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Eutrophication and effects of algal bloom in the south-western part of the Curonian Lagoon alongside the Curonian Spit

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Abstract. The Curonian Lagoon is the largest coastal lagoon of the Baltic Sea. The Curonian Lagoon is a hypereutrophic water body beset with two major problems: eutrophication and algal blooms. Biological and chemical data for the study of water eutrophication and algal blooms were collected from 4 sampling points in the coastal and off-shore areas at distances of 1 km and 4–5 km from the Curonian Spit during the period from April 2007 to November 2016. The ratio of mineral nitrogen/phosphorus forms created conditions for regular Cyanobacteria hyperblooms during the summer and early autumn. Such blooms are followed by an increase in the concentration of ammonia nitrogen, pH and $BOD_{5,}$ their values exceeding the threshold limits for fishery water reservoirs. A distinct peak of chlorophyll *a* concentration was observed in the period of freshwater Cyanobacteria hyperbloom from July to September or October. During the “hyperbloom” of Cyanobacteria, their accumulation and decomposition, which was caused by a constant wind direction, also led to the local oxygen deficit and fish mortality in the coastal zone. Chlorophyll *a* concentration was always at the level of intensive bloom (10–100 μg/l) and over the period of 6 years (2008, 2010, 2011, 2012, 2014, 2016) it reached the hyperbloom state (above 100 μg/l). Water temperature appeared to be one of the key factors determining seasonal and long-term variability in phytoplankton abundance and, therefore, the level of eutrophication in the Curonian Lagoon.

Keywords *• the Curonian Lagoon • pollution • nutrients • chlorophyll a • primary production • phytoplankton • eutrophication*

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INTRODUCTION

Eutrophication and hazardous substances are the most burning environmental issues in water basins (HELCOM 2017). Coastal lagoons are highly vulnerable to both environmental and anthropogenic factors: climate change and pollution in particular. Therefore, analysis of long–term changes in hydrological, chemical and biological parameters could help to demonstrate the actual relationship between global and local changes and also to distinguish between natural and anthropogenic impacts.

Shallowness, strong water mixing, wind currents, river runoff and water exchange with the Baltic Sea are the main features, determining the hydrochemical regime of the Curonian Lagoon.

The Nemunas River enters the lagoon in its central area, dividing the water body into two different parts (Jurevičius 1959). The northern part transports freshwater into the sea but also receives seawater during wind-driven short-term inflow events. The lacustrine southern part is characterized by a relatively closed water circulation and lower current velocities (Ferrarin *et al.* 2008). The lagoon and its catchment area are located in a densely populated area with intensely developed agriculture. In recent decades, eutrophication of the reservoir has become more intensive.

The Curonian Lagoon ecosystem has been fairly well studied. Among contemporary investigations into the lagoon ecosystem, studies into algal blooms (Pilkaitytė 2003; Pilkaitytė, Razinkovas 2007) and cyanobacteria and their toxins in water (Paldavičienė et al. 2009; Belykh et al. 2013) could be mentioned. In the second half of the 20th century, agriculture and cities became the main source of phosphorus and nitrogen, which caused significant eutrophication of the Curonian Lagoon (Zaldívar *et al.* 2008). The concentration of nutrients reaches its maximum in winter and early spring, before the start of intensive development of diatom algae (mainly *Stephanodiscus hantzschii*). A decrease in nitrate concentration at the beginning of summer accompanied by the rapid regeneration and increase in phosphorus, makes the ratio of nitrogen to phosphorus favorable for the bloom of cyanobacteria, mainly *Aphanizomenon flos-aquae* and *Microcystis aeruginosa* (Pilkaitytė, Razinkovas 2006). As *A. flos-aquae* contain microscopic vesicles that regulate their buoyancy, they are an important component of clusters on the water surface (Walsby 1994). Cyanobacteria spread over the lagoon from the end of June and the beginning of July till the end of October, accompanied by intensive bloom (Aleksandrov 2009, 2010; Aleksandrov, Dmitrieva 2006; Gasiūnaitė *et al.* 2008; Olenina, Olenin 2002). During the bloom period, the spatial-temporal concentration of dissolved oxygen in the lagoon greatly varies, resulting in anoxic conditions at high temperatures and low wind speeds (Gasiūnaitė *et al.* 2008).

Harmful algal blooms cause deterioration of water chemical parameters, pollution with toxins and death of fish. Eutrophication and "blooming" of Cyanobacteria have the strongest impact on the coastal zone of the Curonian Lagoon, especially along the coast of the Curonian Spit. The combination of cyanobacteria bloom and anoxic conditions is detrimental to macrophyte communities. The aerophyte belt width ranges from 15 to 150 m and is about 300 m in the northeastern part of the lagoon, where water reaches the depth of 1 m (Sinkeviciene 2004).

The main purpose of this research is to analyze long-term changes in eutrophication and effects of algal bloom in the southern (Russian) part of the Curonian Lagoon, along the coast of the Curonian Spit in particular.

MATERIAL AND METHODS

Initial data for studying the effect of water eutrophication and algal blooms were collected over the period 2007–2016 from 4 sampling points. Sampling points 1 and 2 were located in the coastal zone at a distance of 1 km from the Curonian Spit coast. Sampling points 3 and 4 were located at a distance of 4–5 km from the Curonian Spit coast featuring processes characteristic of the open part of the Curonian Lagoon (Fig. 1). Data were collected monthly from March (April) to November (October). The data, which were biological (chlorophyll *a*, primary production, phytoplankton), chemical (nutrients, 5–day biological oxygen demand (BOD_5), dissolved oxygen, etc.), and physical (transparency, temperature), were analysed in the Laboratory of Hydrobiology and Laboratory of Hydrochemistry of the Atlantic Research Institute of Marine Fisheries and Oceanography.

