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Mathematical modeling of mineral nitrogen, mineral phosphorus transfer and water current in the Curonian Bay

Dmitrijus Styra[1],

Jonas Kleiza[2],

Kęstutis Jokšas[3],

Linas Jonas Gustas[4]

[1] *Department of Physics,*
Vilnius Gediminas Technical University,
Saulėtekio 11, LT-10223 Vilnius, Lithuania
E-mail: styra@fm.vgtu.lt

[2] *Department of Mathematical Modeling,*
Vilnius Gediminas Technical University,
Saulėtekio 11, LT-10223 Vilnius, Lithuania
E-mail: kleiza@mail.tele2.lt

[3] *Marine Research Department,*
Institute of Geology and Geography,
T. Ševčenkos 13, LT-03223 Vilnius, Lithuania
E-mail: joksas@geo.lt
Department of Hydrogeology and
Geology Engineering, Vilnius University,
M. K. Čiurlionio 21, LT-03101 Vilnius, Lithuania

[4] *Laboratory of Nuclear Hydrophysics,*
Vilnius Gediminas Technical University,
Saulėtekio 11, LT-10223 Vilnius, Lithuania
E-mail: linasg@dtiltas.lt

Monitoring of mineral nitrogen, mineral phosphorus concentrations and water current velocities in the northern part of the Curonian Bay was carried out on April 10 and 11, 2002. Investigations of the mentioned parameters were carried out in the Lithuanian part of the Curonian Bay between Kaliningrad Region and the Klaipėda Strait, and the hydrometeorological situations were considered simultaneously.

Mineral nitrogen concentration in the period of observations were varied within 1.240 and 1.711 mg/l, and mineral phosphorus concentrations ranged from 0 to 0.009 mg/l. Water current velocity values ranged between 0.01 and 0.3 m/s.

Nitrogen and phosphorus promote biological water pollution. Transfer of these admixtures depends on water stream velocities and direction. Therefore, mathematical modeling of the processes of admixture transfer and water current was proposed.

The method of objective analysis was used for calculating the concentration field of mineral nitrogen, mineral phosphorus and the field of water current velocities. Because of the lack of measurement results, repeated calculations were carried out to find an optimum coincidence of the calculation and measurement data. Autocorrelation functions of mineral nitrogen, mineral phosphorus and water current velocities were calculated.

The agreement between the measurement and calculation results was satisfactory.

Key words: Curonian Bay, mathematical modeling, method of objective analysis, mineral nitrogen, mineral phosphorus, water current velocities

INTRODUCTION

The Nemunas water brings the largest amounts of biogenic materials to the Curonian Bay. Cleaner water flows to the Curonian Bay from the Baltic Sea. Water pollution with biogenic materials in the Klaipėda Strait is increased by industrial and municipal wastewater from Klaipėda.

Only part of industrial and municipal wastewater is cleaned, therefore, rivers in Lithuania, Belarus and Kaliningrad Region are highly polluted. Large amounts of polluted water also flow from the agricultural regions and forests. The Nemunas and the Deimena, a branch of the Prieglius, bring to the Curonian Bay and the Baltic Sea huge amounts of industrial and municipal pollutants, fertilizers, dungwater from farms, humus from agricultural regions and even radionuclides. In the last 30–40 years, water in the Curonian Bay became unfit for food preparation and recreational requirements.

This water, coming to the Baltic Sea, mostly pollutes the coast from Būtingė to Klaipėda. Sometimes this water spreads to the south as far as Juodkrantė.

Due to aeration, the polluted water flowing along the Nemunas and the Curonian Bay gradually becomes cleaner, but additional pollutants can get into the water. Because of the mixing processes, the concentration of biogenic materials decreases when the polluted water flows to the Curonian Bay and especially to the Baltic Sea. According to the evaluation of the Helsinki Environmental Protection Commission, the pollution of the Baltic Sea reached its maximum in 1987.

Water-cleaning systems were built and implemented to reduce the concentration of pollutants. But even the best water cleaning systems in Lithuania cannot completely clean water from biogenic materials (nitrogen and phosphorus). Nitrogen and phosphorus are good indicators for evaluating the processes of pollution. Nitrogen and phosphorus compounds increase the quantity of plankton, and this is the reason for eutrophication.

Water current in the Curonian Bay depends on the inflow of the Nemunas water, water exchange in the Klaipėda Strait area of the bay, coastline, depth and especially on wind regime (Dubra, 1978; Червинскас, 1959). The velocity and direction of the water current often change, therefore, mathematical modeling is actual to forecast admixture transfer and water current regime in the Curonian Bay.

