MODELLING OF THE RESPONSE OF THE RAZELM-SINOE LAGOON SYSTEM TO PHYSICAL FORCING

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Abstract. Human interventions have drastically altered the hydrologic regime of the Razelm - Sinoe Lagoon System. Over the past four decades, following the closure of the main inlet (Gura Portiței) and the engineering of the other main communication inlets and channels, significant changes have occurred in the hydrological regime. This major disruption of the water and sediment circulation generated, at its turn, significant changes of the water chemistry, biology and lagoon ecosystems, transforming the system in eutrophic environment with all related consequences. Due to the significant decrease in sediment load transported along the coastal zone, the barrier beach separating the Lagoon System from the Black Sea is almost entirely subject to coastal erosion. Environmental improvement and rehabilitation is already a major demand of the local communities. Nevertheless, environmental recovery plans must be based on the detailed understanding of the water circulation in the lagoon system. This can be achieved only by the involvement of numerical modelling.

Simulations have been performed using the hydrodynamic model SHYFEM, in order to obtain a response of the Razelm - Sinoe Lagoon System to the main forcings. The results show that the salinity distribution in the Lagoon System is, mainly, controlled by the freshwater discharge and, secondly, by wind, which can intensify the freshwater input. The calculated renewal times of the Razelm - Sinoe Lagoon System are very high, over one year, and classify the lagoon as a chocked system.

This work represents a first step towards the detailed quantitative study of this sensitive part of the Danube Delta Biosphere Reserve.

Key words: lagoon system, hydrodynamic model, discharge, simulation, salinity

INTRODUCTION

Coastal lagoons worldwide have been subject to ever increasing pressures from human activities. Humans profoundly affected the state of the ecosystems, contributing to the massive depletion of natural resources and affecting a major part of the services provided by the lagoons ecosystems. The Razelm - Sinoe Lagoon System, from the Danube Delta Biosphere Reserve Administration is no exception to this general trend. Once among the richest coastal environments from the north western part of the Black Sea, the 1000 sq.km. lagoon system attached to the southern part of the Danube Delta has been significantly affected by all possible types of human interventions. The dredging of the channels connecting the lagoon system to the southern arm of the Danube, the closure of the Portița Inlet and the engineering works, almost permanently blocking the connections between the various parts of the lagoon system, as well as those between the 2 inlets of the Sinoe Lagoon and the sea, have changed its natural evolution (*e.g*. Stănică, 2012).

The Lagoon System (Fig. 1), originally, a marine bay (the former Halmyris Gulf), became isolated from the sea by the accumulation and redistribution of sand bars. Detailed studies have been presented by a series of authors, the most recent and significant ranging from Panin (*e.g*. 1996, 1998, 1999) to Giosan *et al*. (2006) and Vespremeanu-Stroe *et al*. (2013). Due to the complex evolution of the interaction between the Danube and the Black Sea, the area has been fragmented into many semi-independent lakes, marshes and lagoons. The Razelm - Sinoe Lagoon System is connected with the Sf. Gheorghe arm of the Danube Delta *via* the Dunavăț and Dranov channels.

The main lakes of the Razelm Unit are: Razelm (with a maximum depth of 3.5 m), Golovița and Zmeica. The maximum depth of the Sinoe Lagoon is 2.5 m. The Razelm - Sinoe Lagoon System has a lobate shape and contains a series of fossil barrier beaches interrupted by inlets that separated large bays. Active and relict littoral bars separating the lakes and lagoons consist of Danube-born fine sands and extend for tens of kilometers.

The Razelm - Sinoe Lagoon System was not affected by human interventions till the end of the XIXth Century. As shown by many authors (from Antipa, 1894 to Staras, 2000; Bretcan *et al*., 2008 and others), this was the moment when a succession of major categories of human interventions started to happen. Then, following the dredging of the Dunavăț and Dranov channels as connections with the Danube River, which ended up at the beginning of the XXth century, more freshwater discharged to the lagoon system. During the 1950s, management plans were made to decrease the salinity of the lagoon system waters, in order to increase the (freshwater) fish culture productivity. In the 1960 – 1990 interval, the lagoon suffered severe changes, becoming, partially, a human-controlled hydrotechnic system with a main function in irrigations and a secondary one for fish breeding. Thus, in 1973, the Portița Inlet of the Razelm Lagoon was completely closed by a system of breakwaters and groins, while the northern barrier beach of the inlet was consolidated with a seawall made of earth and clay. In the sector situated south of the former inlet, due to the hard coastal defence structure, the erosion increased in intensity (Spătaru, 1990; Vespremeanu-Stroe *et al*., 2007). The water circulation between the Sinoe Lagoon and the Black Sea is controlled by the Periboina and Edighiol Inlets. The water discharge from the Razelm Lake to the Sinoe Lake is achieved via the artificial canals nos. II and V. In recent years, Canal V has been left open. Permanent circulation between the sea and the Sinoe Lagoon was also restored by the beginning of the years 2000.

All these anthropic interventions in the natural aquatic system have triggered complex changes of the hydrologic regime, of the depth and sediment structure and of the water chemistry and biology.

The coastal erosion affects almost entirely the barrier beach separating the Lagoon System from the Black Sea, except for the northern and southern extremities. Erosion here has been also enhanced by human interventions, in the Danube hydrographic basin, by cutting the sediment supply, and by building major coastal structures (Ungureanu and Stănică, 2000).

Therefore, a study of the Razelm - Sinoe Lagoon System, its water dynamics and the relationship with the Danube and Black Sea could be significantly improved by the use of numerical modelling, in order to estimate its behaviour under various forcing.

We present herein the results of simulations using the SHYFEM model. The purpose of these simulations was to use the available data in order to understand the response of the Lagoon System, as well as the theoretical renewal times under the main forcings represented by water level, freshwater discharge, wind, salinity and temperature.

