Lithuanian Journal of Physics, Vol. **44**, No. 1, pp. 67–73 (2004)

CIRCULATION DYNAMICS IN THE CURONIAN LAGOON WATERS *

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Received 23 July 2003

To complement a scarce knowledge about the hydrodynamic processes in the Lithuanian coastal waters the steady wind water circulation has been simulated. The 3D baroclinic circulation model developed at the Bundesamt für Seeschiffahrt und Hydrographie (BSH) in Hamburg, Germany for the Nord and Baltic Seas and adapted to the Lithuanian marine waters has been employed. The predominant currents as well as characteristic wind-driven circulation patterns in the Curonian Lagoon have been established. The dispersion of the Nemunas river water as well as a passive tracer were followed. Under the steady wind the circulation patterns developed in simulation clearly prevented the intrusion of the tracer to some areas in the southern part of the Curonian Lagoon.

Keywords: hydrodynamics, Curonian Lagoon, circulation model, currents, tracer

PACS: 92.10.Sx, 92.20.Ny

1. Introduction

One of the most significant Lithuanian ecological problems is the contamination of water in the Curonian Lagoon (Fig. 1). River runoff from Belarus, Lithuania, and Russian Kaliningrad region comes to the Curonian Lagoon and then through the Klaipėda Strait to the Baltic Sea. It makes up 5% of the fresh water inflow to the Baltic Sea. As the long-term observations and modelling results show, this water in the Baltic Sea moves mostly along the Lithuanian coast to the north, causing an increase of sea water contamination along this path. The pollution penetrates the Lithuanian marine waters mainly with the Nemunas river inflow. Therefore, the national marine monitoring organizations, including Centre of Marine Research (CMR) at the Ministry of Environment of Lithuania, are paying primary attention to studying the influence of the Nemunas river on the Curonian Lagoon ecosystem and the Baltic Sea.

Hydrodynamic processes determine the transport of pollution and water renewal in the Curonian Lagoon. Although the importance of knowing these processes is recognized, there are only a few studies showing the characteristic patterns of currents circulating in the Lithuanian marine waters, especially in the Curonian Lagoon.

First studies of the hydrodynamic processes in the Curonian Lagoon were published before Word War II. Willer published in 1933 the first scheme of water currents in the Curonian Lagoon (Fig. 2) [1–3]. This

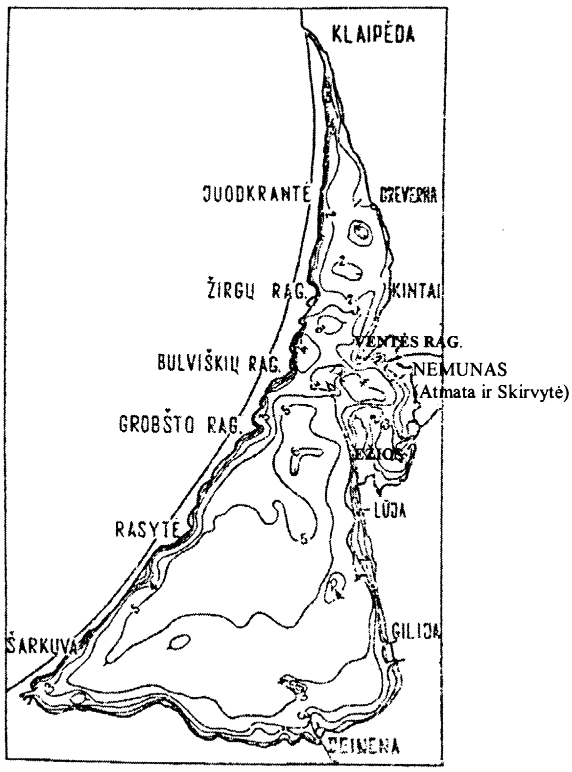

Fig. 1. Topography of the Curonian Lagoon [3].

* The report presented at the 35th Lithuanian National Physics Conference, 12–14 June 2003, Vilnius, Lithuania.