The objective of this research was to compare the measured concentrations of mineral nitrogen, mineral phosphorus and the velocities of water current with the calculated values and to find the optimum coincidence of the measurement results and the calculated values. Another objective was to evaluate the mathematical model in forecasting admixture transfer in the Curonian Bay.

MATERIALS AND METHODS

Measurements of mineral nitrogen, mineral phosphorus and water current velocities were carried out in the northern part of the Curonian Bay. The complex of the measurements included:

1) sounding of the water layer;

2) taking water samples for hydrochemical research.

Water layer was sounded in 1 m intervals (the upper horizon until 1 m of depth and the lower 0.5–1.5 m from the bottom). Water temperature, water turbidity, water current velocity and direction were measured. Water conductivity was measured, too (later it was recalculated to water salinity). Water current velocity and direction were measured with a multifunctional RCM 9 sound (*Aanderaa Instruments*, Norway) (Galkus, Jokšas, 2002). Water current velocity was measured with an RCM 9 Dopler sensing element of sound (0.01 cm/s accuracy). To calculate water current direction, sound position with respect to water current was stabilized with a special wheel (Galkus, 2003).

Water sample conservation in the open air and hydrochemical research (calculation of biogenic material concentrations) were carried out by the procedure of chemical analysis confirmed by the Ministry of Environment of the Republic of Lithuania (Unifikuoti..., 1994). Mineral nitrogen and mineral phosphorus concentrations and water current velocities were measured in 43 points between the Russian border and the Baltic Sea.

Before the mathematical modeling, the coordinates of the measurement points were recalculated by the formula:

$$D_1 = D + \frac{M}{60} + \frac{S}{3600},$$

where:

D_1 – recalculated longitude and latitude (degrees);

D, M, S – degrees, minutes and seconds.

Data on mineral nitrogen and mineral phosphorus concentrations and water current velocities are given in Table.

During the measurements, wind velocity was from 1 to 5 m/s. Wind direction was unstable: north, east-northeast, east, south and southeast winds blew.

The maximal concentration of mineral nitrogen (1.711 mg/l) was measured on 10 April nearby the Nemunas mouth. Nearby the Ventės Ragas, the concentration of mineral nitrogen was 1.24 mg/l. Near Nida, this concentration was 1.599 mg/l and near Preila and Pervalka 1.384 mg/l, near Juodkrantė 1.457 mg/l, and near the Klaipėda Strait 1.536 mg/l.

The maximal concentration of mineral phosphorus (0.009 mg/l) was measured on April 10th near Nida. At the Nemunas mouth, the concentration of mineral phosphorus was 0.005 mg/l, near the Ventės Ragas was 0.006 mg/l, near Preila 0.008 mg/l, and near Juodkrantė the concentration of mineral phosphorus was 0 mg/l (the reason for this result is method sensitivity).

Near the Klaipėda Strait, the concentration of mineral phosphorus increased to 0.007 mg/l.

The maximal velocity of water current (0.3 m/s) was measured on April 11th near Juodkrante. Between the Nemunas mouth and Nida, water current velocities were 0.1–0.13 m/s and in the northern part of the Curonian Bay 0.11–0.15 m/s. Near Preila, water current velocity was 0.01–0.03 m/s. It decreased near the coast (Galkus, Jokšas, 2002).

The method of objective analysis was chosen for mathematical modeling in this research. By using this method, the concentrations of biogenic materials and water current velocities can be calculated in places where measurements were not carried out.

The measured concentrations of mineral nitrogen and mineral phosphorus and water current velocities were interpolated into the chosen grid nodes of the Curonian Bay.

The method of objective analysis is commonly used in dynamic meteorology and oceanology.

The stages of objective analysis are:

1) optimal interpolation of the measured element into places where measurements were not carried out, or into nodes of a regular grid;

2) adjustment of the process, using the relationship of the same element field at different time moments;

3) finding of errors, fault data, correction and deletion of mistakes.

The initial (real) field is specified by the following parameters: the point position in bidimensional space (longitude and latitude) and the real concentration. The space of the calculated field is described by three analogous parameters, but the third parameter is the reproduced concentration.

Some preconditions were accepted before calculating the mineral nitrogen and mineral phosphorus concentration fields.

