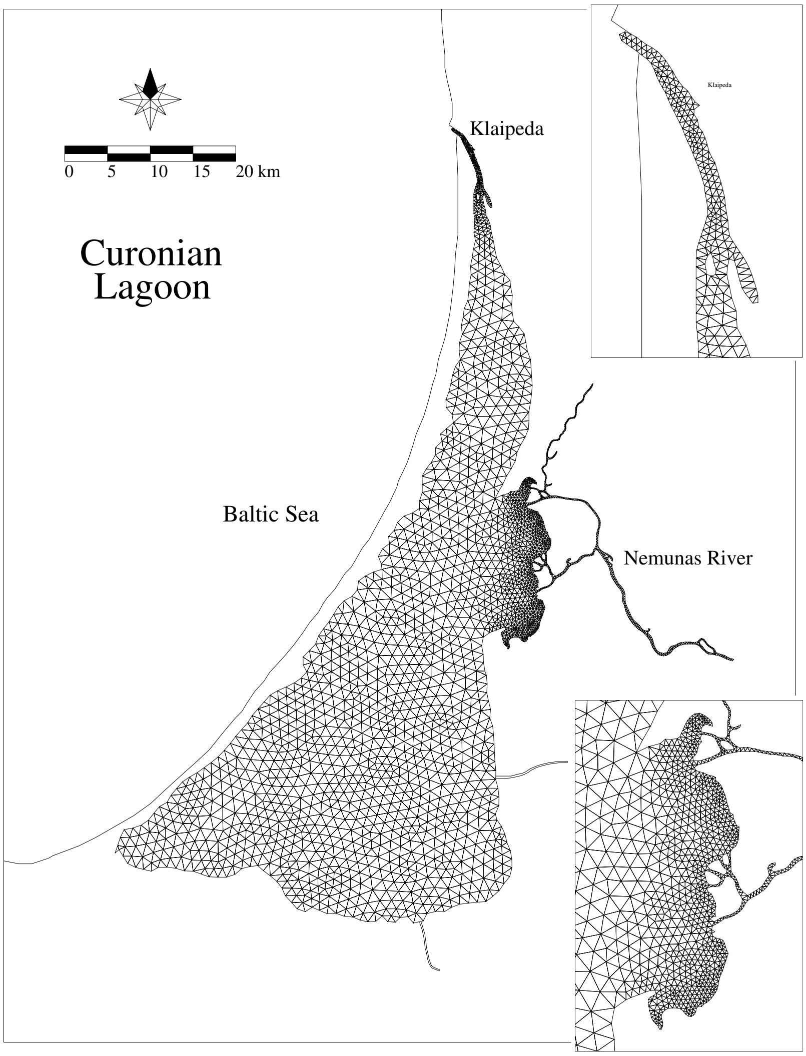

Figure 1. Computational grid of the Curonian Lagoon and a part of the Nemunas River. In the small windows are showed the areas with higher resolution.