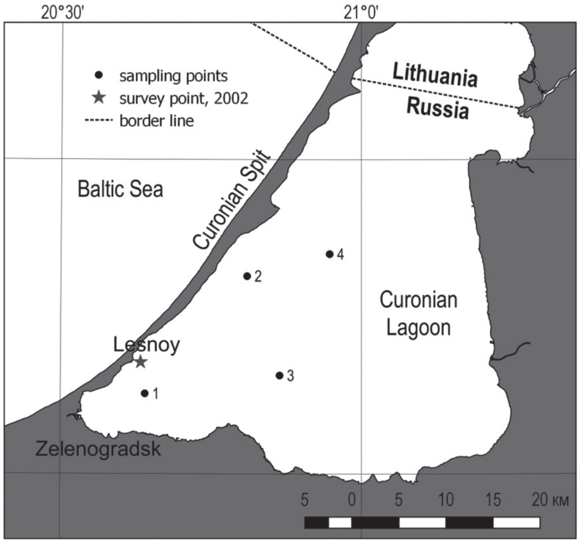

Fig. 1 Location of sampling points in the Curonian Lagoon

The hydrological, hydrochemical and biological parameters (water temperature, concentration of chlorophyll *a* and nutrients, including phosphate, nitrate, ammonia nitrogen, total phosphorus and total nitrogen) were assessed in the surface layer employing standard methods (ICES 2004; Koroleff 1972) (Table 1). The chlorophyll *a* was extracted from 0.3 μm filters using a 90% acetone solution, the optical density of the extract being measured at 4 wavelengths, i.e. 750, 664, 647, and 630 nm (Edler 1979; ICES 2001).

Photosynthesis intensity was measured using the light and dark bottle technique in its oxygen modification with short-period (3–5 hours) exposition of samples. When calculating the primary production per unit area (m^2), the rates of photosynthesis and mineralization of organic matter were measured at 4 depth levels of the photic zone, and in the near-bottom layer (Vollenweider *et al.*, 1974).

The state of the Curonian Lagoon eutrophication was assessed based on the trophic classification (Hakanson, Boulion 2002; Nurnberg 1996; Wasmund *et al.* 2001) using long-term monthly samplings (from April 2007 to November 2016). According to these

Table 1 Methods of quantitative analysis used for the processing of samples

The analysed parameter	Standard methods	Device	Measurement range, mg / l	Probability, % (mg/l)
Ammonia nitrogen	Photometric method with Nessler reagent	Spectrophotometer UNICO 1201	0.05–0.15	30%
			0.15–1.0	24%
			1.0–4.0	20%
Nitrite nitrogen	Photometric method with Griss reagent	Spectrophotometer UNICO 1201	0.01–0.25	$0.004 + 0.13 \cdot X$ X – concentration, mg/l
Nitrate nitrogen	Photometric method with Griss reagent after recovery in cadmium-shaft gearbox	Spectrophotometer UNICO 1201	0.01–0.08	$0.004 + 0.24 \cdot X$
			0.08–0.30	$0.006 + 0.24 \cdot X$
Total nitrogen	Photometric method after oxidation with potassium persulfate	Spectrophotometer UNICO 1201	0.04–0.20	35%
			0.20–0.40	25%
Phosphate phosphorus	Photometric method with ammonium molybdate	Spectrophotometer UNICO 1201	0.01–0.20	$0.002 + 0.092 \cdot X$
Total phosphorus	Photometric method after oxidation with potassium persulfate	Spectrophotometer UNICO 1201	4.6%	
Chlorophyll *a*	Spectrophotometric method using acetone solution	Spectrophotometer LEKI SS 2109	0.2–0.7	20%
			> 0.7	10%

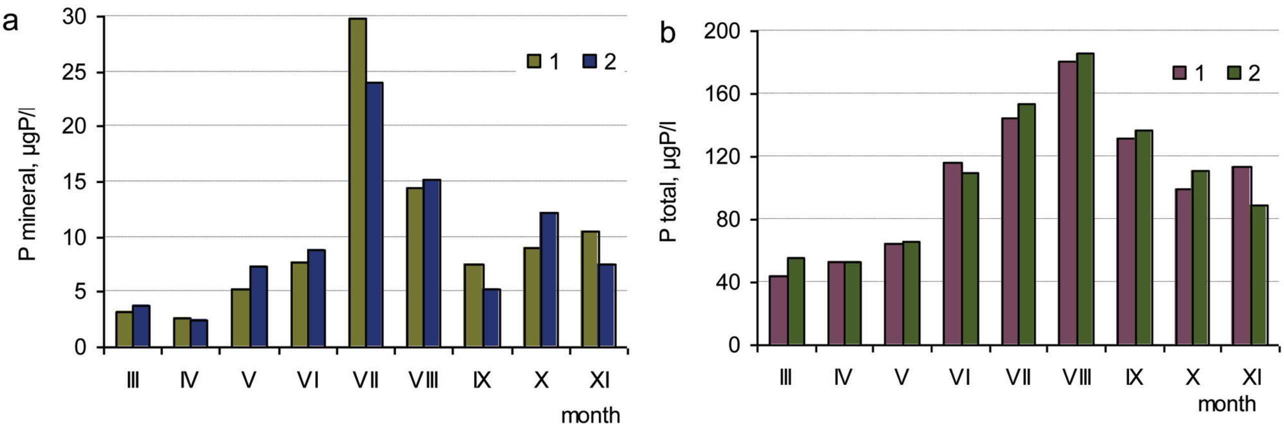

Fig. 2 Seasonal changes in the concentration of mineral phosphorus (a) and total phosphorus (b) in the coastal (1) and off-shore (2) areas of the Curonian Lagoon (mean for 2007–2016)

classifications (on the basis of chlorophyll *a*, nutrients and primary production), 4 types of the trophic state are distinguished: oligotrophic, mesotrophic, eutrophic and hypereutrophic.

To illustrate the phenomenon of fish mortality alongside the coast of the Curonian Spit, we used high temporal resolution data, which were obtained from the survey conducted in the summer of 2002 (Fig. 1).

Water temperature was estimated on the basis of the daily observation data at a standard hydrometeorological station in the Curonian Lagoon (v. Otkrytoye), which were submitted by the Kaliningrad Center for Hydrometeorology.

RESULTS AND DISCUSSION

Hydrochemical regime in the Curonian Lagoon

The analysis of long-term sampling data revealed the following pattern in the seasonal dynamic of mineral phosphorus concentrations. After a decrease to minimum values (2–4 µgP/l) in spring, when active vegetation of phytoplankton begins, the concentration of mineral phosphorus increased to maximum annual values in summer before the blooming of Cyanobacteria (24–30 µgP/l in July) (Fig. 2a). This phenomenon was observed despite the intensive use of phosphates in the summer period and the river flow slowdown. Such excess of mineral phosphorus in water was a chemical prerequisite and an indicator of the eutrophic state of the lagoon. The mineral phosphorus concentration began to decrease in August (14–15 µgP/l) together with intensive algal bloom and continued in autumn (5–12 µgP/l).