Suppose that C_i is the concentration of mineral nitrogen or mineral phosphorus in i-points, $\bar{C} = \frac{1}{N}\sum_{i=1}^{N} C_i$ is the average concentration, and C'_i is deviation from the average concentration:

$$C'_i = C_i - \bar{C}. \quad (1)$$

The main characteristic of the method of optimal interpolation is the normalised autocorrelation function $\mu_k = \mu_k(\rho_k; \rho_{k+1})$ which depends on the concentration of biogenic materials in

Table. **Measurement results in the Curonian Bay on April 10–11, 2002 (Galkus, Jokšas 2002)**

Coordinates of the measurement points		Day	Hour	Depth, m	Wind velocity, m/s	Wind direction	Water temperature, °C	Water current velocity, m/s	N_{min}, mg/l	P_{min}, mg/l
Longitude, degrees	Latitude, degrees									
21°13′28″	55°16′01″	10 Apr	13.00	1	3–5	East	7.1	0.04	1.711	0.005
21°14′25″	55°14′59″	10 Apr	13.20	1	3–5	East	7.5	0.15	1.711	0.005
21°15′12″	55°26′05″	10 Apr	13.40	1	3–5	East	6.9	0.13	1.711	0.005
21°15′21″	55°17′04″	10 Apr	14.00	1	3–5	East	7	0.07	1.711	0.005
21°11′38″	55°17′02″	10 Apr	14.30	1	3–5	East	6.4	0.03	1.711	0.005
21°07′35″	55°17′01″	10 Apr	15.00	1	3–5	East	6.47	0.09	1.599	0.009
21°03′58″	55°17′10″	10 Apr	15.30	1	3–5	East	5.8	0.13	1.599	0.009
21°01′44″	55°17′46″	10 Apr	15.50	1	3–5	East	6.6	0.2	1.599	0.009
21°03′04″	55°14′18″	10 Apr	16.20	1	3–5	East	6.8	0.1	1.599	0.009
21°06′02″	55°19′18″	10 Apr	16.50	1	3–5	East	6.5	0.01	1.599	0.009
21°10′02″	55°19′18″	10 Apr	17.20	1	3–5	North	6.8	0.15	1.711	0.005
21°13′33″	55°19′22″	10 Apr	17.40	1	3–5	North	6.6	0.1	1.711	0.005
21°14′53″	55°20′08″	10 Apr	16.10	1	3–5	North	6.7	0.11	1.711	0.005
21°12′36″	55°20′04″	10 Apr	18.30	1	3–5	North	7.2	0.15	1.711	0.005
21°10′48″	55°20′17″	10 Apr	18.50	1	3–5	North	7.5	0.05	1.711	0.005
21°07′54″	55°20′17″	10 Apr	19.20	1	3–5	North	6.6	0.24	1.599	0.009
21°04′24″	55°20′46″	11 Apr	8.50	1	1	Unstable direction	5.9	0.03	1.599	0.009
21°05′32″	55°21′53″	11 Apr	9.10	1	1	Unstable direction	6	0.16	1.384	0.008
21°07′18″	55°21′53″	11 Apr	9.30	1	3–5	East– northeast	6	0.18	1.384	0.008
21°08′24″	55°21′52″	11 Apr	9.50	1	3–5	East– northeast	6.1	0.25	1.384	0.008
21°10′37″	55°21′50″	11 Apr	10.20	1	3–5	East– northeast	6.75	0.08	1.24	0.006
21°11′35″	55°21′49	11 Apr	10.20	1	3–5	East– northeast	7.05	0.06	1.24	0.006
21°12′52″	55°23′20″	11 Apr	10.50	1	3–5	East– northeast	6.8	0.05	1.24	0.006
21°11′35″	55°23′31″	11 Apr	11.10	1	3–5	East– northeast	6.4	0.1	1.24	0.006
21°08′45″	55°23′30″	11 Apr	11.30	1	3–5	East– northeast	6	0.11	1.384	0.008
21°05′11″	55°23′34″	11 Apr	12.00	1	3–4	North	6	0.18	1.384	0.008
21°06′52″	55°25′45″	11 Apr	12.40	1	3	East– southeast	6.1	0.17	1.384	0.008
21°08′11″	55°25′49″	11 Apr	13.00	1	3	East– southeast	6.4	0.05	1.384	0.008
21°11′05″	55°25′43″	11 Apr	13.20	1	2–3	East	6.4	0.1	1.24	0.006
21°14′01″	55°25′41″	11 Apr	13.50	1	3–4	East– southeast	7	0.22	1.24	0.006
21°14′02″	55°26′47″	11 Apr	14.20	1	3–4	East– southeast	7.2	0.13	1.24	0.006
21°13′27″	55°26′48″	11 Apr	14.30	1	3–4	East– southeast	7	0.14	1.24	0.006
21°12′49″	55°29′02″	11 Apr	15.00	1	3–4	East– southeast	7.05	0.15	1.536	0.007
21°10′07″	55°28′55″	11 Apr	15.15	1	2	North	7.1	0.17	1.457	0
21°09′10″	55°28′55″	11 Apr	15.30	1	2	North	7	0.24	1.457	0
21°07′20″	55°28′58″	11 Apr	15.50	1	2	North	6.4	0.26	1.457	0
21°07′16″	55°30′37″	11 Apr	16.10	1	3	Southeast	7	0.25	1.457	0
21°10′14″	55°30′37″	11 Apr	16.40	1	3	Southeast	7.4	0.16	1.457	0
21°11′11″	55°30′34″	11 Apr	17.00	1	3	Southeast	7.5	0.15	1.536	0.007
21°13′02″	55°30′40″	11 Apr	17.10	1	2	North	7.5	0.11	1.536	0.007
21°11′09″	55°33′14″	11 Apr	17.50	1	2	South	7.6	0.12	1.536	0.007
21°10′15″	55°33′18″	11 Apr	18.00	1	2	South	7.3	0.2	1.536	0.007
21°08′17″	55°33′15″	11 Apr	18.20	1	2	South	6.9	0.3	1.457	0