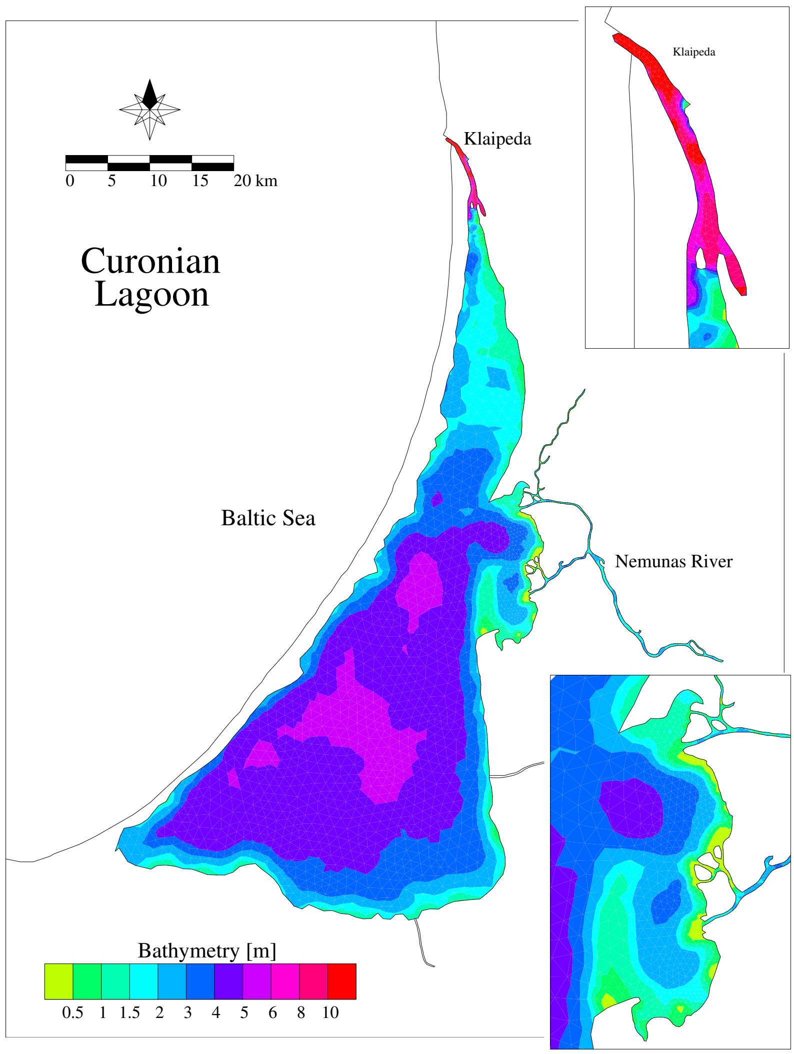

Figure 2. Bathymetry of the Curonian Lagoon as computed by the model.

2 Data analysis

We have just to remember that for a good modelling study good data are needed. Good model are not usefull if they use bad data. The data as great importance as the model itself. The principal forcings the Curonian lagoon is subjected to are the wind and the Nemunas river. Other factors which influence temperature and salinity are the sea water inflow, rain, evaporation and radiative forcing.

Luckily for the Curonian lagoon a lot of data where available to be used as input for the model and for the calibration and validation. Unfortunaly the data ware available only for the lithuanian part of the lagoon and not for the russian one.

Figure 3 shows the position of the stations where data were available.

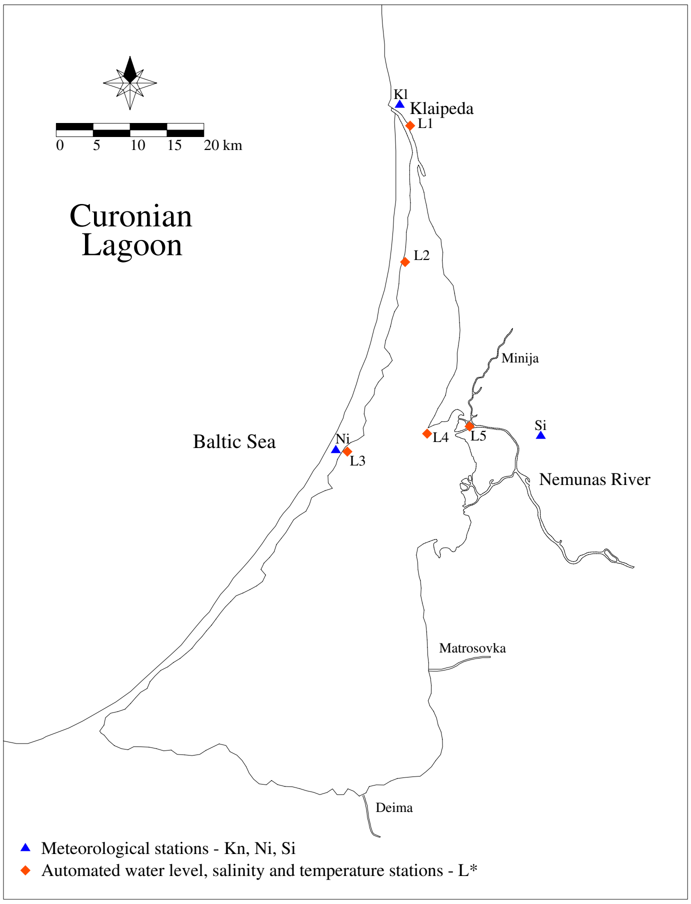

Figure 3. Data station used as input in the model: $L*$ = water level stations, $Km*$ = current velocity and direction, salinity and water temperature stations, Kl and Ni = meteorological stations.

In table 2 are reported the coordinates of the station.