ISSN 1648-8504

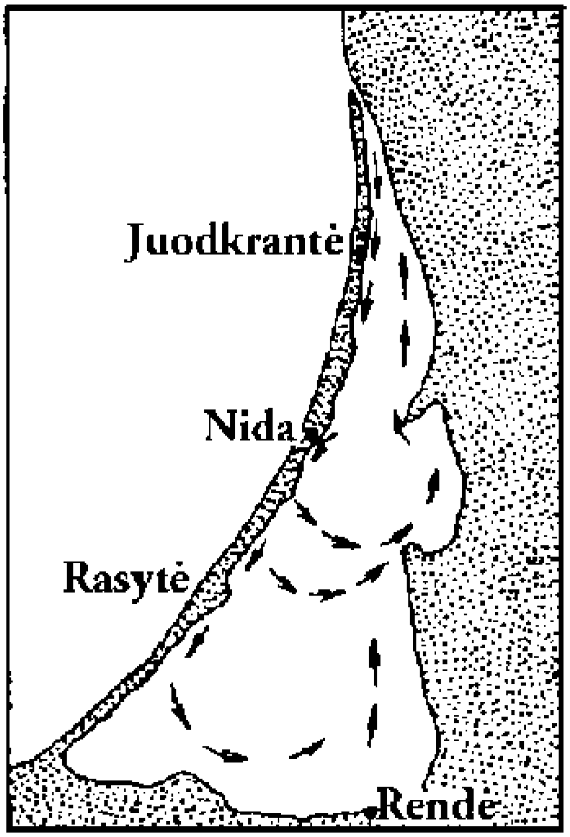

Fig. 2. The first scheme of currents in Curonian Lagoon published by Willer in 1933 [2].

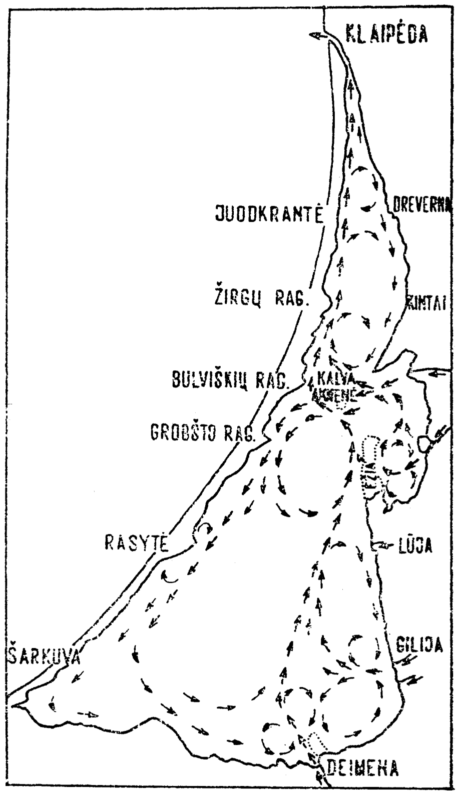

Fig. 3. The current scheme in the Curonian Lagoon constructed after the experimental results with model of the Curonian Lagoon [5].

scheme was based on indirect observations, i. e. on the measured variations of the physical and chemical water parameters and also on the observed peculiarities of the plankton distribution. The obtained current distribution represented just one particular situation in the Curonian Lagoon that evolved under the westerly and southwesterly winds. The distinctive feature of this study was that currents in the central and southern parts of the Curonian Lagoon showed the cyclonical patterns.

Schmidt-Ries in 1932 started measurements of water currents in the Curonian Lagoon using windmills. However, his studies showed a rather opposite direction of the water currents [3, 4] and no general scheme was published. Nevertheless, he demonstrated a relationship between the wind and current velocities.

According to the subsequent measurements [3], under the weak easterly wind the upper water layer in the southern part of the Curonian Lagoon tends to move from the southeast to northwest. The compensating currents in the water layer near the bottom were also detected.

In 1959 water currents in the Curonian Lagoon were studied by constructing a reduced physical model of the Curonian Lagoon topography [5]. The resulting scheme of water currents showed the appearance of some cyclonic circulation patterns in the central and southern parts (Fig. 3). These patterns were evolving due to the flow of Deimena and Gilija rivers.

The most recent study of water currents in the Curonian Lagoon was made by using a 2D hydrodynamic model [6]. The typical patterns of water currents developing under steady wind blowing from eight different directions were modelled by using radiation boundary condition at the Klaipėda Strait. The estimates of water transport between the counterparts of the Curonian Lagoon were also represented. This study showed some two-gyre circulation system in the southern part of the Curonian Lagoon establishing under the wind blowing from northwest and southeast, and from south and north. The main drawback of this study was that no river inflow was taken into account. Although the grid used for the simulation was 62 m, the topography data used for the simulations were for 1 nmi (nautical mile, 1852 m).