points, the distance between which lies within $\rho_k < \rho \le \rho_{k+1}$. This function depends also on the coordinates of these points. Then, before calculating the autocorrelation function $\mu(\rho_k)$, the measurement points should be divided into groups according to the distance between them. For automatisation of the calculating process, the distance between the *i* and *j* points was calculated by the formula:

$$\rho_{ij} = 6377 \arccos\begin{pmatrix}\cos\alpha_i \cos\alpha_j \cos(\beta_i - \beta_j) + \\ + \sin\alpha_i \sin\alpha_j\end{pmatrix}, \quad (2)$$

where:

α_i – the latitude of the *i* point;

β_i – the longitude of the *i* point;

$\arccos(\cos\alpha_i \cos\alpha_j \cos(\beta_i - \beta_j) + \sin\alpha_i \sin\alpha_j)$ is in radians;

$\rho_{i,j}$ – the distance between *i* and *j* points, km.

Then the normalised autocorrelation function is calculated for each group of the points:

$$\mu(\rho_k) = \frac{1}{\mu_0 N_k} \sum_{i,j=1}^{N_k} C_i^{'} C_j^{'}, \tag{3}$$

where:

$$C_i^{'} = C_i - \frac{1}{N} \cdot \sum_{j=1}^{N} C_j, \quad \mu_0 = \frac{1}{m_k} \sum_{i=0}^{m_k} \left(C_i^{'}\right)^2,$$

N – the number of the measurement points;

C_i – the concentration of mineral nitrogen or mineral phosphorus in the i point;

m_k – the number of points between which the distance belongs to the interval $[(k-1)\,\Delta\rho; k\Delta\rho)$, $\rho_k = (k - 0{,}5)\Delta\rho$;

$k = 1, 2, 3, \ldots$ – the number of groups;

N_k – the number of all possible products of $C_i^{'} C_j^{'}$.

When the $\mu(\rho_k)$ values are calculated in the points ρ_k, the discrete values of the autocorrelation function are aproximated by the least squares method (Стыро, 1989).

The field of water current velocities is calculated by the same method, but the concentrations in this case are changed to water current velocities.

Autocorrelation functions are calculated by the formula $\mu(d) = e^{-a \cdot d} \cos(\beta d)$,
where:

d – the distance between the measurement points, km,

α and β – the parameters of approximation.

The autocorrelation function of the concentration of mineral nitrogen is obtained by the formula $\mu(d) = e^{-0.04 \cdot d} \cos(0.19d)$, and the same for phosphorus is $\mu(d) = e^{-0.11 \cdot d} \cos(0.08d)$. The calculation results are illustrated in Figs. 1 and 2. Comparison of the obtained curves shows a higher correlation for mineral phosphorus because the autocorrelation function crosses the zero point at the longer distance of 19 km (Fig. 2).