The Nemunas river discharge data where available for several year from a station placed in Smalininkai (more then 110 km up to the delta). These data as to be rearranged to consider the time that the water takes to arrive to the delta. By a comparison of the current velocity and the river discharge, measured in Smalininkai, was possible to find out this time dalay, that can be approssimated by a logaritmic function of the discharge (as shown in figure 4):

Being Smalininkai let say 90 km from the point in which the discharge is prescribed in the model, and considering a costant current velocity of 0.5 m/s the water takes about 50 hours to arrive at the delta. Moreover because of the data taken in Smalininkai don't take into account the tributaries which flow into the Nemunas river in the last part of it, the discharge has been increased by the 15 % of the discharge measured in Smalininkai.

station		*Coordinate*			
type	name	Lat	Lon	x	y
Huorly	Klaipėda sau.				
Water lev,	Klaipėda sas.	55 55'1	21 07'18		
sal, temp	Juodkrante	55 31'9	21 07'6		
	Nida	55 17'9	21 00'81		
	Vente	55 20'0	21 10'2		
	Uostadvaris	55 20'7	21 17'4		
Montly	Km1	55.4350	21.0570	317533.27	6180541.52
Sal, temp,	Km2	55.4170	21.0790	319691.77	6177144.01
current	Km3	55.3900	21.0820	319768.50	6172061.70
	Km5	55.3190	21.0760	319976.40	6158873.52
	Km8	55.2500	21.0720	317675.59	6146136.01
	Km10	55.1190	21.0080	315422.21	6133066.42
	Km12	55.2000	21.1020	320261.04	6136766.70
	Km14	55.1560	21.0640	316121.94	6128761.28
Meteo	Klaipėda				
	Nida				

Table 1
Coordinates of the station

For the Nemunas river water temperature data were available too.

2.2 Baltic sea - lagoon exchange

There are few data about the water mass fluxes trohght the Klaipėda strait, only some montly measures. Then those has not been used as input for the model. As boundary condition we use water level data from Klaipėda Sausin. From the same station data about water temperature and salinity were available.

2.3 Meteorological forcing

The most probable winds on the Lithuanian coast are south-west, west and south-east Davulienė et al. (2002). These winds, with constant intensity of 10 m/s, have been imposed whole over the lagoon to simulate the circulation pattern evolving under different conditions.

Moreover meteorological data from the meteorologic station placed in Klaipėda and Nida (point *Kl* and *Ni* in figure 3) have been used whole over the lagoon. The solar radiation data, being not available, has been computed using wind speed, air temperature, pressure, humidity and cloud cover data measured in Klaipėda (see Ferrarin (2002) about the solar radiation computation).

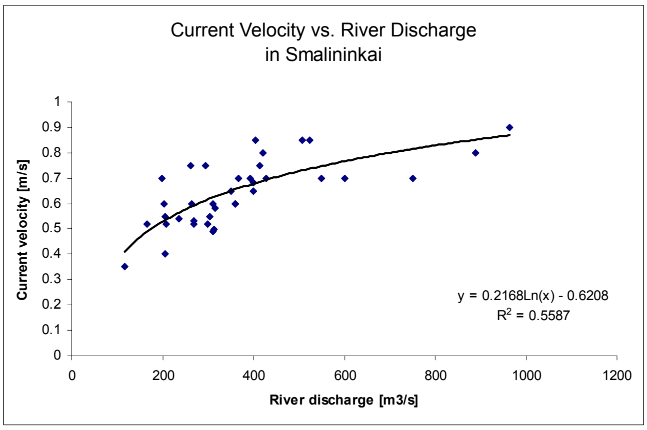

Figure 4. Relation between the current velocity and the river discharge in Smalininkai. The water arrived to the Nemunas delta with a dalay respect to Smalininkai which depend on the velocity, and then to the discharge.

2.4 Calibration data

To calibrate and validate the hydrodynamic model is necessary to compare the simulation results against experimental data. Water level, salinity and water temperaure data from 3 station inside the lagoon (points *L2*, *L3*, *L4* and *L5* in figure 3) has been used. Moreover some current speed and velocity, salinity and water temperature data were available, with montly frequency, for other station inside the lagoon (points *Km** in figure 3).

3 Numerical simulation

The lagoon open boundaries are the Nemunas river and the end of the Klaipėda strait. For the first one, daily values of the discharge (in m^3/s) from Smalininkai (adjusted in function of the delay)while for the second one hourly water level data measured in Klaipėda (point *L1* in figure 3) have been imposed to the model.

All simulations have been carried out with a time step of 300 s. The initial condition is always the calm state. This is certainly no problem for the current velocity and the water level, since these quantities approach a dynamic steady state very fast (less then a day). For the salinity and temperature variables a costant average value has been chosen as initial condition and the model was allowed to go to stady state for 2 months.