Thus, it could be concluded that data concerning a general scheme of water currents in Lithuanian marine waters are scarce and the presented schemes could be related only to the distribution evolving under some particular meteorological conditions. The evolving of some circulation patterns in the Curonian Lagoon (including all its three parts) and in the Baltic Sea near the Klaipėda Strait should be investigated. The influence of the water flow circulation due to the Nemunas water distribution is of main interest.

For the numerical experiments, the hydrodynamic model developed at the BSH and adapted to the Lithuanian marine waters [7, 8] was used. Water circulation in a steady situation was simulated for the steady wind of 5 and 10 m/s velocity blowing from eight directions. Main attention was paid to the most probable wind directions at the Lithuanian coast, i. e. westerly, south-westerly, and south-easterly winds. The aim of this work was to analyse the typical current circulation patterns in the Lithuanian marine waters and to assess the influence of the Nemunas river on the pollution distribution.

2. Hydrodynamic model

A three-dimensional circulation model developed at the BSH for the Nord and Baltic Seas and adapted to the Lithuanian coastal waters was used [7, 8]. The main parameters in momentum equations for the current components are as follows: A_h and A_v are the horizontal and vertical eddy viscosity coefficients, mean values 30 m^2/s and 30 cm^2/s, respectively; $\Delta\tau$ is the difference between stretch at water surface and at the water layer h bottom,

$$\tau_\lambda^\mathrm{wind} = C_\mathrm{D}(W)\cdot\rho_\mathrm{air}\cdot W_\lambda\cdot|W|$$

and

$$\tau_\lambda^\mathrm{bottom} = r\cdot u\cdot\sqrt{u^2+v^2},$$

where u and v are current velocities in λ and ϕ directions; λ and ϕ are the longitude and the latitude, respectively; $C_\mathrm{D}(W) = 0.001\cdot(0.07\cdot W+0.5)$ is the wind stress coefficient, W is the wind speed at the height of 10 m. For the wind velocities of 5 and 10 m/s the wind stretches at the water surface, $\tau_{\lambda,\phi}^\mathrm{wind}$, are 0.027 and 0.155 $\mathrm{N/m}^2$, respectively. The value of 0.0025 for the bottom stress coefficient r was used.

The area selected for modelling (with the upper left corner at $19°55'25''$E, $56°20'45''$N) covers the Lithuanian part of the Baltic Sea including the Curonian Lagoon, part of Latvian and Kaliningrad (Russia) coastal waters. The horizontal grid of $1'\times 1'40''$, approximately 1 nm^2, was chosen. The vertical water column was divided into five layers of $(8+8+8+26+50)$ m depth. The Curonian Lagoon (average depth of 3.7 m) is covered by one layer. Due to minor debits of Deimena and Gilija rivers (see Table in [1]) only the average Nemunas river input has been taken into account.

The current distributions in the Curonian Lagoon and in the Baltic Sea near the Lithuanian coast, evolving under the wind blowing from eight different directions, have been considered. The steady situation in the Curonian Lagoon was reached after one-day simulation with a steady wind blowing. After the steady situation was reached, the tracer transport together with the Nemunas river water, 100 $\mathrm{a.u./m}^3$, was started in order to trace the distribution path of the Nemunas water in the Curonian Lagoon and in the Baltic Sea.

The stationary currents develop due to the interaction of steady wind and bottom friction. The direction of the currents depends on the wind direction relative to the shallowest coastal line [6], i. e. the developing circulation system depends on the coastal line and the topography. The wind stress tends to move the water of the shallow shore windwards.

According to the wind roses for the Lithuanian coast, the most probable winds are southwest, west, and southeast [8]. The average wind velocity in the warm period of the year is about 5 m/s, and the winds stronger than 15 m/s (stormy winds) are rather rare. Therefore, most attention was paid to the current schemes for the most probable wind directions, and two wind velocities of 5 and 10 m/s have been used for wind forcing. The different wind velocities were analysed in order to examine the influence of the wind velocity on the stability of circulation patterns. However, no marked differences in current directions were noticed, except for the current velocity increasing with a stronger wind.