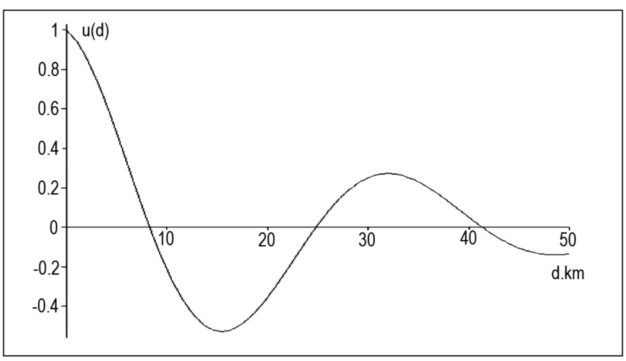

Fig. 1. Autocorrelation function of mineral nitrogen concentration

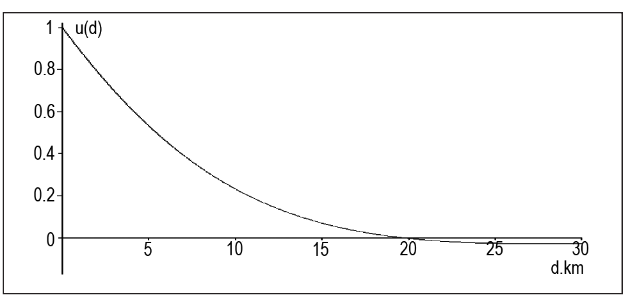

Fig. 2. Autocorrelation function of mineral phosphorus concentration

The autocorrelation function of water current velocities is calculated by the formula $\mu(d) = e^{-1.16 \cdot d} \cos(0.00155d)$, and the obtained results are presented in Fig. 3. It means that the correlation of water current elements is less than the same function for mineral nitrogen (Fig. 1) and phosphorus (Fig. 2).

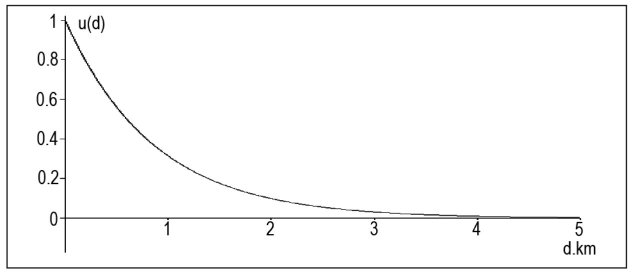

Fig. 3. Autocorrelation function of water current velocities

Another part of the problem is the solution of a system of linear equations. If this system is solved, the unknown weights are calculated:

$$\sum_{j=1}^{N} \mu_{i,j} P_j^{(\theta)} = \mu_{j,\theta}, \quad i = 1, 2, 3, \ldots, \mathrm{N}, \tag{4}$$

where:

$\mu_{i,j} = \mu(\rho_{i,j})$;

$P_j^{(\theta)}$ – unknown weights;

$\rho_{i,\theta}$ – the distance between the i and θ points in which the concentration is obtained.

After solving the system of equations (4), the weights P_1, P_2, ..., P_n are known, and the unknown concentrations $C_{i,\theta}$ can be calculated:

$$C_{i,\theta} = C_{i,\theta}^{'} + \frac{1}{N} \sum_{j=1}^{N} C_j = \sum_{j=1}^{N} P_j^{(\theta)} C_j^{'} + \frac{1}{N} \sum_{j=1}^{N} C_j. \tag{5}$$

In this method, the reproduced concentration field should be stationary, homogeneous and isotropic, and the efficiency of the method depends on fulfilment of these preconditions (Нелепо, 1970).

Then the concentrations calculated by the method of optimal interpolation should be chosen; for them, the variance of the calculated values should be less than or equal to the variance of measurement results (Стыро, 1989).

RESULTS AND DISCUSSION

The measured concentrations of mineral nitrogen were compared with the obtained data by the optimal interpolation method (Fig. 4). The same comparison for the measured and the calculated concentration results for mineral phosphorus is illustrated in Fig. 5.

Figures 4 and 5 show that the largest amount of biogenic materials flows to the Lithuanian part of the Curonian Bay from the Nemunas, the Danė, the Akmena and wastewater from Klaipėda and Neringa.