The values of total phosphorus in water underwent seasonal changes. Maximum values (up to 144–186 µgP/l) were characteristic of the Cyanobacteria "blooming" period (July–August). Minimum values (44–66 µgP/l) were recorded from March to May before the algal bloom (Fig. 2b). The total phosphorus level mainly depended on the organic phosphorus forms present in phytoplankton biomass. In the ice-free period of 2007–2016, organic phosphorus accounted for 90% of the total phosphorus on average, reaching 94–95% in some months.

Seasonal dynamic of nitrate concentrations in the Curonian Lagoon was characterized by maximum values at the beginning of spring (up to 484–595 μgN/l) due to winter accumulation and floodwater intake. A sharp decline in nitrate concentrations was recorded in May due to the uptake by phytoplankton. The minimum concentrations of nitrate were recorded in summer (5–18 μg/l), with an increase observed only in October (110–120 μgN/l) and November (220–232 μgN/l) after the algal bloom and at the beginning of winter accumulation (Fig. 3a). Nitrate concentrations were low throughout the year from March to November (1–10 μgN/l).

The ammonium nitrogen concentrations reach peak values three times per year: the maximum was observed in July (up to 100–124 μgN/l), when Cyanobacteria began to bloom. Other two peaks were in March (67–112 μgN/l) before the intensive algal growth and in October–November after the algal bloom (Fig. 3b). Ammonium nitrogen concentrations were found to be particularly high in coastal zones of phytoplankton accumulation (up to 600–1000 μgN/l).

Total nitrogen concentrations also showed seasonal fluctuations. The minimum values (1100–1500 μgN/l) were observed in April–May before the blooms of Cyanobacteria. During algal blooms, the total nitrogen concentration increased, reaching 2400 μgN/l (Fig. 3c). From May to September, inorganic nitrogen accounted for 2–6%, reaching 20–40% in March–April, before the active vegetation of phytoplankton.

Our studies did not reveal any significant differences in the concentration of mineral and total nitrogen and phosphorus and their seasonal dynamics between areas along the coast of the Curonian Spit (sampling point 1, 2), and off-shore areas (sampling points 3, 4).

The mineral nitrogen/phosphorus ratio (N/P) in summer ranged from 1 to 5, which is several times lower than the stoichiometric ratio for phytoplankton (N/P = 7) nutrients (Fig. 4) and concentrations of nitrogen were an obstacle for algal growth in summer. Consequently, Cyanobacteria had an opportunity for intensive development due to nitrogen fixation ability, compensating for the lack of nitrogen. This fact together with high phosphorus concentrations caused Cyanobacteria bloom in the Curonian Lagoon.

Oxygen regime in the lagoon was determined by the intensity of biochemical processes, shallowness and pollution level. Water column in the Curonian Lagoon was well oxygen saturated (usually 100–120%) for two main reasons: active photosynthesis and shallowness, which causes mixing and aeration. As a result, optimum conditions were created for hydrobionts. The dissolved oxygen concentration varied

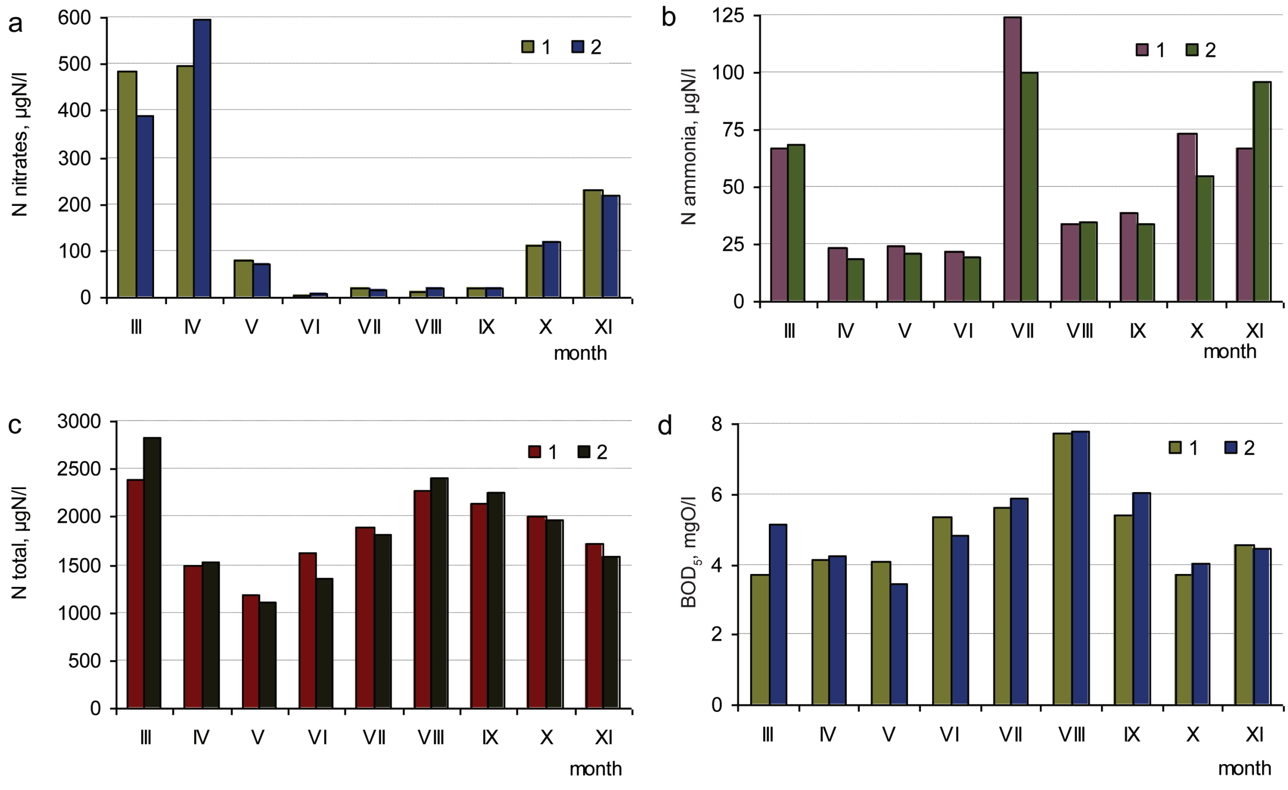

Fig. 3 Seasonal changes in concentration of nitrates (a), ammonia nitrogen (b), total nitrogen (c) and BOD_5 (d) in the coastal (1) and off-shore (2) areas of the Curonian Lagoon (mean for 2007–2016)