METHODS

Model description

The SHYFEM model (Umgiesser *et al*., 2004; Umgiesser, 2010) has been developed at the Institute of Marine Sciences in Venice and it is based on the method of the finite elements to solve the hydrodynamic equations in lagoons, coastal seas, estuaries and lakes. The model was applied in several cases around Europe (see *e.g*. Ferrarin and Umgiesser, 2005; Bellafiore *et al*., 2008; Ferrarin *et al*., 2008; De Pascalis *et al*. 2009 and 2012, Umgiesser *et al*., 2014), as well as on the Black Sea and the Romanian Black Sea Coast (Tescari *et al*., 2006; Dinu *et al*., 2013; Bajo *et al*., 2014).

The shallow water equations are:

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

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

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

where η is the water level [L], U and V are the vertically-integrated velocities (total transports) [L^2T^{-1}] in x and y directions, t is the time [T]; g is the gravity acceleration [LT^{-2}]; $H = h + \eta$ is the total water depth and h is the undisturbed water depth [L]; R [T^{-1}] is the friction parameter and f is the variable Coriolis parameter [T^{-1}]. The terms X and Y contain all the terms, such as wind stress and the non-linear terms, that do not need to be treated implicitly in the time discretization.

The bottom friction term is defined as:

$$R = c_B \frac{|u|}{H}$$

In the equation above, u is the modulus of velocity, c_B is the non-dimensional bottom friction parameter, that can be assumed constant or depth-dependent by the Strickler formula, as follows:

$$c_B = \frac{g}{C^2} \quad \text{and} \quad C = k_s H^{\frac{1}{6}}$$

where C is the Chézy coefficient [$L^{1/2}T^{-1}$] and k_s is the Strickler coefficient [$L^{1/3}T^{-1}$] (Umgiesser, 2010).

The computation of the salinity field is based on the transport and diffusion equations:

$$\frac{\partial S}{\partial t} + \frac{\partial uS}{\partial x} + \frac{\partial vS}{\partial y} = K_H \left(\frac{\partial^2 S}{\partial^2 x} + \frac{\partial^2 S}{\partial^2 y} \right)$$

where S is salinity [psu], u and v are the barotropic velocities [LT^{-1}] and K_H [L^2T^{-1}] is the horizontal eddy diffusivity.

In order to compute the renewal time, the methodology of Cucco and Umgiesser (2006) can be applied. A conservative tracer is released inside the basin and its fate is monitored how it decreases in the basin due to incoming freshwater fluxes and water from the Black Sea. If the initial concentration of the tracer is P_0=$P(0)$, and $P(t)$ is the time varying tracer concentration, then it can be shown (Cucco and Umgiesser, 2006) that the renewal time can be written as

$$\tau = \int_0^\infty P(t) / P_0 dt$$

What is, therefore, to be done is to integrate the concentration for a certain time and compute for every point in the basin the time scale τ which represents the renewal time. If after the integration period the concentrations have not gone to zero, some corrections have to be made to the integral. The way to do this is also described in the above-mentioned article.

Data

Sinoe Lagoon is connected to the Black Sea through the Periboina and Edighiol inlets. The sea water level varies between 0.5 and 0.92 m. The salinity time series near the inlets show values ranging between 8.93 and 18.77 psu. The sea water temperature near the inlets ranges between 0.2 and 27.5°C. Time series of water level, salinity and water temperature have been introduced as boundary conditions at the locations of the inlets.

Wind data were available from the National Administration of Meteorology. Wind measurements were taken every 6 hours at the Midia coastal point, located south of the Razelm - Sinoe Lagoon System. The maximum wind speed is 16 m/s and the most frequent wind direction is from north.

Discharge data into the Razelm Lagoon were provided by the Danube Delta National Institute and are the results of modelling, taking into account discharges along Sf. Gheorghe branch and distribution towards Razelm - Sinoe Lagoon System. A combined 1D-2D model has been used to estimate the discharge into the lagoon system. Calibration of the hydrological model has been done through the roughness factor. The computation has been made for the hydrological extreme regimes of the Danube (2003, for minimum levels and 2006, for maximum levels).

The available discharges into the Lake Razelm from the Sf. Gheorghe distributary of the Danube, *via* the Dunavăţ, Mustaca and Dranov channels (see Fig. 1), are summarized in Table 1. The daily discharge time series are prescribed at the corresponding locations of the junctions between the channels and the Lake Razelm.

Data from 2003, 2004 and 2006 were selected as they are representative to the various water discharges in the Danube watershed – the Danube Delta, respectively. If 2004 can be considered as "normal" from the point of view of water discharges, 2003 and 2006 are significant extremes. The year 2003 was characterised by very low waters in the Lower Danube and the Danube Delta. 2006 was the opposite, as it marked record high water levels over the past century.

Therefore, the data are relevant to understand the behaviour under normal, but also extreme draught and high water conditions.

During 2003, the year with low water discharge, the discharge into the Lake Razelm was higher during winter and spring, reaching almost 30 m^3s^{-1} on Dranov channel, in January, then, decreased to lower values, then, increased again, in October - November, only to decrease to negative values, in December. These negative values indicate that the flow from

Table 1. Discharges (m^3s^{-1}) into the Lake Razelm from the Sf. Gheorghe distributary of the Danube (positive values – inflow; negative values – outflow)

Year	Dunavăţ channel		Mustaca channel		Dranov channel	
	Min/Max	Average	Min/Max	Average	Min/Max	Average
2003	-9.89 / 28.00	11.37	-9.22 / 13.41	4.45	-14.53 / 29.78	9.91
2004	-4.25 / 37.14	15.84	-4.09 / 18.83	6.86	-5.88 / 41.95	15.12
2006	-7.62 / 51.26	22.82	-7.17 / 27.42	10.9	-10.86 / 59.30	23.92