3.1 Hydrodynamic circulation

The lagoon water circulation is predeteminated essentially by the wind and by the Nemunas river discharge. By a hydrodynamic point of view the Curonian lagoon can be divided into two parts: the norther one which is heavy influenced by the Nemunas river and the souther one where the wind is the main driving factor (figure 5).

In the southern part of the lagoon the current regime is mainly driven by the wind which, depending on its direction and speed creates different circulation sub-systems. Simulations carried out using constant wind from different directions showed the presence in this area of a circulation structure similar to the one reported by Davuliene Davulienė et al. (2002). In most cases the system evolves into a dominant gyre, with anticlockwise (wind from west, figure 6a) and clockwise (wind from south-east, figure 6c) direction, and some smaller gyres. In case of south-west wind, the circulation pattern is characterized by a two-gyre system (figure 6b).

The water level in the lagoon usually higher then in the Baltic sea (literature data report that the mean water level in the lagoon is 12 cm higher than in the Baltic Sea (Svazar et al., 1999)), due to the Nemunas fresh water input, there is a south-north current that moves from the Nemunas delta to the north towards the Klaipėda strait and sometimes widening till the middle of the central part of the lagoon (figure 7a). This current is usually more evident during the spring period, when the ice melts and the river discharge reaches the highest values. During these periods the Klaipėda strait is caraterizated by an uniderectional flow of fresh water from the lagoon to the baltic sea with current speed in the order of 1.5-2 m/s. Such values agree with the ones

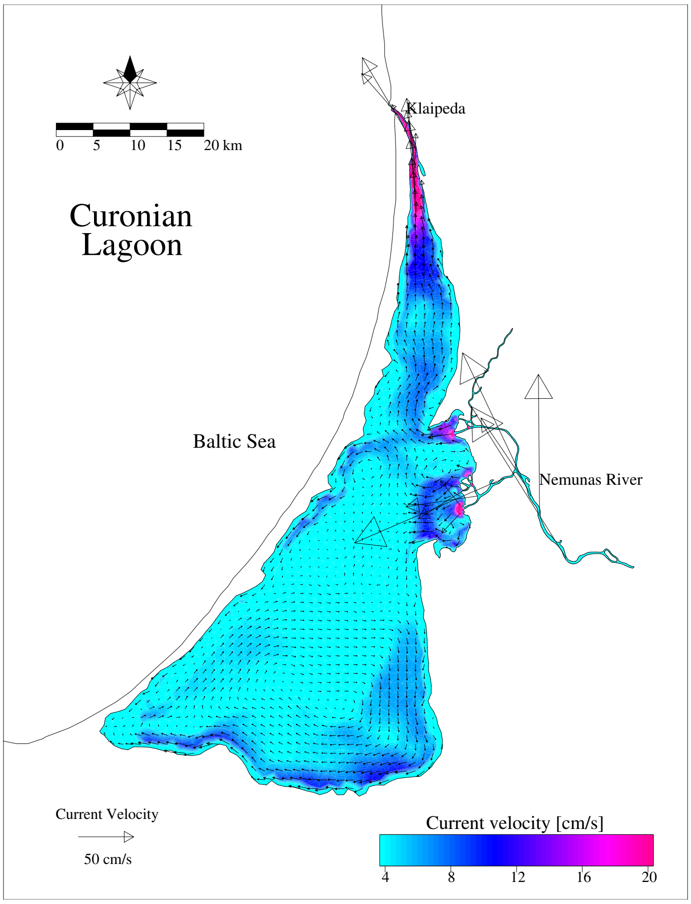

Figure 5. Water circulation field in the Curonian Lagoon (March 1999).

reported by Pustelnikovas Pustelnikovas (1998). Anyway, in case of strong north or north-west winds and small river discharge the salty sea water is pushed into the lagoon and during extreme wind events it penetrates deep southward into the lagoon (figure 7b).

To characterize better the area of interaction between these two forcing factors on the hydrodynamic of the Curonian lagoon we computed the daily root mean square (RMS) of the current velocity considering the Nemunas river and the wind separately. A river discharge of 1500 m^3/s (corresponding to a spring situation) and a south-east wind with constant intensity of 8 m/s has been consider in these simulations. According to the simulation results (figure 6a and 6b), the Nemunas river effect is relevant only in the northern part of the lagoon, particularly in the Klaipėda strait, while the wind is the main factor deciding the water circulation over the whole lagoon. From the comparison of these two figures it is evident that, at high river discharge, in the Klaipėda strait the water current forced by the Nemunas river has higher velocity than the one generated by the wind.