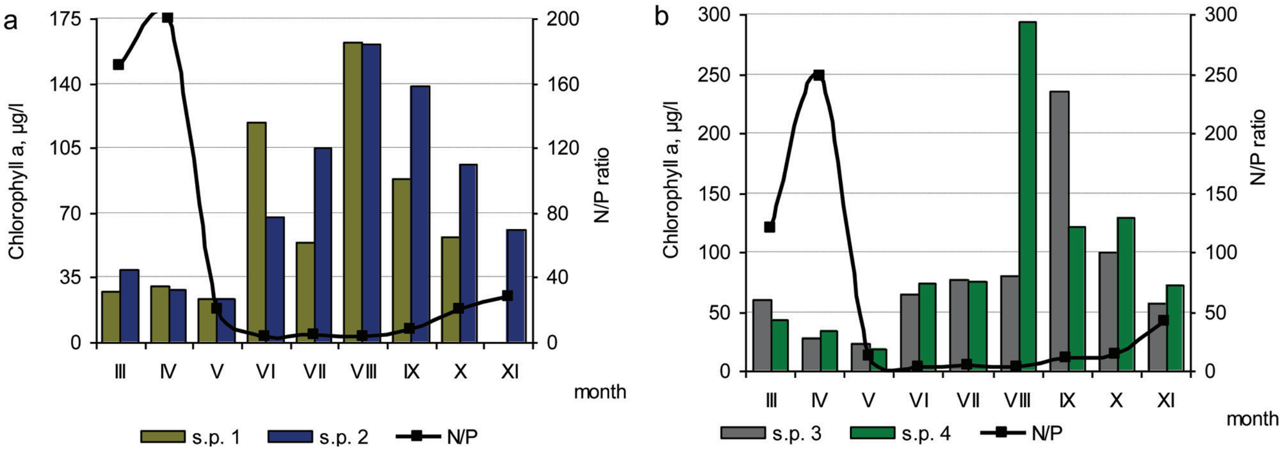

Fig. 4 Seasonal changes in the concentration of chlorophyll *a* in the coastal area at sampling points 1, 2 (a), in the off-shore area at sampling points 3, 4 (b), and the ratio between mineral forms of nitrogen and phosphorus (mean for 2007–2016)

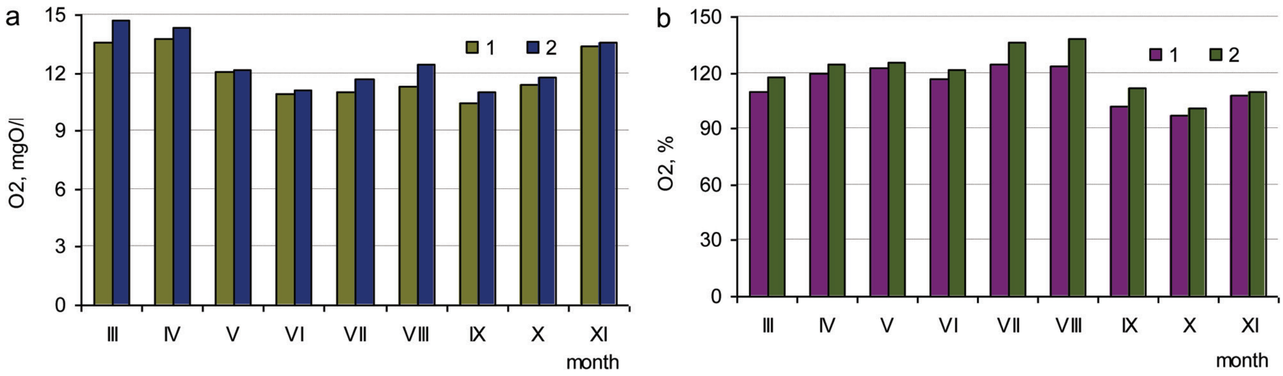

Fig. 5 Seasonal changes in the concentration of oxygen (a) and oxygen saturation (b) in coastal (1) and off-shore (2) areas of the Curonian Lagoon (mean for 2007–2016)

seasonally: the spring maximum recorded in March and April (14–15 mgO_2/l) during intensive photosynthesis at low temperatures was followed by a summer decrease (10–11 mgO_2/l) due to water warming (Fig. 5). Strong supersaturation was observed (125–138%) during algal blooms (July–August) in the open part of the lagoon. Local surface peaks of dissolved oxygen concentrations up to 18–20 mgO_2/l (200–250%), which is twofold higher than in the bottom layer, were observed during the hyperbloom of Cyanobacteria.

Although the difference between coastal and off-shore area sampling points was negligible, during intense algal blooms, coastal sampling points located amid macrophyte bushes showed a periodic drop in oxygen concentration (until the hydrogen sulfide appearance). Such a phenomenon was observed when strong winds drove large masses of algae to the coast, where they decomposed, causing fish death, mainly that of fingerlings. The phenomenon was of local nature and it was determined by the direction and force of the wind.

High values of biological oxygen demand (BOD_5) in the Curonian Lagoon indicated biocontamination during the phytoplankton growing season. Minimum values were recorded before and after algal blooms: in spring from March to May (3.4–4.2 mgO_2/l) and in October–November (3.7–4.5 mgO_2/l). The peak of BOD_5 (7.7–7.8 mgO_2/l) was recorded within the algal bloom period in August (Fig. 3d). In local areas of the open part of the lagoon, BOD_5 reached 11–19 mgO_2/l during the hyperblooming of Cyanobacteria in July–August. Values of BOD_5 in the Curonian Lagoon always exceed the maximum permissible concentration for fishery water reservoirs in Russia (2.1 mgO_2/l), while the threshold limit value for sanitary water use (6 mgO_2/l) was exceeded only during algal blooms. However, this excess of MPC was induced exclusively by natural processes that cause development of algae in the Curonian Lagoon, and was not associated with anthropogenic pollution of the lagoon.

During the hyperbloom of Cyanobacteria, the concentration of ammonia nitrogen could reach 800–1000 µg N/l, BOD_5 – 21–25 mg O_2/l, and pH of water – 9.8–10.0, i.e. the maximum permissible concentrations for fishing water bodies were considerably exceeded. The concentration and decomposition of Cyanobacteria led to oxygen deficit up to its absolute absence (16–0% saturation) and fish death in the coastal zone. The years with persistent east winds in

July–August resulted in the wind–driven aggregation of Cyanobacteria near the Curonian Spit, which is a densely inhabited and recreationally developed area.

Algal blooms and chlorophyll *a* concentration in the Curonian Lagoon

Various studies of phytoplankton in the Russian part of the Curonian Lagoon have been carried out for more than 80 years (Schmidt-Ries 1940; Olenina 1998; Pilkaitytė 2003; Belykh *et al.* 2013). In terms of phytoplankton species composition, the lagoon was classified as a typical freshwater body; brackish–water species dwell only in its northern part.