The Curonian Lagoon could be divided into three parts: north – from the Klaipėda Strait to Ventės spit, central – up to the Ežios shoal, and the southern part. The hydrodynamic regimes in these parts are expected to be different and the processes in each part should be analysed.

3. Results of simulations

In the northern part the steady flow towards the Klaipėda Strait is noticeable under the wind blowing from any direction. For the stronger winds, e. g., 10 m/s, some circulation patterns evolve.

In the central part, where the Nemunas river penetrates the Curonian Lagoon, the evolving of circulation pattern was observed in all cases (Fig. 4). The direction

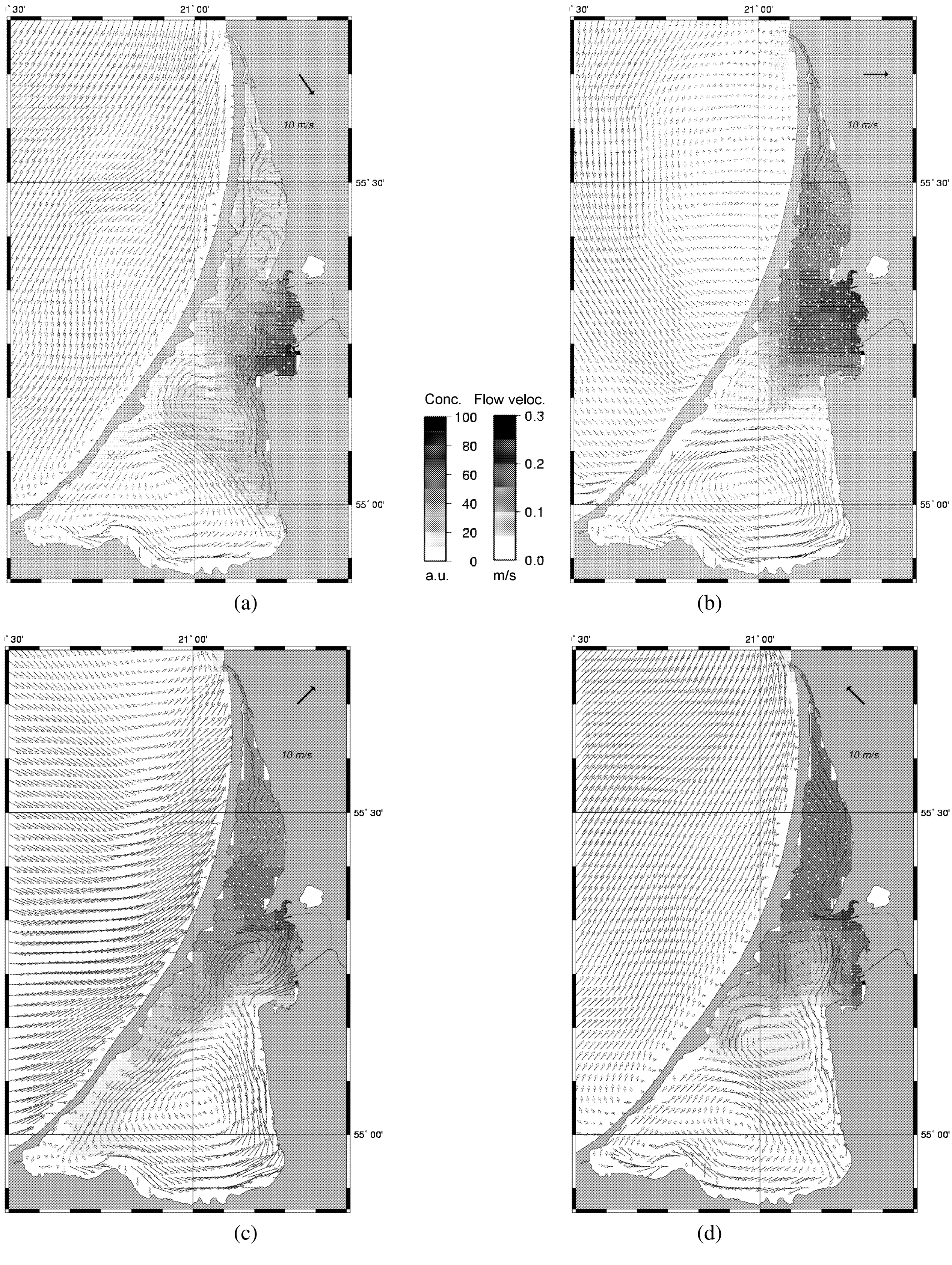

Fig. 4. Currents and tracer distribution in the Curonian Lagoon in case of 10 m/s steady wind from the dominating directions: (a) northwest, (b) west, (c) southwest, (d) southeast. Conservative tracer, 100 a.u., penetrates the Curonian Lagoon with the Nemunas river inflow (Atmata and Skirvytė). Tracer distributions after one-month simulation are presented. Currents in the Baltic Sea are reduced by a factor of 2.

of circulation depends on the wind direction relative to the Ežios shoal, whereas the flow follows the wind direction. However, for the weaker winds (5 m/s) the flow of the Nemunas river prevails in the central part.

In the southern part a two-gyre system develops under any wind direction, except for the eastern and western winds, when only one gyre covering the whole area was observed (Fig. 4). In most cases (except the south-eastern and the north-western wind) one dominating gyre and some smaller gyres were obtained (Figs. 4(b) and (c)). The extension of dominating gyre depends on the wind direction relative to the basin shape: the gyre is stretched in the wind direction. At southern and northern winds the gyre is stretched along the eastern coast, and the second smaller gyre of the opposite direction develops in the left corner of the southern part of the Curonian Lagoon. At south-westerly and north-easterly winds this two-gyre system in the southern part is most expressed (Figs. 4(b) and (d)).