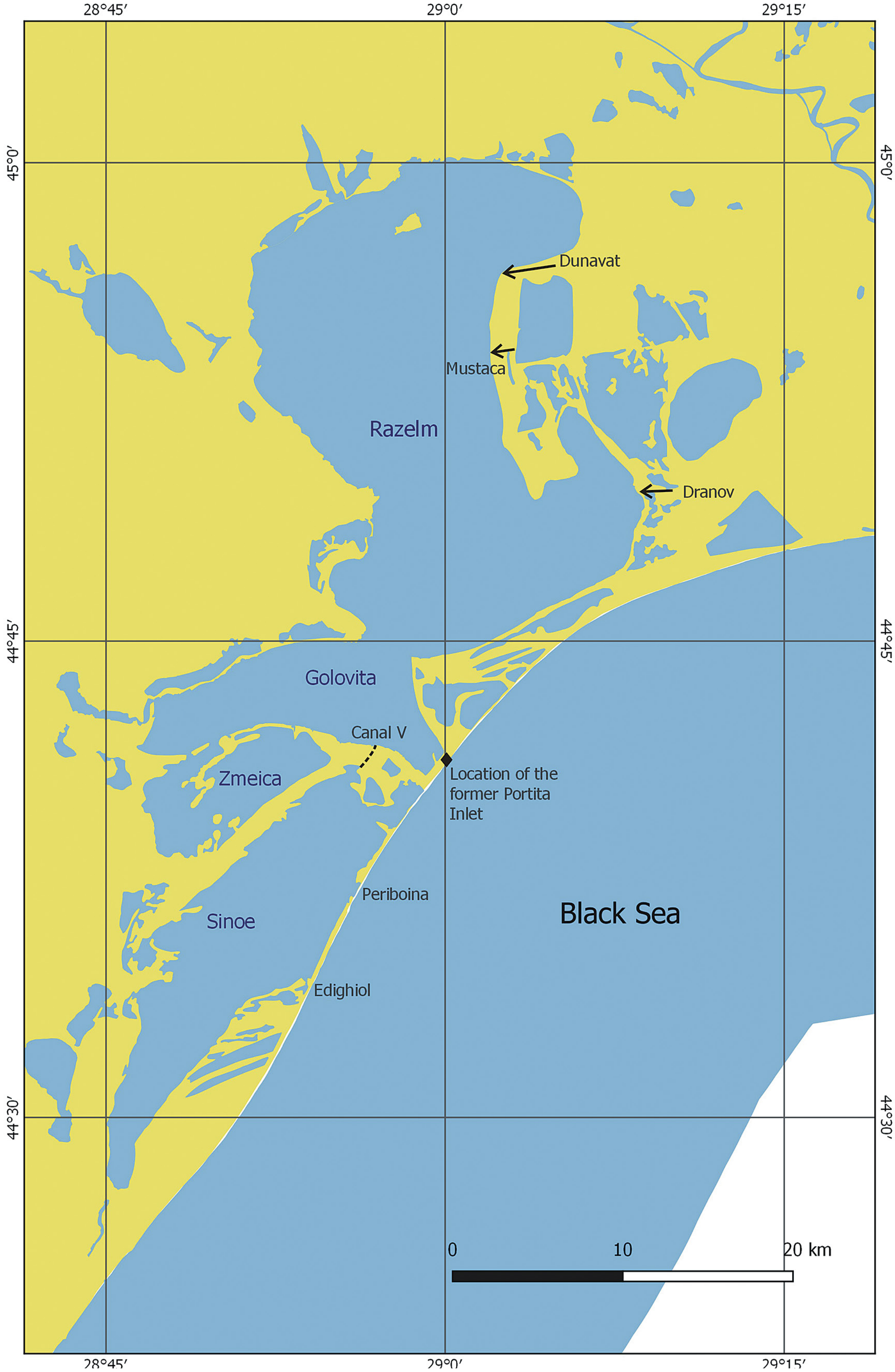


Fig. 1. Location of the Razelm-Sinoe Lagoon System

the Danube to the lagoon reverses and that water is withdrawn by the Danube River out of the lagoon.

During 2004, which is a year with average values and variation of the water discharges along the Danube, the discharge into the Lake Razelm showed high values in the first half of the year. In that interval, it reached more than 40 m^3s^{-1} on Dranov channel, then, it decreased to low and even negative values in August - September. Another increase occurred in November - December, but to lower values than those during the first part of the year, and, finally, decreased to negative values, in December.

During 2006, the year of high discharges, the discharge into the Lake Razelm showed moderate values at the beginning of the year, than it rose abruptly, reaching almost 60 m^3s^{-1} on Dranov channel, and then, decreased to low and even negative values, in the second half of the year. The time interval with high discharge values was longer than in 2003 and 2004, from the end of March to the beginning of July.

The average discharges reported on Table 1 show that, in our analysis, we can roughly consider 2003 as a low-discharge year and 2006 as a high-discharge year, while 2004 is a more or less medium discharge year.

The discharge of the Dranov channel for the years 2003, 2004 and 2006 is shown on Fig. 3.

Simulations setup

The grid of the Razelm - Sinoe Lagoon System (Fig. 2) has been built the SHYFEM modelling framework. The coastline of the lagoon system and the bathymetry data have been provided by GeoEcoMar, as well as daily discharge data on the Dunavăț, Mustaca and Dranov channels. The Canal V that connects the Lakes Razelm and Sinoe is represented by 1.5 m depth elements.

For the salinity simulations, in order to eliminate the dependence on the unknown initial conditions, the input data for every year is replicated three times. The model was, therefore, run for three years (every year having the same input data) and only the last year was analysed. In this way, the spin-up of the system was 2 years, an interval considered to be long enough to reach a dynamic steady state condition.

In order to calculate the water renewal times in the Razelm - Sinoe Lagoon System, we performed 3 one-year-long simulations. As discharge data were not available for 3 consecutive years, we ran the SHYFEM model in low, medium and high discharge conditions, based on the data from 2003, 2004 and 2006, respectively, computing the residence time for each of these years, separately.