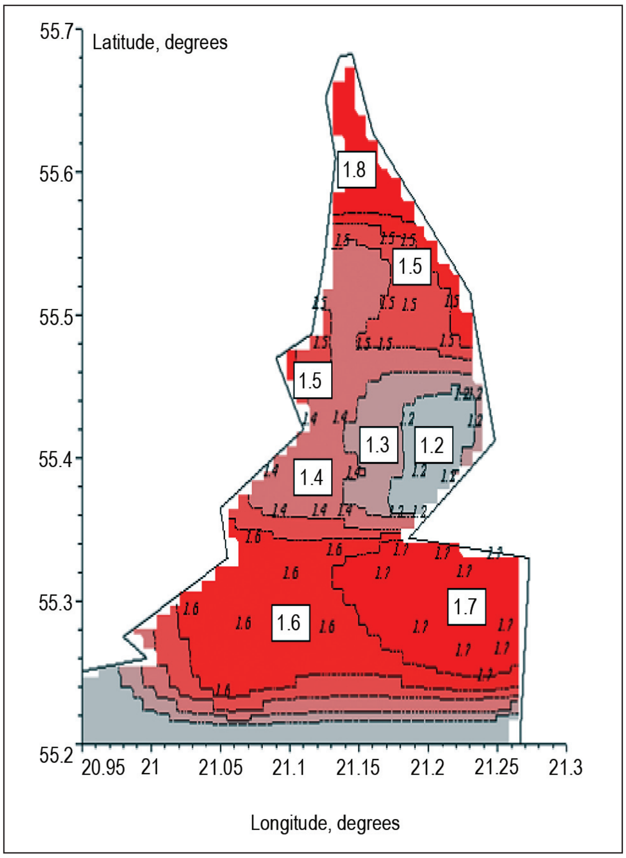

Fig. 4. Theoretical data on mineral nitrogen concentration in the Curonian Bay. Measured results are marked with black numbers, and theoretical results are shown by black numbers on the white background (April 10–11, 2002)

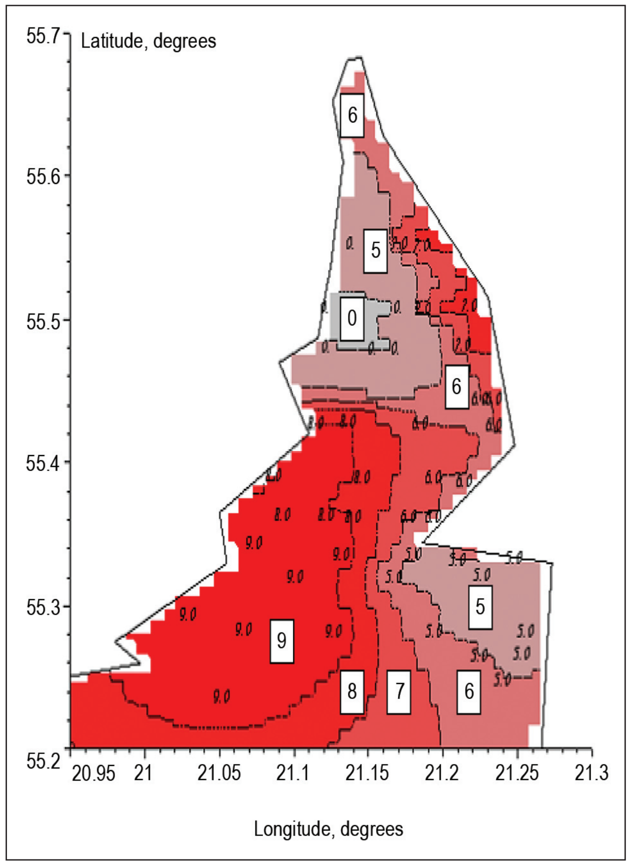

Fig. 5. Theoretical results of mineral phosphorus concentration in the Curonian Bay. Measured results are marked with black numbers, and theoretical results are shown by black numbers on the white background (April 10–11, 2002)

The admixture transfer depends on wind velocity and direction, which form the water currents. Water mass inflow to the Curonian Bay is 3.7 times more than its volume (6.2 km^3, Stankevičius, 1998). The surface waters of the Curonian Bay have an inclination from south to north, therefore, the largest part of the water mass is directed to the Klaipėda Strait. The system of water current is complicated because of many factors such as water mass dynamic, continental water penetration, change of surface water level in the Curonian Bay and the Baltic Sea, bottom relief, coastline, etc.

Research of water balance in the Curonian Bay shows that maximal water inflow from rivers to the Curonian Bay occurs in March (4.3 km^3). It decreases by half (2.03 km^3) in April (Gailiušis, Jurgelėnaitė, Kovalenkovienė, 1992). About 94% of water inflow into the Curonian Bay comes from the Nemunas, about 5% from the Deimena, a branch of the Prieglius, and about 1% from small rivers. Near Panemunė, the Nemunas is divided into Rusnė (about 82% of inflow) and Matrosovka (Gilija) (18% of inflow). The bulk of water (18 km^3) flows to the central part of the Curonian Bay, and the rest (5 km^3) flows to the southern part (Dubra, Dubra, 1999).