The direction of circulation in southern and central parts depends on the wind direction, while the circulation patterns do not. For the opposite wind direction, identical circulation patterns evolve with the counter-currents.

To simulate the dispersion of pollution, a passive tracer (100 a.u./m^3) has been applied, penetrating the central part of the Curonian Lagoon with the Nemunas river water. The developing circulation patterns in the Curonian Lagoon influence the dispersion of the tracer. One possible path to the southern part, and another, most probable, path to the Baltic Sea have been established. The evolving circulation patterns showed influence on the dispersion path of the tracer.

At southerly winds (S, SW, SE), and at westerly and easterly winds, the most probable path for the Nemunas river water is to the north, into the Baltic Sea. Only a small part penetrates the southern part: after a one-month simulation of the tracer distribution, the tracer concentration in the flow penetrating the southern part (at 5 m/s wind) was on average less than 10 a.u./m^3, and that penetrating the northern part up to 70 a.u./m^3 (Figs. 4(c) and (d)). At a stronger wind the tracer concentration in northern part decreases and a larger amount of tracer penetrates the southern part of the Curonian Lagoon. That is related to the rise of water level in the Klaipėda Strait at the stronger winds. At the most probable wind direction for the Lithuanian coast, i. e. south-westerly wind, the tracer in southern part moves along the westerly coast (Fig. 4(c)).

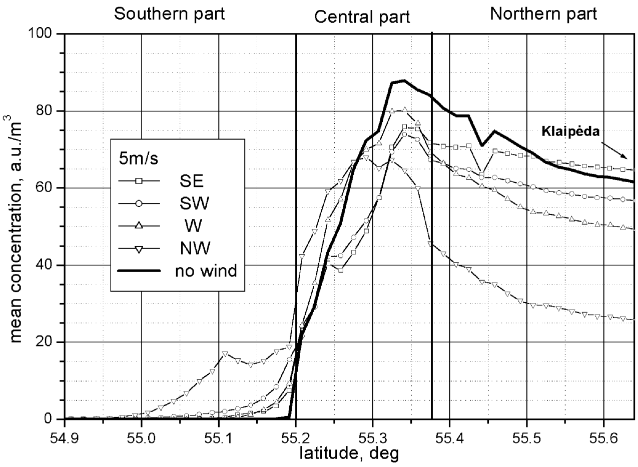

Fig. 5. The distribution of the tracer concentration averaged across the east-west sections along the Curonian Lagoon.

At northerly winds (N, NW, NE), the tracer concentration in the northern part is comparable with that going southwards. In this case the tracer in southern part is transported along the easterly coast (Fig. 4(a)). Thus, the tracer penetrating the central part of the Curonian Lagoon with the Nemunas river water is being transported into southern part at northern winds along the westerly coast, and at southerly winds along the easterly coast.