The maximum time step was set to 300 s, and was dynamically changed in order to satisfy the stability condition. For the horizontal viscosity and diffusivity, a Smagorinsky formula was used with a coefficient of 0.2. The wind drag coefficient was set to 2.5 10^{-3}, a standard value. The Stickler friction parameter was set to 30.

RESULTS

Salinity simulations

In this section, we present the results of the 3 year-long simulations considering low, medium and high discharge regime. At this preliminary stage, we selected few salinity distribution snapshots from March, May, July and December for low discharge (Fig. 4), medium discharge (Fig. 5) and high discharge (Fig. 6).

For the highest freshwater discharge considered in our analysis, the salinity decrease in the Lagoon System is also highest. Freshwater fills the whole Razelm Lagoon - Lakes Razelm and Golovița, but also Zmeica, where there is usually low freshwater input.

Salinity decrease in the Sinoe Lagoon occurs due to freshwater input only in Canal V. Sometimes, the wind from the north sector can enhance this freshwater input, as shown in Fig. 6c (occurring in each scenario – of low, average and high Danube water discharges).

When the freshwater input is lower, high salinity values occur in the Sinoe Lagoon, in the zone of the Periboina and Edighiol inlets (fig. 4a-d).

Renewal time simulations

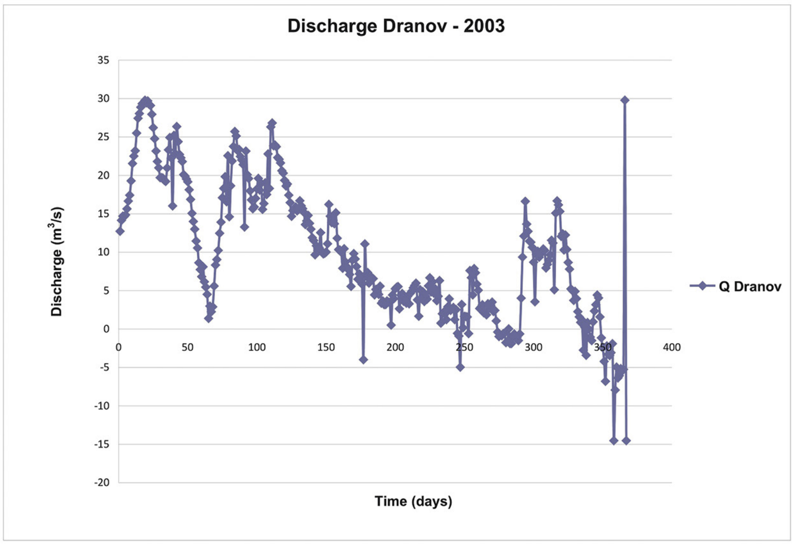
Fig. 7 shows the water renewal time distribution in the Razelm - Sinoe Lagoon System after 3 years, assuming the constant low discharge, medium discharge and high discharge.

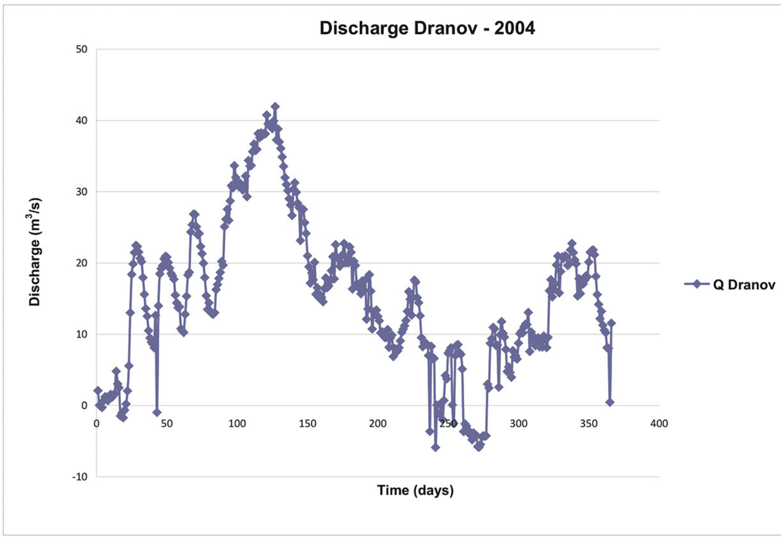
For low discharge conditions, the water renewal times are between 300 and 500 days on the widest part of the lagoon system. The lowest values, around 100 days, are on very narrow strips, at the junction between Lake Razelm and the Dranov channel, and on the Sinoe Lagoon, in the area of the two inlets, while on Lake Zmeica, the water renewal time is around 750 days.

The water renewal times for average discharge are between 250 and 300 days on more than half of the Razelm Lagoon and on the eastern part of the Sinoe Lagoon. The lowest values, around 100 days, are on a more extended area, at the junction between Lake Razelm and the Dranov channel, and on a very narrow strip on Sinoe Lagoon, in the area of the two inlets, while on Lake Zmeica, the water renewal time is around 650 days.

The water renewal times for high discharge are between 200 and 250 days on the widest part of Lake Razelm and on almost the entire Sinoe Lagoon. Values less than 100 days appear at the junction between Lake Razelm and the Dranov channel and, on a very narrow strip, in the area of the junctions with the Dunavăț and Mustaca channels, while the zone with values around 100 days is significantly more extended (fig. 7). On Lake Zmeica, the water renewal time is around 500 days.