It has been reported by some authors that in the in case of calm weather

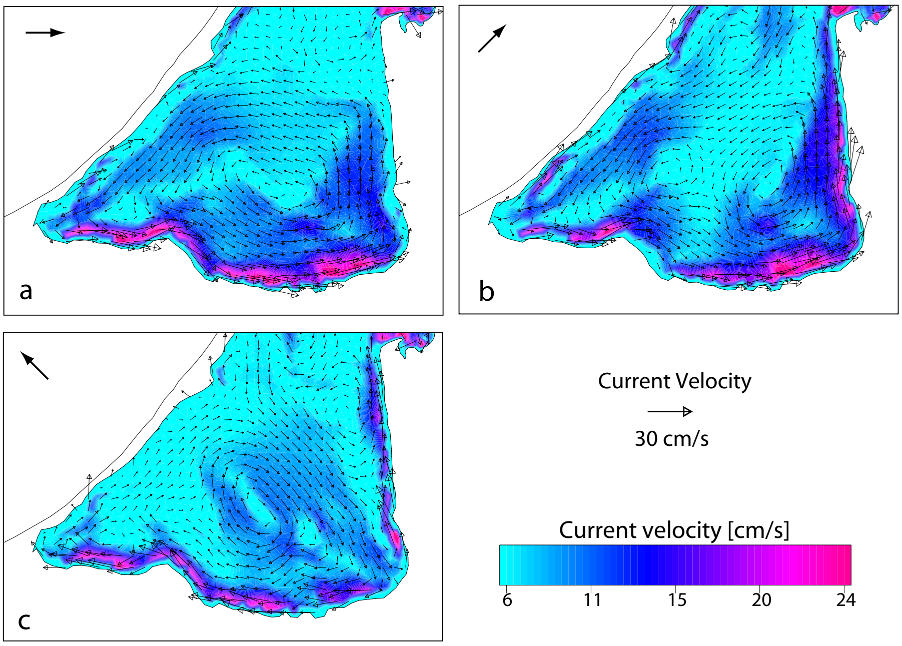

Figure 6. Wind driven circulation in the southern part of the Curonian lagoon. a) west wind, b) south-west wind, c) south-east wind [wind intensity = 10 m/s].

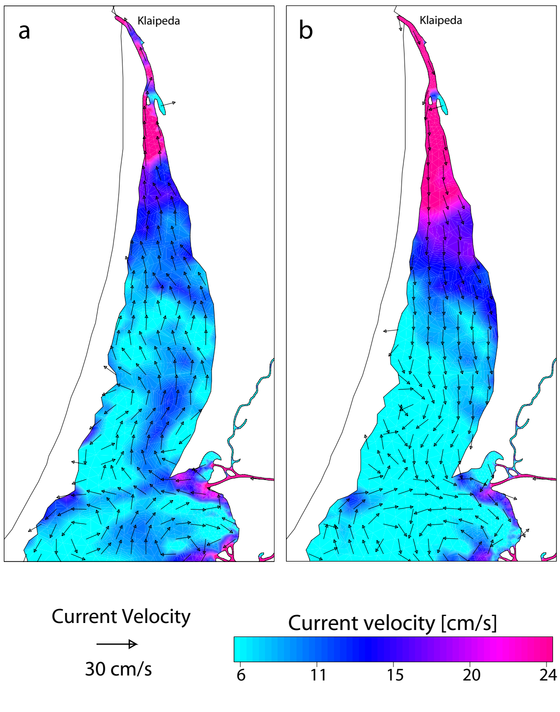

Figure 7. Water current field in the northern part of the Curonian lagoon. a) outgoing flow (situation with high Nemunas discharge), b) ingoing flow (situation with strong north wind).