Throughout the study period, a principally invariable model of seasonal phytoplankton succession was observed: Bacillariophyta were dominant in winter and spring, while Cyanobacteria were dominant in summer and autumn (Pilkaitytė 2003; Aleksandrov, Dmitrieva 2006).

Very high chlorophyll *a* concentrations in the Curonian Lagoon indicated abundance of phytoplankton throughout the growing season. Minimum values were recorded before and after algal blooms: in spring from March to May (22–51 μg/l) and in November (61–64 μg/l). The difference in chlorophyll *a* concentrations between coastal and off–shore sampling points significantly increased in the period of August–September: 139–163 μg/l and 235–294 μg/l accordingly (Fig. 4). The chlorophyll *a* concentration at sampling points 3 or 4 sometimes reached 904 mg/m^3, while primary production increased to 9–16 gC/·m^{3}day. Distinct peaks of chlorophyll *a* concentration, primary production and phytoplankton biomass were observed in the period of Cyanobacteria hyperbloom (Pilkaitytė 2003; Aleksandrov, Dmitrieva 2006), which is typical of eutrophic water bodies. A similar model of seasonal dynamics was already recorded in 1974–1976 (Krylova 1985).

Long-term dynamics of the chlorophyll *a* concentration in the Curonian Lagoon is characterized by high variability in different years. The mean chlorophyll *a* concentration in the growing season (March–November) in 2007–2016 varied between 42 and 137 (mean 88 ± 37) μg/l in the coastal zone and between 46 and 197 (mean 99 ± 46) μg/l in off-shore areas of the Curonian Lagoon.

The concentrations of chlorophyll *a* in the summer hydrological period (July–September) were significantly higher than the average of the whole growth season. The measured chlorophyll *a* concentrations in this period varied between 49 and 197 (mean 120 ± 66) μg/l in the coastal zone and between 58 and 454 (mean 160 ± 124) μg/l in off-shore areas. Peaks of chlorophyll *a* concentration were observed in the years of pronounced Cyanobacteria hyperbloom (2008, 2010, 2011, 2012, 2014, and 2016) (Fig. 6). Results of the environmental studies performed in the period 2007–2016 did not show any significant improvement in indicators of eutrophication in the Curonian Lagoon.

Algal bloom effects in the coastal area of the Curonian Lagoon

Results of the current and previous research (2001–2016) indicate that accumulation of phytoplankton, oxygen deficit and fish death could be observed in the coastal zone during the Cyanobacteria bloom in July and August.

The survey conducted in the summer of 2002 shows processes taking place in the coastal zone within algal blooms. The excess of phytoplankton along the south-western lagoon shore (including the study area near the Lesnoy village) was caused by

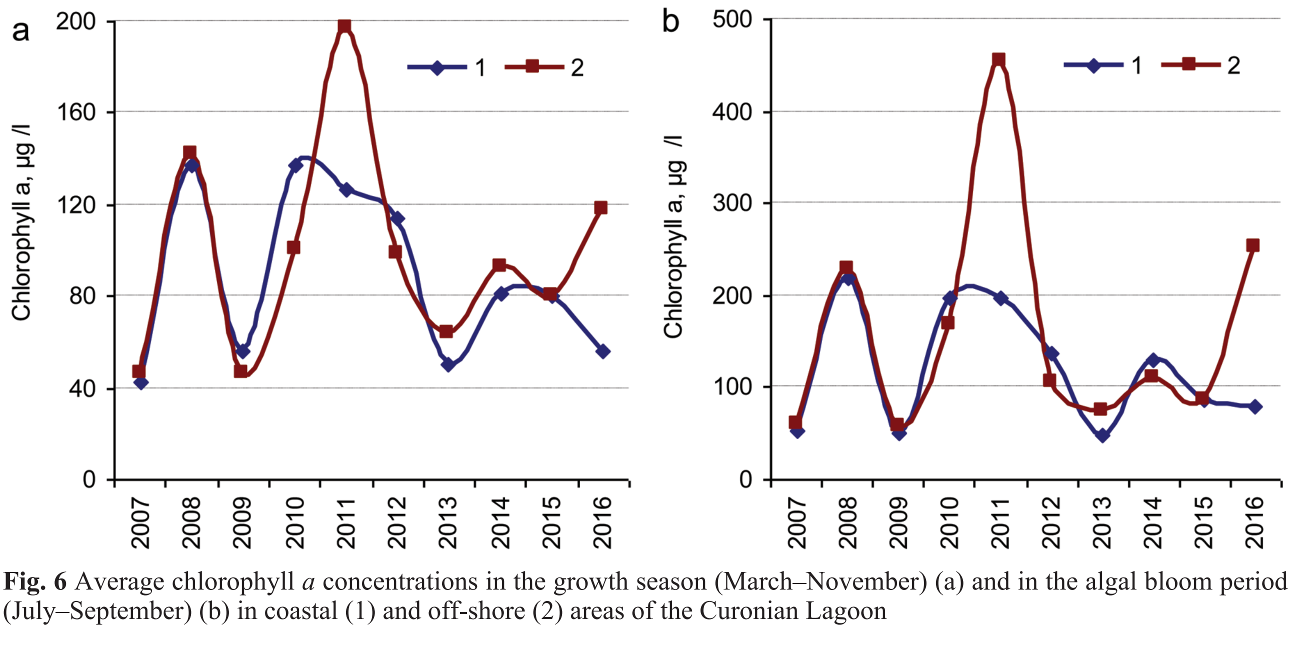

Fig. 6 Average chlorophyll *a* concentrations in the growth season (March–November) (a) and in the algal bloom period (July–September) (b) in coastal (1) and off-shore (2) areas of the Curonian Lagoon

constant winds of east direction from July 28 (wind speed 4–5 m/s). In the meantime, Cyanobacteria hyperbloom (dominated by *Aphanizomenon flos-aquae*) was observed in the open part of the lagoon with chlorophyll *a* concentrations reaching up to 84–185 mg/ m^3 (average 160 mg/m^3).