Fig. 2. Grid of the Razelm – Sinoe Lagoon System





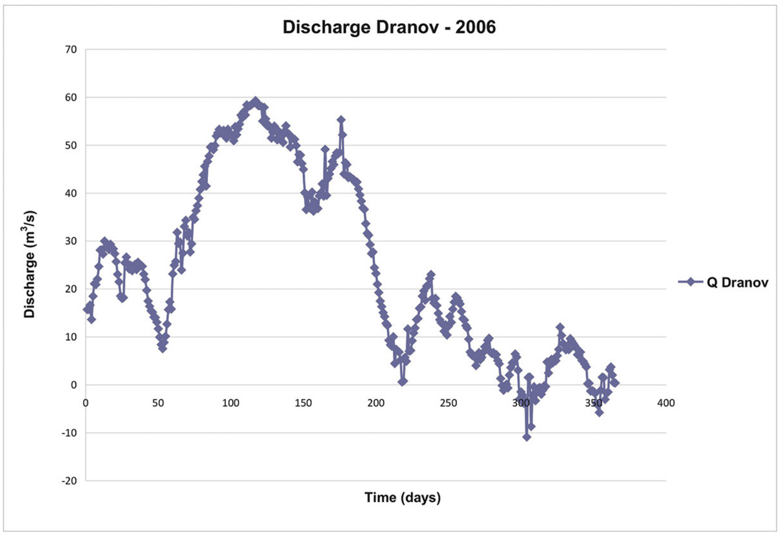


Fig. 3. Discharge on the Dranov channel

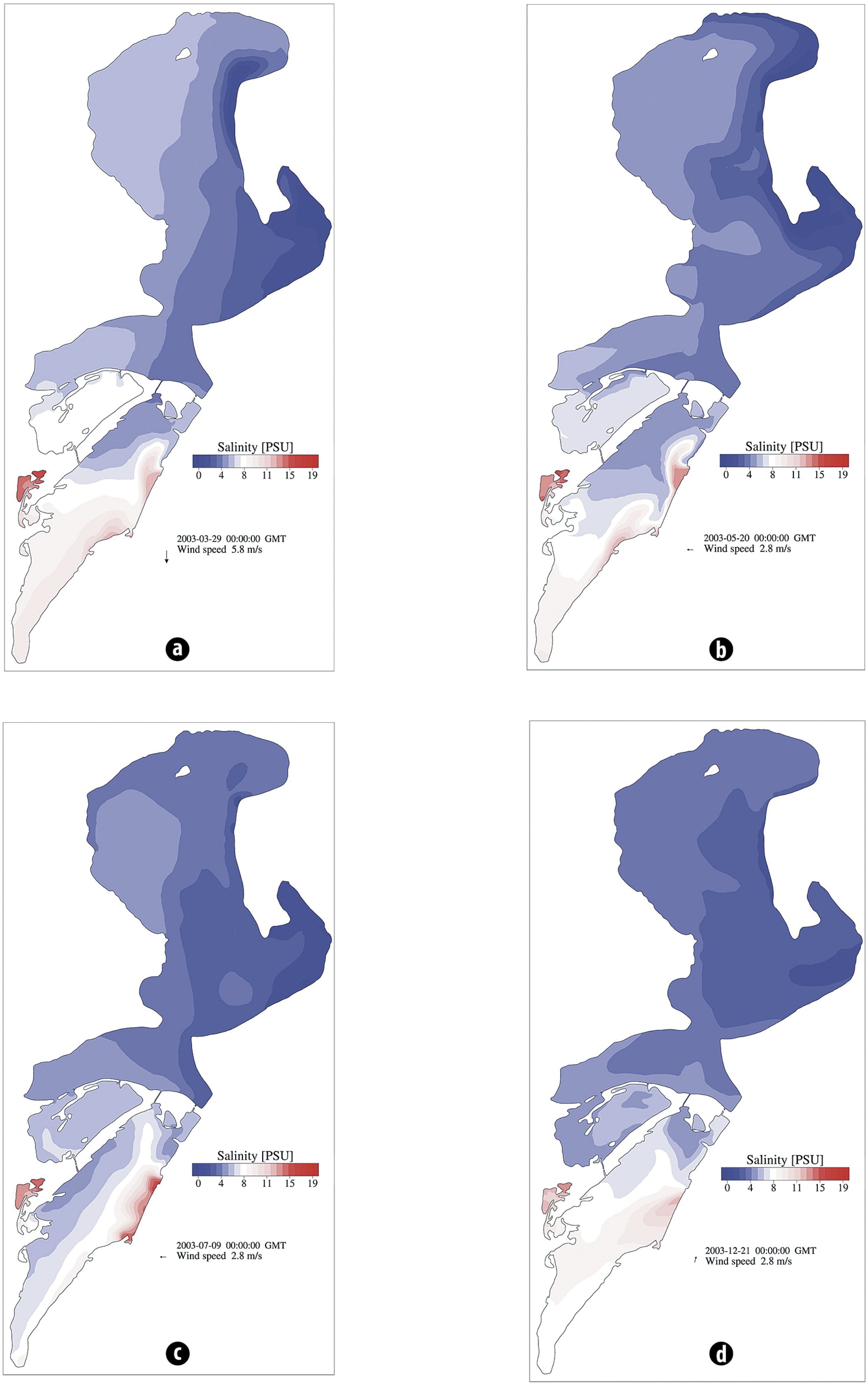


Fig. 4. Salinity distribution in the Razelm – Sinoe Lagoon System for low discharge conditions