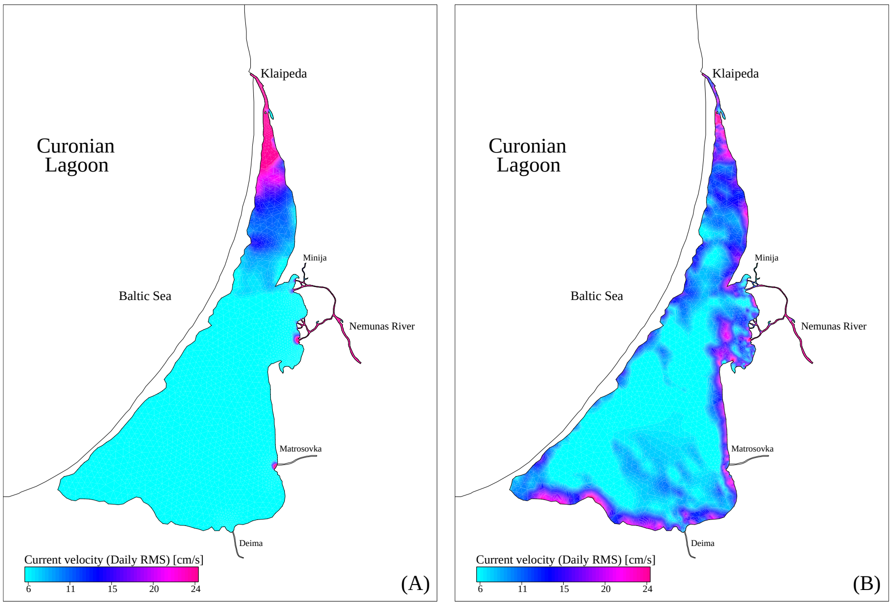

Figure 8. Daily RMS current velocity: a) case with Nemunas river; b) case with wind. The Nemunas river influences only the northern part of the lagoon, while the wind acts on the whole basin.

and negligible sea level differences between the lagoon and the sea (especially in summer time), a two-layer movements exists in the Klaipėda strait: fresh water of the lagoon flows on the surface layer out into the sea and, at the same time, in the deeper layer, heavier water flows from the sea to the lagoon (Pustelnikovas, 1998; Žaromskis, 1996) This dynamic has not been described here by the 2-D model, but it is hoped to reproduce it in the future using the 3-D version hydrodynamic model.

3.2 Water level

Model results are generally in good agreement with the available water level data from 3 station inside the lagoon (points *L2*, *L3*, *L4* and *L5* in figure 3). Figure 9 shows the one year time series of the numerical results and the experimental data.

The long term, seasonal and synoptic, water lavel fluctuations in Baltic Sea influence the simulated water level in the whole basin. The hight value measured and simulated during the spring period are due to the Nemunas river, which with its hight fresh water input increse the water level in the whole lagoon. Thus to a Nemunas discharge peak usually correspond a water level increase in the lagoon. During this floding period are found the greathest differences between model results and experimental data, because due to hight river dischrge the delta area is innunded and the increasing of the basin area is not simulated by the model. For the same reason the simulated water levels result to be in all the station hygher than the one measured in the same points.

Differences between the 3 stations are essentially due to the wind, which in function of its direction and speed, models the water surface elevation in the lagoon.

3.3 Salinity and temperature

A one year simulation has ben run to reproduct the salinity and the temperature field in the lagoon. This simulation is quite important for verifying that the model simulates properly the transport and diffusion processes. The heat

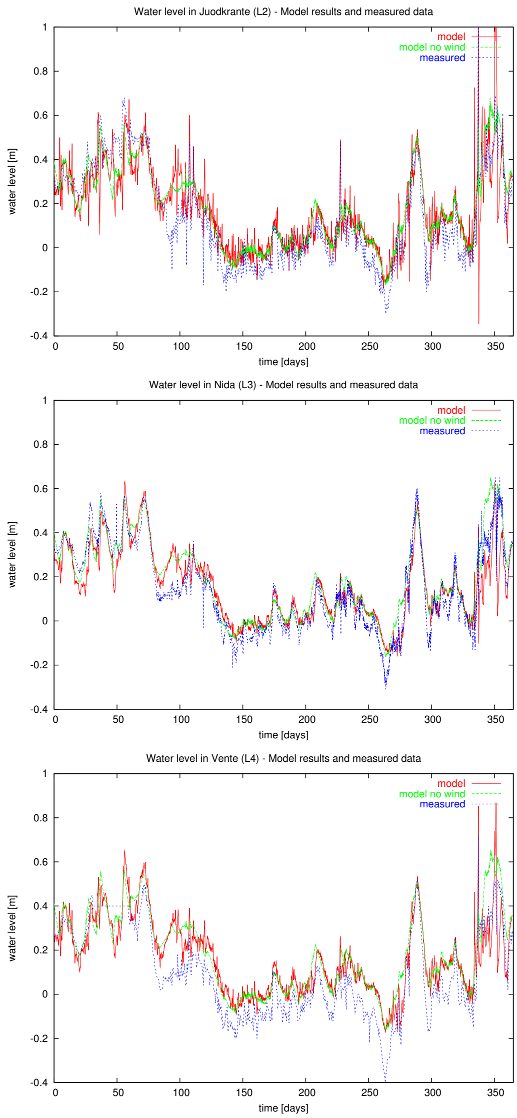

Figure 9. Water level: numerical results and experimental data in 3 station inside the lagoon [year 1999].