In April 2002, there was almost no spring flood in the northern part of the Curonian Bay. The wind was not strong. There was no inflow of water from the Baltic Sea, and the circulation of admixture and water depended on the dispersion of the Nemunas water in the Curonian Bay (Galkus, 2003).

A scheme of water current in the Lithuanian part of the Curonian Bay on April 10 and 11, 2002 is presented in Fig. 6.

Experimental results of water current velocities were chosen to get the field of water mass velocities in the Curonian Bay, using the optimal interpollation method. The measured and the calculated data on water current velocities for 10–11 April 2002 are compared in Fig. 7. The obtained results were in the range of experimental error.

The main characteristics of water circulation in the Lithuanian water area of the Curonian Bay were found to be the following:

1) some of the water flowing into the Curonian Bay by the Nemunas delta branches moves slowly southward to the eastern part of the Curonian Bay;

2) the remaining portion of the Nemunas water joins the water flow coming from the southern part of the Curonian Bay and moves to the north in the western part of the bay;

3) to the north of the Ventės Ragas cape in the eastern part of the Curonian Bay, the water circulation develops with the dominant clockwise whirling (Galkus, 2003).

Water circulation in the study part of the Curonian Bay and the water current moving northward transferred mineral nitrogen and mineral phosphorus brought from the Nemunas.

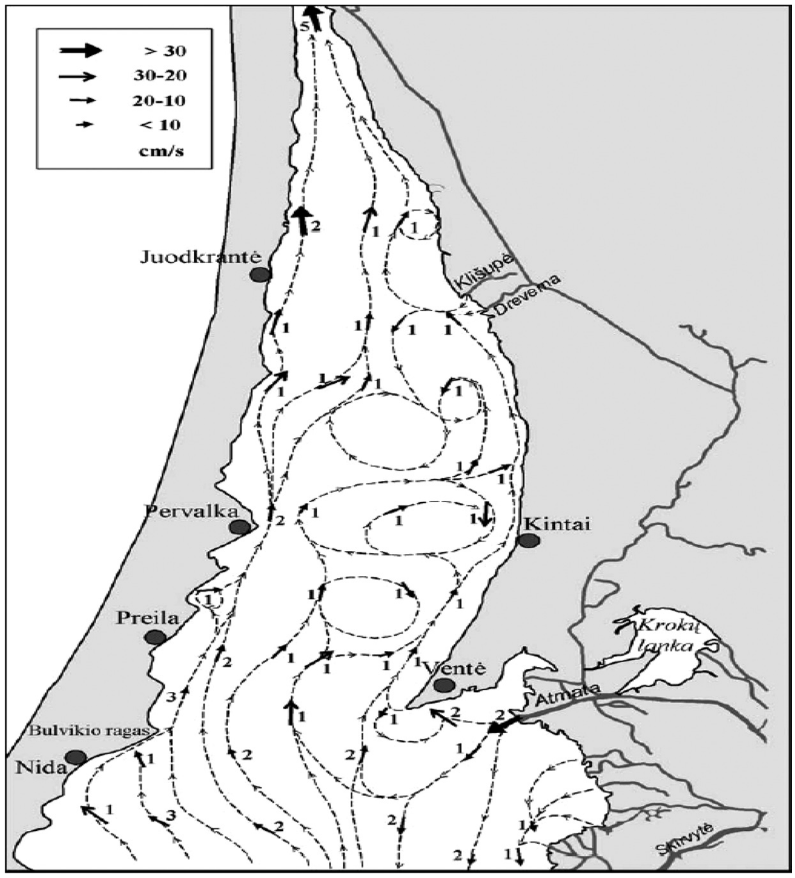

Fig. 6. Scheme of water current (10–11 April 2002) in the Lithuanian water area of the Curonian Bay. The sites of the vertical measurements and the directions and velocities of the currents are shown by arrows. The numbers near the arrows indicate the water horizon (m) where current velocity is the highest (Galkus, 2003)