At the beginning of the study period on July 30, 2002, the phytoplankton density in the study area was small, the primary production level was very high (0.30 gC·m^{-1}·h^{-1}) and daily oxygen was supersaturated (11.4 mg/l or 140%). However, in the bays formed by macrophyte thickets, where algae accumulated and decomposed, rates of organic matter destruction were higher than the primary production level. In these bays, dissolved oxygen rapidly decreased leading to fish deaths. Fish mortality occurred within 30 minutes from 19:30 to 20:00. One small bay (600 m^2), almost completely enclosed from the open water area by reed thickets, was affected particularly badly and death of several hundred fish individuals (up to 20–30 cm in length) with obvious signs of asphyxia was recorded. The concentration of dissolved oxygen was 0.4 mg/l (5%).

An even higher primary production level was observed 500 m away from the coast on the next day (July 31, 2002), which was induced by the continuing influx of phytoplankton from the open part of the lagoon (Fig. 7). The accumulation of algae led to the increased isolation of metabolites and the resultant autotoxicosis and algal decomposition. Oxygen uptake in water sharply increased and destruction of organic matter began to increase exceeding primary production in the water column. The content of oxygen in water sharply decreased, actually reaching zero by the evening. The mass migration of large fish (bream, pike perch) to the open part of the Curonian Lagoon was noted during the evening and night of that day. The fish individuals (mostly young), which did not leave the study area were thrown ashore.

In the morning of August 1, when algae continued to drift to the coastal zone (500 m from the reed belt), an anomalously high chlorophyll concentration (22500 mg/m^3) was recorded (at a value of 100 mg/ m^3 the reservoir is considered hypereutrophic). The entire water column (2.0 m depth) was basically a suspension saturated with half-decomposed *Aph. flos-aquae*, the water transparency was only 3–4 cm, and the oxygen concentration was about zero. During this period, the oxygen method did not allow to record either primary products or decomposition. Quantitative estimation of algal cells with such a biomass is also difficult, so the degree of phytoplankton abundance was measured by chlorophyll *a* and by weighing the filtered samples.

The extremely high concentration of phytoplankton in the coastal zone of the lagoon (500 m away from the reed belt) did not last for a long time and algae were driven by the wind to the shore. The accumulation of algae was especially dangerous for hydrobionts living in the areas covered with macrophyte reeds and in small bays, as was observed during this survey. During the accumulation–decomposition cycle, the biomass of algae varied from 1 to 408 kg wet weight/m^3 (or 3200–280600 mg Chl/m^3) depending on the intensity of their intake from the open lagoon area. The oxygen concentration remained close to zero (0.1–0.7 mg/l) for a long period of time (month and more) (Figs. 7, 8). Due to algal decomposition, the pH value decreased from 8.5–9.0 to 6–7. Consequently, the coastal lagoon area, potentially the most productive one, turned into a lifeless place in terms of ichthyofauna where the incoming masses of phytoplankton were constantly decomposed.

The study of the Curonian Lagoon coastal area (100 and 500 m away from the macrophyte belt) showed that under a constant wind, conditions unsuitable for fish life (oxygen absence in particular) can persist for a sufficiently long period (up to 8 days) (Fig. 8). The survey of the all Russian area of the Curonian Lagoon, carried out on August 14, 2002, when the oxygen content in

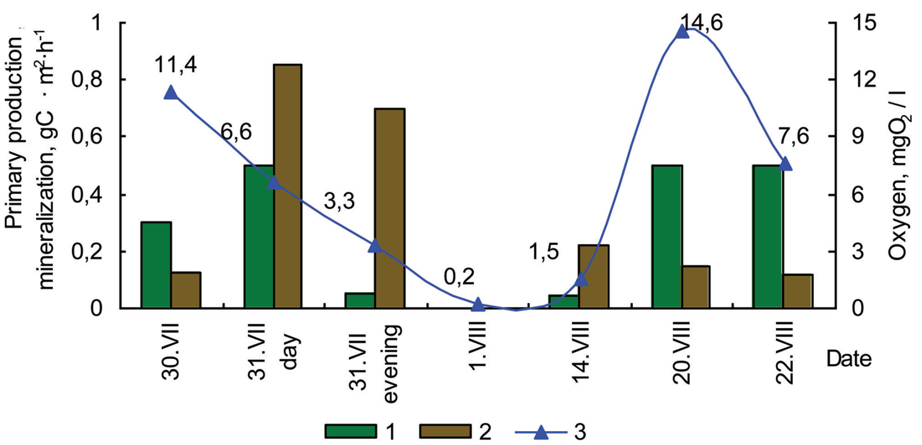

Fig. 7 Primary production level (1), mineralization (organic matter decay) (2) and oxygen concentration (3) in the coastal zone at a distance of 0.5 km from the Curonian Spit coast during the hyperbloom (July–August 2002)

the coastal part of the lagoon was only 0.2 mg/l, made it possible to estimate the scale of this phenomenon. In the open part of the Curonian Lagoon, the primary production exceeded destruction in the water column, and oxygen saturation was more than 100%. Only near the coast of the Curonian Spit, in the area near the village Lesnoe, a very low oxygen content (0.8 mg/l) was noted at a distance of 1.5 km from the coast. In this local area, processes of organic matter destruction greatly exceeded the primary production.

It turned out that the main reasons for the long-term oxygen absence and fish mortality in the coastal zone were the massive Cyanobacteria development and almost steady easterly winds, causing phytoplankton accumulation and decomposition. Nevertheless, the research revealed that this phenomenon is of local nature.

In the second half of August 2002, the process of photosynthesis in the coastal zone of the Curonian Lagoon intensified again. The primary production of plankton significantly exceeded the destruction of organic matter in the water column (Figs. 7, 9). The oxygen concentration in the daytime increased rapidly to 100% saturation and above. The background survey conducted in August 2002 showed a very high level of primary production, high concentrations of chlorophyll *a* and dissolved oxygen (up to 200% and higher) all over the Russian part of the Curonian Lagoon. It took three weeks to overcome the consequences of the massive Cyanobacteria accumulation, to restore the phytoplankton community structure and biomass in the coastal part of the Curonian Lagoon and also to equalize hydrochemical conditions (O_2, pH) in the coastal and open parts of the lagoon. It took several months to overcome the consequences of accumulation and decomposition of Cyanobacteria in small bays, separated from the open water area by macrophyte thickets.