flux through the water surface, important for the temperature evolution, has been modeled through the application of a radiative module that simulates the exchange of heat between the atmosphere and the sea water (Zampato et al., 1998).

The years of reference are 1999 and 2000. For those periods experimental salinity and temperature data for comparison from 8 stations inside the lagoon (points *Km** in figure 3) were available.

The seasonal cicle of the water temperature is well reproduced by the model as confirmed by the comparison between model results and experimental data. Inside the lagoon there are small spatial differences due essentially to the colder fresh water caming from the Nemunas river and the salty water caming from the Baltic Sea. Being the seasonal water temperature variation lower in the Baltic Sea than in the Curonian Lagoon (due to the low thermal inertia of the shallow water lagoon) during the winter time there is, in case of north, north-west wind, an inflow of wormer salty water into the lagoon.

3.4 Residence times

To compute the water residence times in the Curonian Lagoon, a passive tracer has been released into the basin with an initial concentration of 100 % over all the lagoon. Under the action of the forcings (Nemunas river discharge, wind and flux throught the Klaipėda Strait), the tracer leaves the lagoon exiting through the inlet. This leads to a time decaying of its concentration. The rate of concentration decaying in a given area depends both on the distance from the inlet and on the activity of the local water circulation.

The Nemunas river discharge creates a watershed like boundary which divides the lagoon into two parts: the northern one that, being highly influenced by the Nemunas river and connected with the Baltic sea, has a hight water exchange; the southern one which is not subjected to an adeguate water renewal.

3.5 Model calibration and validation

Calibration of the hydrodynamic model has been performed changing the value of the bottom friction factor (equation 1.1). With the use of the element index different areas have been identified that have been given different values of the Strickler coefficient. The hydrodynamic model has been calibrated by changing the Strickler coefficent and comparing model output against experimental data of water level from 4 station inside the lagoon (points *L2*, *L3 L4* and *L5* in figure 3). Initially the default value of the Strickler coefficient has been set