The tracer moving along the current velocity isolines forms a patchy distribution and thus the tracer gradients. The lowest concentrations relative to the surrounding area could be expected in the centre of circulation pattern on the south. Gradients of the tracer concentration between the neighbouring circulation patterns evolve. Thus, the circulation patterns make the relatively isolated zones for the tracer to penetrate.

The tracer concentration averaged along the longitude indicates three parts in the Curonian Lagoon with different tracer behaviour (Fig. 5). The highest tracer concentrations after the one-month simulation are observed in the Nemunas river inflow area. High tracer concentration was obtained along the most probable path of the Nemunas river waters, too, i. e. in the northern part. The smallest average concentration was obtained in the southern part. However, the tracer forms the most apparent patchy distribution here.

Some features of the modelled distributions of currents can be compared to the schemes described in the introduction. The current scheme proposed by Willer corresponds to the current patterns simulated for westerly and southwesterly winds. The cyclonical circulation patterns in southern and central parts well compare (see Fig. 2 and Figs. 4(b) and (c)).

The currents scheme in the Curonian Lagoon studied by constructing the reduced physical model of the Curonian Lagoon topography also corresponds to the modelled distribution at westerly and south-westerly winds. However, the circulation structures in southeastern corner of the southern part (see Fig. 3) are not realistic indeed. The simulations, even after including the Deimena and Gilija rivers inflow, gave no comparable patterns.

4. Conclusions

The two-gyre circulation in southern part develops under any wind direction except for the eastern and western winds. It is most developed in case of southeastern and north-western wind directions. The circulation direction then depends on the wind direction relative to the shallower south or east shores, respectively, as compared to the Curonian Spit shore.

The evolving circulation pattern was also obtained in the central part, where the Nemunas river penetrates the Curonian Lagoon. Due to proximity of the Ežios shoal the circulation currents always follow wind direction.

Thus the tracer penetrating the central part of the Curonian Lagoon with the Nemunas river water is being transported into the southern part at northern winds along the westerly coast and at southerly winds along the easterly coast.

The circulation patterns in the southern part make a relatively closed structure for the tracer to penetrate.

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LIETUVOS PAJŪRIO VANDENŲ SROVIŲ DINAMIKA

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Santrauka

Hidrodinaminiai vyksmai lemia taršos plitimą ir apsivalymą hidrosferoje, tačiau Lietuvos pajūrio vandenyse jie nėra nuodugniai nagrinėti. Kuršių marios yra seklūs vandenys, kurių judėjimą įtakoja vėjas, įtekantis gėlas upių vanduo bei vandens mainai per Klaipėdos sąsiaurį. Pateikti srovių cirkuliacijos tam tikru laikotarpiu bei nuostovių srovių pasiskirstymo, pučiant pastoviam vėjui, modeliavimo rezultatai. Pastarieji gauti Lietuvos pajūrio vandenims pritaikytu Hamburgo Bundesamt für Seeschiffahrt und Hydrographie (BSH) naudojamu trimačiu baroklininiu cirkuliaciniu modeliu, sukurtu Šiaurės ir Baltijos jūroms [1]. Taip pat buvo analizuotas trasiklio, patenkančio į Kuršių marias kartu su Nemuno vandeniu, plitimas. Skaičiavimais parodyta, kad, priklausomai nuo vėjo krypties, Kuršių marių pietinėje, centrinėje (ties Nemuno delta) ir šiaurinėje dalyse pučiant pastoviam vėjui nusistovi sūkurinės srovės, kurios lemia vandens cirkuliaciją, atsinaujinimą bei mainus tarp minėtų sričių. Ryškiausia dviejų sūkurių sistema pietinėje Kuršių marių dalyje, ribojamoje įtekančio Nemuno srovės bei krantų topografijos, susidaro pučiant šiaurės vakarų bei pietryčių vėjams. Šiaurinėje Kuršių marių dalyje dviejų sūkurių sistema susidaro pučiant vakarų bei šiaurės vėjams. Tie cirkuliaciniai srovių dariniai lemia atskirų, taršos sklaidos požiūriu izoliuotų, sričių susidarymą.