Effects of harmful algal blooms and climate change on the Curonian Lagoon eutrophication level

Based on the results of numerous hydrochemical and biological investigations, the Curonian Lagoon

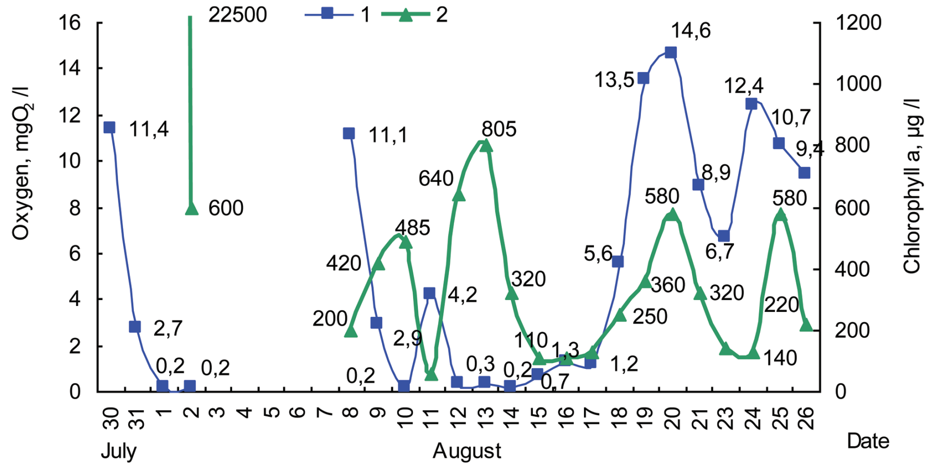

Fig. 8 Concentration of oxygen (1) and chlorophyll *a* (2) in the coastal part of the Curonian Lagoon during the Cyanobacteria hyperbloom (July–August 2002)

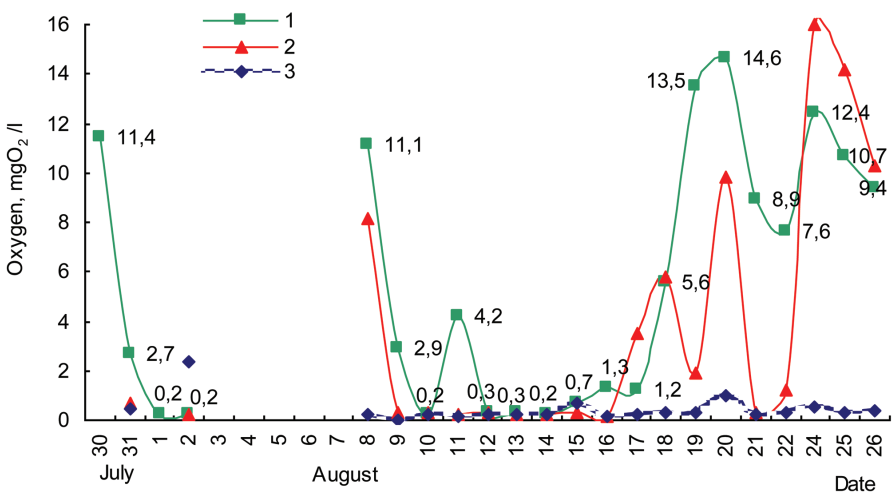

Fig. 9 Oxygen contents in the coastal zone in the period of algal accumulation (1, 2 – 500 and 100 m from the reed bed, 3 – channel in the reeds)

can be classified as a hypertrophic water body (Aleksandrov 2009, 2010).

The hypereutrophic state was observed in the whole water area of the Curonian Lagoon. Environmental conditions in central and southern parts of the Curonian Lagoon, i.e. slow water exchange, water freshness, shallowness, high concentration of nutrients in bottom sediments with its resuspension, enhance Cyanophyta development. The concentration of chlorophyll *a* and primary production in the Curonian Lagoon were found to be among the highest in water bodies of the Baltic Sea basin (Aleksandrov 2010).

In 2007–2016, in the Russian part of the lagoon, the number of stations with the average chlorophyll concentration in the growing season exceeding 100 mg/m^3 increased, and eutrophication reached an extremely high level.

Initially, the main reason for the hypertrophic state of the Curonian Lagoon and Cyanophyta (*Aphanizomenon flos-aquae, Microcystis aeruginosa*) blooms was intensive loading of external nutrients in the 20th century from the densely populated catchment area. The peak of the annual input of phosphorus (3.7–8.5 g/m^2) and nitrogen (61–110 g/m^2) was reached during the 1980s, the period of the maximum use of fertilizers in agriculture and industrial development in the USSR. The 1990s were marked by production shortfall and reduced use of fertilizers resulting in a three–fourfold decrease in nutrient intake (Cetkauskaite *et al*. 2000). Therefore, it was expected that nutrient concentrations will decline and so will the phytoplankton biomass and the trophic state of the Curonian Lagoon. However, the research showed that neither the trophic state nor the ecological situation in the Curonian Lagoon improved. The research of phytoplankton in 2007–2016 showed that chlorophyll *a* concentration was always at the level of intensive bloom (10–100 µg/l) and over 6 years (2008, 2010, 2011, 2012, 2014, 2016) it reached the hyperbloom state (above 100 µg/l).

The observed long-term variability in phytoplankton abundance and chlorophyll concentration in the Curonian Lagoon was considerable. For instance, in the coastal area, the chlorophyll concentration during the blooming period (July–September) could vary five-fold from 49–53 g/m^2 in 2007, 2009, 2013 to 196–219 g/m^2 in 2008, 2010, 2011 (Fig. 6).

In the hydrological and hydrochemical conditions existing in most parts of the lagoon, water temperature appeared to be one of the key factors determining seasonal and long–term variability in phytoplankton abundance, and therefore, the level of the Curonian Lagoon eutrophication. Pearson's correlation coefficient between chlorophyll *a* concentrations in the coastal area of the Curonian Lagoon during the algal bloom period (July–September) and water temperature in July was 0.62. The optimal water temperature for the reproduction "outburst"of the Cyanobacteria (*Aphanizomenon flos-aquae*) species, which produces water «blooming» in the Curonian Lagoon and nitrogen-fixing, is 20–22° C (Waughman 1977; Whitton 1973). Only in some "warm" years did water temperature rise higher than 20° C in July. Therefore, in these "warm" years, *Aphanizomenon flos-aquae* formed high biomass in summer and autumn owing to the "outburst" reproduction pattern in combination with the consumption of ammonia nitrogen and nitrogen fixation and high concentration of phosphorus in water, which resulted in "hyperblooms" in the Curonian Lagoon. Years with water temperature lower than 20°C (2007, 2013, and 2016) usually did not demonstrate "hyperbloom" (Fig. 10).