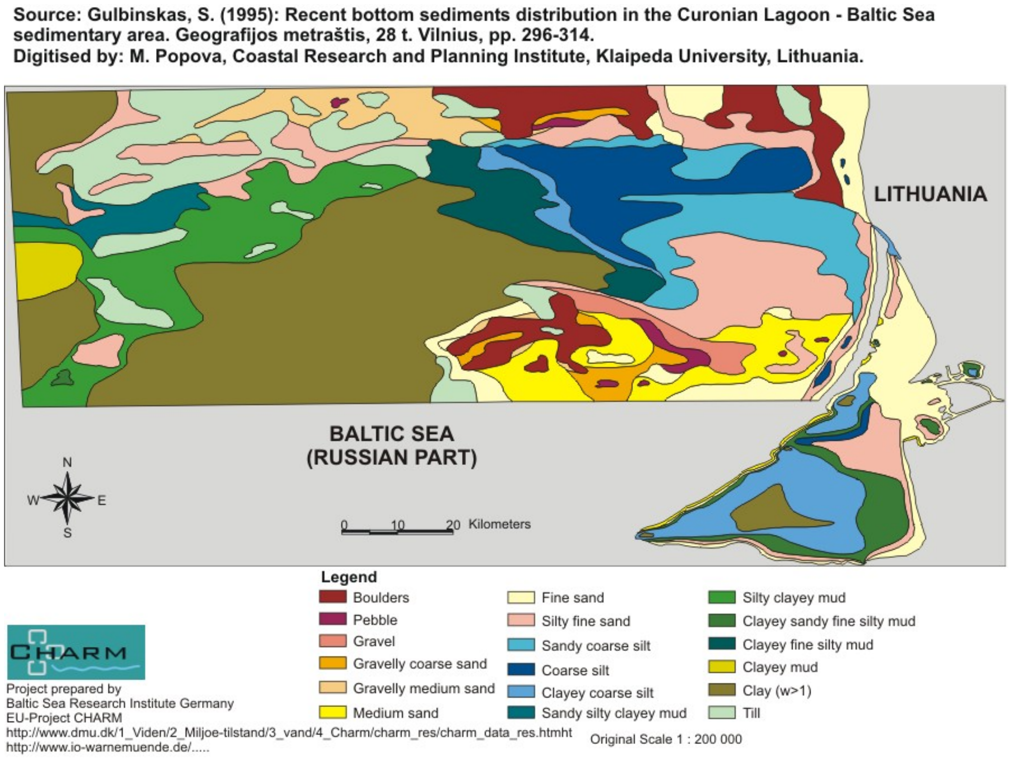

Figure 10. Recent bottom sediment distribution in the Curonian Lagoon - Baltic Sea sedimentary area. Gulbinskas, 1995.

to 30. For the calibration simulations real forcing data of the year 1999 data have been used.

A first simulation was carried using the value of 30 for the Strickler coefficient which is a standard value reported in literature. The results of this sumulation show that the model well reproduce the experimental water level data in all the 3 stations.

To improve the model results we assign different Strickler coefficient for different areas. This zone distinction was based on the bottom sediment distribution in the Curonian lagoon (Gulbinskas, 1995) shown in figure 10. For the main sediment type a different value of the Strickler coefficient has been assigned.

By comparing the model results with observed water level data measured in four station inside the lagoon the final Strickler coefficient have been found. The model results show good agreenment with the experimental water level data in all the 3 stations.

The Klaipėda wind data being measured every 3 hours give more fluctuation that the one from Nida (by Lina). The wind intensity in Nida is usually lower than the ones measured in Klaipėda. The wind Dragg coefficient has been change too. A drag coefficient of 0.0018-0.0021 gives better results.

It seams that without wind the results are better during the winter period. The explanation of this fact can be that during that period probably the lagoon was frozen and the wind had no action on the water surface.

The measured water level in Vente and Joudkrante are always lower than the one in Klaipeda and Nida. This seams to be a sistematic error in the measurements: Joudkrante +5, Vente +7. Inga Dailidiene from the Klaipėda Center of Marine Research confirmed that the data in Vente and Joudkrante have sistematic error of about 6 cm.

Further outlook

A future step could be the implementation of a water quality model that will run in parallel with the finite element hydrodynamic model and will describe the fundamental nutrients and phytoplankton dynamics of the lagoon.

Moreover it could be intersting to study the sediment transport dynamics of the Curonian Lagoon with a sediment transport model that is currently under development.

Acknowledgements

The authors want to thank the CNR - Short term mobility for the funding of this research.

References

Cucco, A., Umgiesser, G., 2006. Modelling the Venice Lagoon residence time. Ecological Modelling 193, 34–51.

Davulienė, L., Davulienė, I., Dick, S., Trinkūnas, G., Valkūnas, L., 2002. Validation of the circulation model for Lithuanian coastal waters. Journal of Environmental and chemical Physics 24(4), 226–231.

Ferrarin, C., 2002. Studio dell'idrodinamica e della qualità delle acque dello Stagno di Cabras. Master's thesis, University Ca' Foscari, Venice, pp 141.

Gulbinskas, S., 1995. Recent bottom sediment distribution in the Curonian Lagoon -Baltic Sea sedimentary area. Geografijos metraštis 28 t., 296–314.

Pustelnikovas, O., 1998. Geochemistry of sediments of the Curonian Lagoon. Institute of Geography, Vilnius, Lithuania.

Svazar, S., Drobelis, E., Balciauskas, L., Raudonikis, L., 1999. Important wetlands in Lithuania. Ompo Vilnius, Vilnius, Lithuania.

Umgiesser, G., 1997. Modelling the Venice Lagoon. International Journal of Salt Lake Research 6, 175–199.

Umgiesser, G., Bergamasco, A., 1995. Outline of a Primitive Equations Finite Element Model. Rapporto e Studi, Istituto Veneto of Scienze, Lettere ed Arti XII, 291–320.

Zampato, L., Umgiesser, G., Peron, F., 1998. Sviluppo di un modello di scambio termico all'interfaccia acqua-aria nella Laguna di Venezia. Tech. Rep. 221, ISDGM/CNR, Venice, pp 33.

Žaromskis, R., 1996. Okeani Juros Estūarijos. Geografijos Institutas, Vilnius, Lithuania, in litunian.