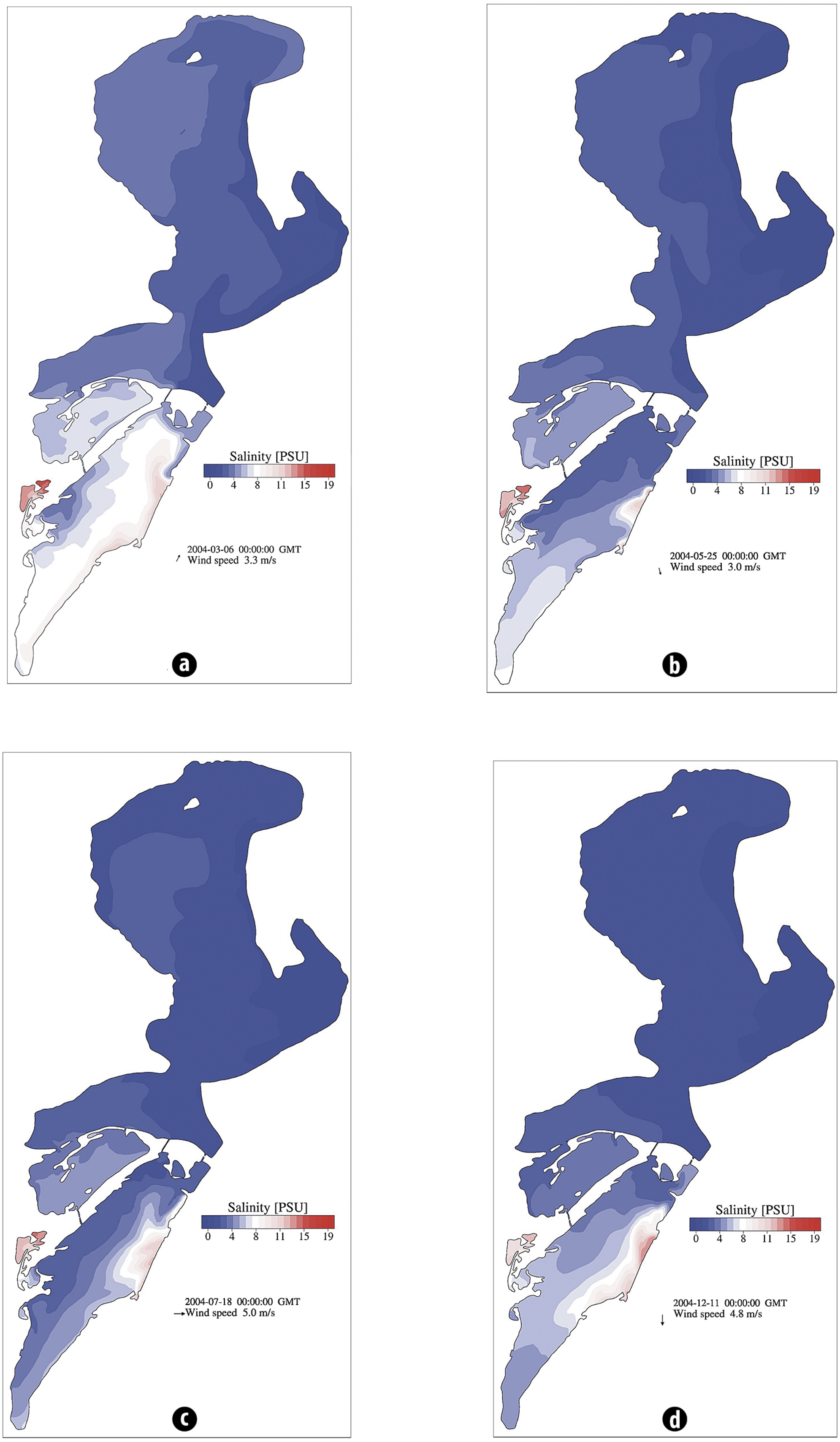


Fig. 5. Salinity distribution in the Razelm – Sinoe Lagoon System for medium discharge conditions