According to the assessment of the current state of the Baltic Sea ecosystem and forecasts for its change (HELCOM 2007, 2017), climate-related increases in water temperature in the Baltic Sea are further expected to lead to the all-year-round production of phytoplankton, and thus to higher amounts of nutrients bound in phytoplankton biomass compared to dissolved forms. The increase in water temperature can affect nutrient recycling and have influence on phytoplankton species composition and primary production. For example, warming will inhibit the spring bloom of cold-water diatom species and may stimulate the summer bloom of warm-water Cyanobacteria. In the Curonian Lagoon, a relationship between the concentration of chlorophyll and water temperature was also observed during the growth season (March–November) (Fig. 11).

The years of peak chlorophyll *a* concentration and primary production level coincide with the years of maximum water temperature and the Cyanophyta hyperbloom. The mean annual primary production level

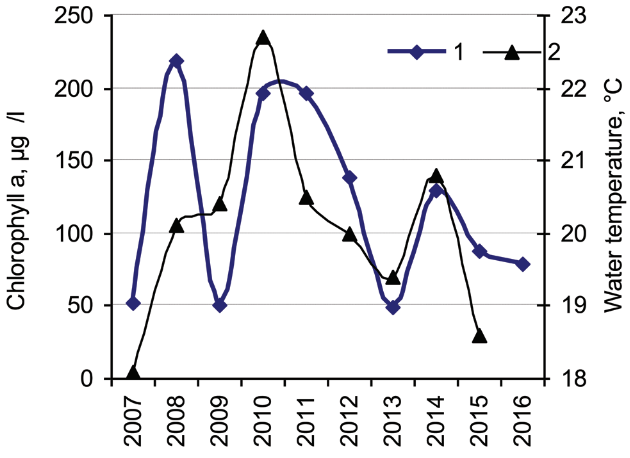

Fig. 10 Average chlorophyll *a* concentrations during the algal bloom period (July–September) in the coastal area of the Curonian Lagoon and water temperature in July

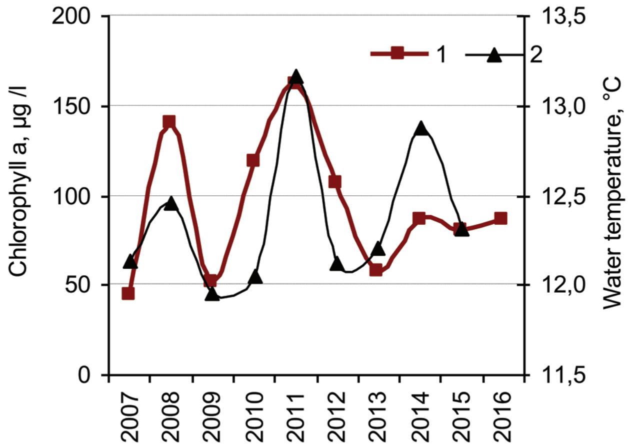

Fig. 11 Average chlorophyll *a* concentrations and water temperature during the growth season (March–November) in the south-western part of the Curonian Lagoon

in 2000s and 2010s (490 and 570 gC/m^2·per year accordingly) was considerably higher than in the middle of the 1970s (300 gC/m^2·year) (Aleksandrov 2009, 2010). That can, probably, testify to the significant eutrophication of the Curonian Lagoon where the hyperbloom of Cyanobacteria has been observed over the last thirty years.

The local climate change with the temperature rise in the Baltic region is a probable reason behind the ongoing eutrophication and harmful algal blooms in the Curonian Lagoon despite a significant reduction in the load of external nutrients in the 1990–2010 period. Cyanobacteria blooms have become a serious problem in recent decades, because many bloom–forming species produce secondary metabolites that are toxic to many organisms, including fish, mammals and even humans. The potentially toxic Cyanobacteria species *Microcystis aeruginosa* and *Aphanizomenon flos-aquae* are commonly found in the Curonian Lagoon and can produce microcystins, neosaxytoxins, and anatoxin. During the period of Cyanobacteria bloom, the concentration of microcystins in water varied between 0.1 and 134 µg/l, while the safe level for drinking water is 1.0 µg/l (Paldaviciene *et al.* 2009). Algal toxins were also detected in water, sediments, mussels and fish. Fish are most vulnerable to the Cyanobacteria effect, as intoxication with Cyanobacteria toxins results in pathological damage. In the period of Cyanobacteria hyperbloom in the Curonian Lagoon, morphopathological and histopathological changes were detected in 70–80% of mature bream (*Abramis brama*) individuals. The detected pathological changes in fish were similar to the symptoms produced by Cyanobacteria toxins, which were dominant in summer and autumn (Chukalova, Dmitrieva 2010). This fact indicates the possible toxic impact of Cyanobacteria on fish and pollution effect on the ecosystem. Therefore, the global climate change-induced water warming poses a risk to coastal water bodies as it stimulates hyperblooms of Cyanobacteria.

CONCLUSIONS

On the basis of long-term chemical and biological data, the Curonian Lagoon may be characterized as a hypertrophic water body. The ratio of mineral nitrogen/phosphorus forms created conditions for regular Cyanobacteria hyperblooms during summer and early autumn. Such blooms are followed by an increase in the amount of ammonia nitrogen, pH and BOD_5, their values exceeding he threshold limits for fishery water reservoirs. Distinct peaks of chlorophyll *a* concentration and phytoplankton biomass were observed in the period of Cyanobacteria hyperbloom from July to September or October.

The current study did not reveal any significant differences in the concentration of mineral and total nitrogen and phosphorus, BOD_5, dissolved oxygen and their seasonal dynamics between sampling points located along the coast of the Curonian Spit, and sampling points located away from the shore in the open-part of the Curonian Lagoon. However, during the "hyperbloom" of Cyanobacteria, accumulation and decomposition of Cyanobacteria, caused by a constant wind direction, led to the local oxygen deficit and fish mortality in the coastal zone. Continuous east winds in July–August resulted in the wind-driven aggregation of Cyanobacteria near the western coast of the lagoon, which is intolerable as this area is of high recreational value: Zelenogradsk city and the Curonian Spit National Park are located there.

The study of phytoplankton in 2007–2016 showed that chlorophyll *a* concentration was always at the level of intensive bloom (10–100 µg/l) and over 6 years (2008, 2010, 2011, 2012, 2014, 2016) it reached the hyperbloom state (above 100 µg/l). Water temperature appeared to be one of the key factors determining seasonal and long–term variability in the abundance of phytoplankton, and, therefore, eutrophication of the Curonian Lagoon. The local climate change with temperature rise in the Baltic region is a probable reason behind the ongoing eutrophication and harmful algal blooms in the Curonian Lagoon despite a significant reduction in external nutrient loads in the period 1990–2010.

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