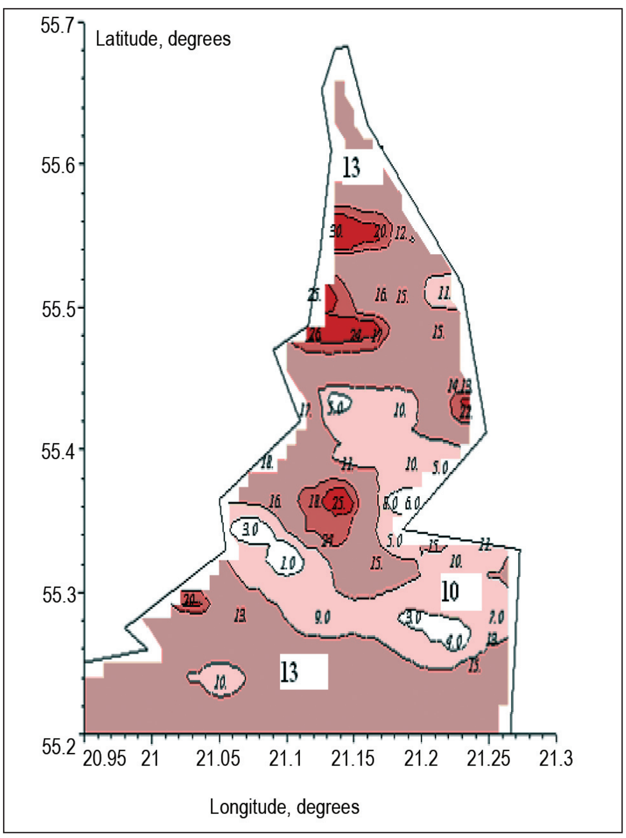

Fig. 7. Theoretical results of water current velocities in the Curonian Bay. Measured results are marked with black numbers, and theoretical results are shown by black numbers on the white background (10–11 April 2002)

CONCLUSIONS

The autocorrelation functions of mineral nitrogen and mineral phosphorus concentrations and the water current velocities were calculated using the method of objective analysis. The concentration fields of mineral nitrogen and mineral phosphorus concentrations and water current velocities in the northern part of the Curonian Bay were reproduced.

The agreement between the measured and the calculated results was satisfactory.

This method could be used for investigating the distribution of admixtures in the Curonian Bay and the sites of their maximum concentration.

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Dmitrijus Styra, Jonas Kleiza, Kęstutis Jokšas, Linas Jonas Gustas

MINERALINIO AZOTO, MINERALINIO FOSFORO PERNAŠOS IR VANDENS TĖKMIŲ KURŠIŲ MARIOSE MATEMATINIS MODELIAVIMAS

Santrauka

2002 m. balandžio 10 ir 11 d. Kuršių mariose buvo matuojamos mineralinio azoto, mineralinio fosforo koncentracijos ir vandens tėkmių greičiai. Tirta visa Kuršių marių Lietuvos akvatorija nuo sienos su Kaliningrado sritimi iki Klaipėdos sąsiaurio žiočių. Tuo pačiu metu buvo įvertinta ir hidrometeorologinė situacija. Maksimali mineralinio azoto koncentracija buvo 1,711 mg/l, minimali – 1,240 mg/l. Maksimali mineralinio fosforo koncentracija buvo 0,009 mg/l, minimali – 0 mg/l. Maksimalus vandens tėkmės greitis buvo 0,3 m/s, minimalus – 0,01 m/s.

Azoto ir fosforo junginiai Kuršių mariose skatina planktono vystymąsi, kartu sukeldami biologinę vandens taršą, vadinamą vandens žydėjimu. Šių junginių pernaša priklauso nuo vandens tėkmių greičio ir krypties, kuri dažnai keičiasi dėl hidrometeorologinės situacijos pokyčių. Todėl aktualu plėtoti priemaišų pasiskirstymo procesų ir vandens tėkmių Kuršių mariose matematinį modeliavimą.

Siekiant atstatyti mineralinio azoto, mineralinio fosforo koncentracijų lauką ir vandens tėkmių greičių lauką, taikytas objektyvios analizės metodas. Atlikti daugkartiniai skaičiavimai, siekiant nustatyti Kuršių mariose atliktų matavimų ir skaičiavimo rezultatų optimalų sutapimą. Skaičiuojant buvo keičiama mineralinio azoto, mineralinio fosforo koncentracijos ir vandens tėkmių greičių autokoreliacinė funkcija.

Nustatytas apskaičiuotų duomenų sutapimas su matavimų duomenimis eksperimento paklaidų ribose.

Raktažodžiai: Kuršių marios, matematinis modeliavimas, objektyvios analizės metodas, mineralinis azotas, mineralinis fosforas, vandens tėkmių greičiai