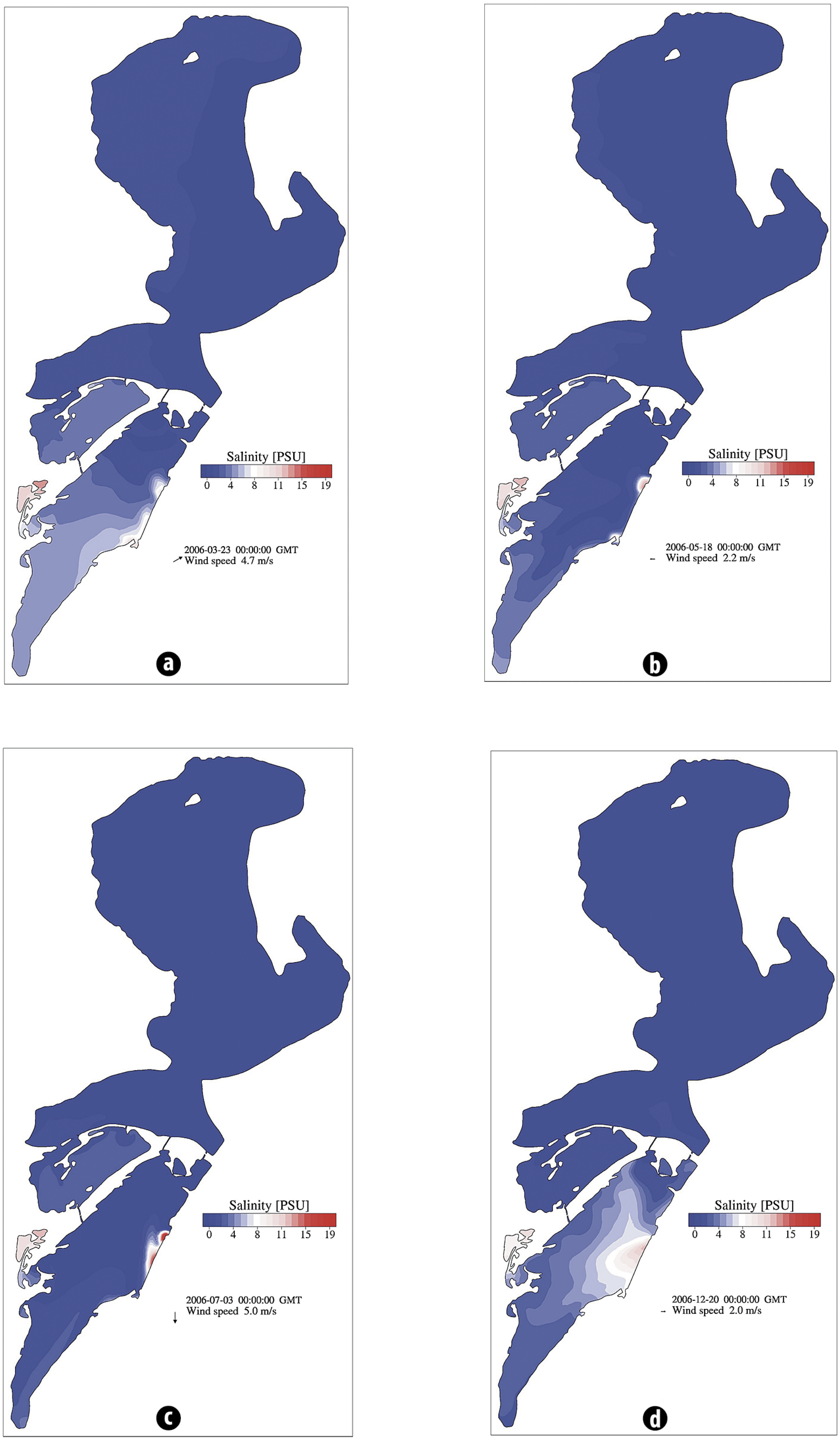


Fig. 6. Salinity distribution in the Razelm – Sinoe Lagoon System for high discharge conditions

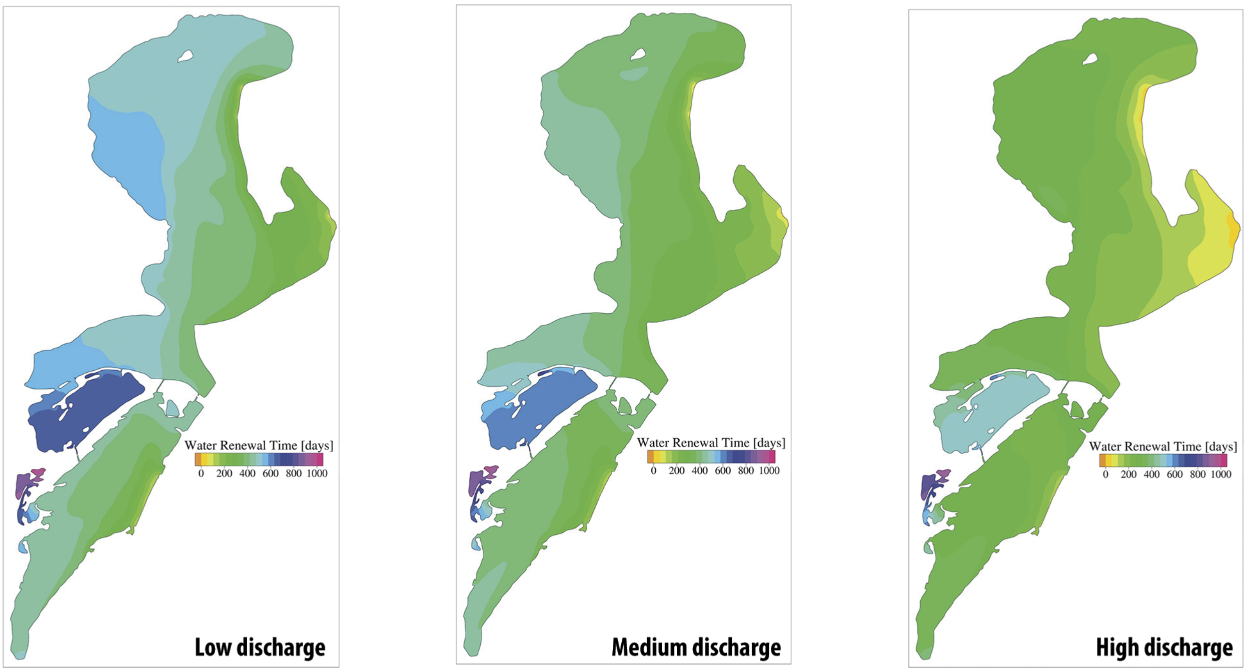


Fig. 7. Water renewal time distribution in the Razelm – Sinoe Lagoon System for low, medium and high discharge conditions

At this stage, we used the available bathymetry and forcing data to study the behaviour of the Razelm - Sinoe Lagoon System, by means of the simulations performed.

Table 2 shows the water renewal times determined in few points from the Razelm - Sinoe Lagoon System, under the low, medium and high discharge conditions. The locations of these points are shown on Fig. 8.

These simulations show that the calculated renewal times of the Razelm - Sinoe Lagoon System are very high. The wind can intensify the freshwater input, especially, on the Lake Razelm and, occasionally, on the Sinoe Lagoon. Under high discharge conditions, salinity may decrease, even in the Lake Zmeica, which is the westernmost part of the Lagoon System, located at the longest distance from the Canal V, where the freshwater input occurs.

DISCUSSION AND CONCLUSIONS

At this stage, we used the available bathymetry and forcing data to study the behaviour of the Razelm – Sinoe Lagoon System, by means of the numerical simulations performed.

The salinity simulations give us a hint on how water is circulated and distributed inside the Razelm - Sinoe Lagoon system. The fact that the results are shown only after a spin up period of 2 years shows the extremely long period for transition to steady state. This time scale is also compatible with the computed renewal times, which reach up to 500 days in the central part of the lagoon, under low discharge conditions.

The simulated salinity distribution in the Lagoon System appears to be controlled, primarily, by the freshwater discharge and, secondarily, by wind. The salinity in Sinoe Lagoon

Table 2. Renewal times (days) for selected points in the Lake Razelm (locations shown on Fig. 8)

Location	low discharge	medium discharge	high discharge
Dunavăţ mouth	200	100	50
Dranov mouth	100	100	50
Lake Razelm north	500	400	300
Lake Razelm south	400	300	200
Sinoe Lagoon	400	400	300
Lake Goloviţa	500	400	300
Lake Zmeica	700	600	500

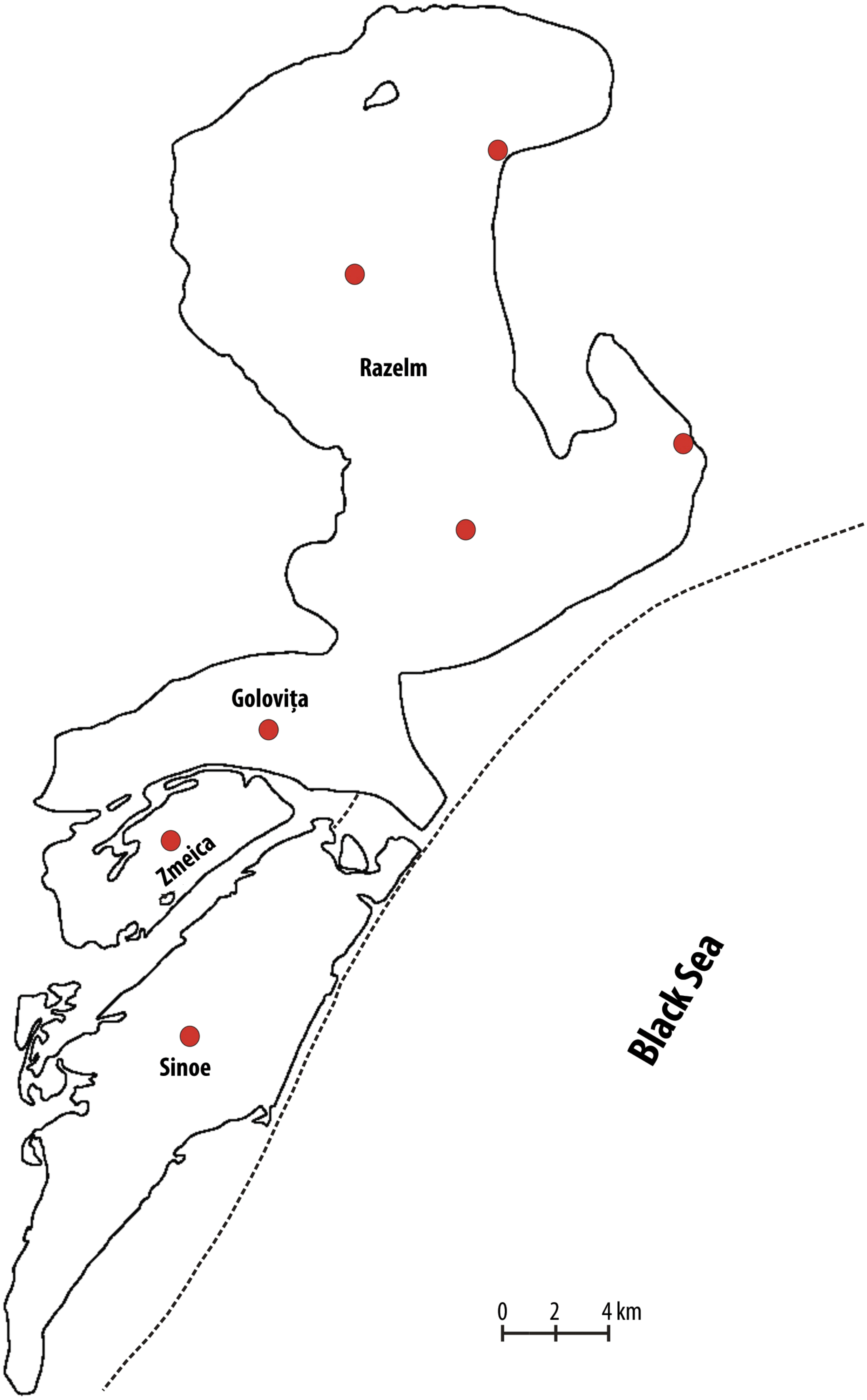


Fig. 8. Locations of selected points for water renewal time computation

is nevertheless strictly controlled also by the Black Sea water which enters the lagoon under specific wind and Danube water discharge conditions.

The renewal time simulations show that the calculated renewal times of the Razelm – Sinoe Lagoon System are very high. These very high renewal time values explain the transformation of the Lagoon System into an almost eutrophic environment. Wind can intensify the freshwater input, especially on the Lake Razelm and, occasionally on the Sinoe Lagoon. In high discharge conditions, salinity may decrease even in the Lake Zmeica, which represents the westernmost part of the Lagoon System, located at longest distance from the Canal V, where the freshwater input occurs into the Sinoe Lagoon.

Further studies will focus on improving and calibrating the water circulation model in the Razelm - Sinoe Lagoon System, once observed data will be available, as well as collecting a more comprehensive meteorological data set. It is furthermore interesting to study how the sea level rise and extremely high winds would affect the Lagoon System. The model will offer the needed tool to be involved in simulating the different protection and rehabilitation scenarios. The analysis concerning the environmental rehabilitation of the Razelm - Sinoe Lagoon System has in this model a powerful quantitative tool. This model allows the quantitative estimation of critical possible interventions, such as the re-opening of the Portița Inlet and other needed works along the connection ways between the various parts of the Lagoon system. It also gives critical quantitative feedback on the estimated impacts in terms of water renewal, changes in salinity and other for each of the proposed measures.

ACKNOWLEDGEMENTS

This work has been started under the 'Executive Programme for Scientific and Technological Co-operation between the Italian Republic and Romania for the Years 2013 – 2014' – Project 'A coupled wave-current operational model on the Black Sea' (COMBS), contract 639/01.01.2013, made possible by the initial CLASS (32130/2008 Partnership) Romanian funded Project. The idea and other significant information were gathered under the FP7 project ARCH (EC contract 282748) and the Romanian Core Programme PN 09 41 03 02. Other critical data were collected under the CERES1-174 Project and FP7 Projects FAST (EC contract 607131) and RISES-AM (EC contract 603396). This research was also partially funded by the Flagship Project RITMARE (SP3-WP4-AZ5) - The Italian Research for the Sea - coordinated by the Italian National Research Council and funded by the Italian Ministry of Education, University and Research within the National Research Program 2011–2014.

The authors thank Dr. Constantin Bondar and all the GeoEcoMar staff who participated in the field surveys of the before mentioned projects.

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