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MARINE BIOLOGY

Influence of Hydrometeorological Conditions on the Plankton Distribution in the Estuary of the Pregolya River and the Coastal Part of the Baltic Sea

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Abstract—The patterns of changes in the composition and quantity of zooplankton and concentration of chlorophyll *a* in the estuary of the Pregolya River and adjacent waters of the Baltic Sea are considered depending on hydrological and meteorological conditions in 2021–2022. Three zones of the estuary were identified: estuarine, mixing, and marine. In the water mixing zone, there are salinity gradients, the position of which is influenced by wind forcing and river discharge. The largest concentration of chlorophyll *a* was noted in the estuarine zone and at the boundary of the water mixing zone, where the flow of nutrients from the drainage area is most noticeable. The removal of water from the lagoon affects the concentration of chlorophyll *a* and the composition of zooplankton. The estuarine zone is characterized by the highest level of eutrophication, where it approaches the threshold of hypertrophy; in the marine zone, the concentrations of chlorophyll *a* corresponded to eutrophic water. Depending on the inflow–outflow phenomena, the proportion of zooplankton species differs in relation to changes in salinity, and there is a sharp increase in deaths of organisms of species not adapted to a given salinity.

Keywords: nontidal estuary, Pregolya River, Baltic Sea, salinity, wind forcing, chlorophyll *a*, zooplankton

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INTRODUCTION

The catchment area of the Pregolya River is 13600 km^2, and the volume of annual runoff is about 1.53 km^3 [34, 39]. The receiving reservoir is the Kaliningrad Lagoon of the Baltic Sea. The artificially dredged estuary of the Pregolya flows into the Kaliningrad Marine Canal (KMC), a hydraulic structure fenced from the lagoon by bulk islands (dams) with shallow straits, about 43 km long. According to the hydrological regime and other indicators, the KMC, the depth of which is 5–8 m greater than in the lagoon, is a continuation of the river, its estuary [17, 32], which governs the unity of hydrodynamic and hydrochemical processes and variability of their characteristics. The hydrological regime of the study area is governed by river flow and water exchange with the sea, which are influenced by the wind regime. The lower reaches of the river, the KMC, the Baltic Strait, and the adjacent part of the Baltic Sea together are a marginal filter where mixing of river and seawaters occurs [17].

In addition to sedimentation and sorption processes, biological processes (bioassimilation, biofiltration) take place in marginal filters [16]. The marginal filter of the Pregolya has been partially studied from the physicochemical viewpoint [17, 31, 48]. The biological conditions of the the Pregolya River estuary have been studied to a lesser extent [25, 27], and some parameters (e.g., the proportion of dead zooplankton individuals in the salinity gradient) have not been studied. The aim of this study was to identify patterns of changes in the composition and quantitative development of plankton in the river–seawater mixing zone in 2021–2022.

MATERIALS AND METHODS

Research was carried out at 21 stations: 1 station at the Pregolya estuary, 15 in the KMC, and 5 in the coastal zone of the Baltic Sea (Fig. 1). A total of five surveys were carried out in different seasons (August 29 and October 19, 2021; March 2, May 25 and October 13, 2022). Wind speed and direction were analyzed based on data from the weather station of the Hydrometeorological Center in Baltiysk (height above sea level 4 m; 54°39′ N, 19°55′ E) (www.rp5.ru). The synoptic situation was assessed using surface atmospheric pressure

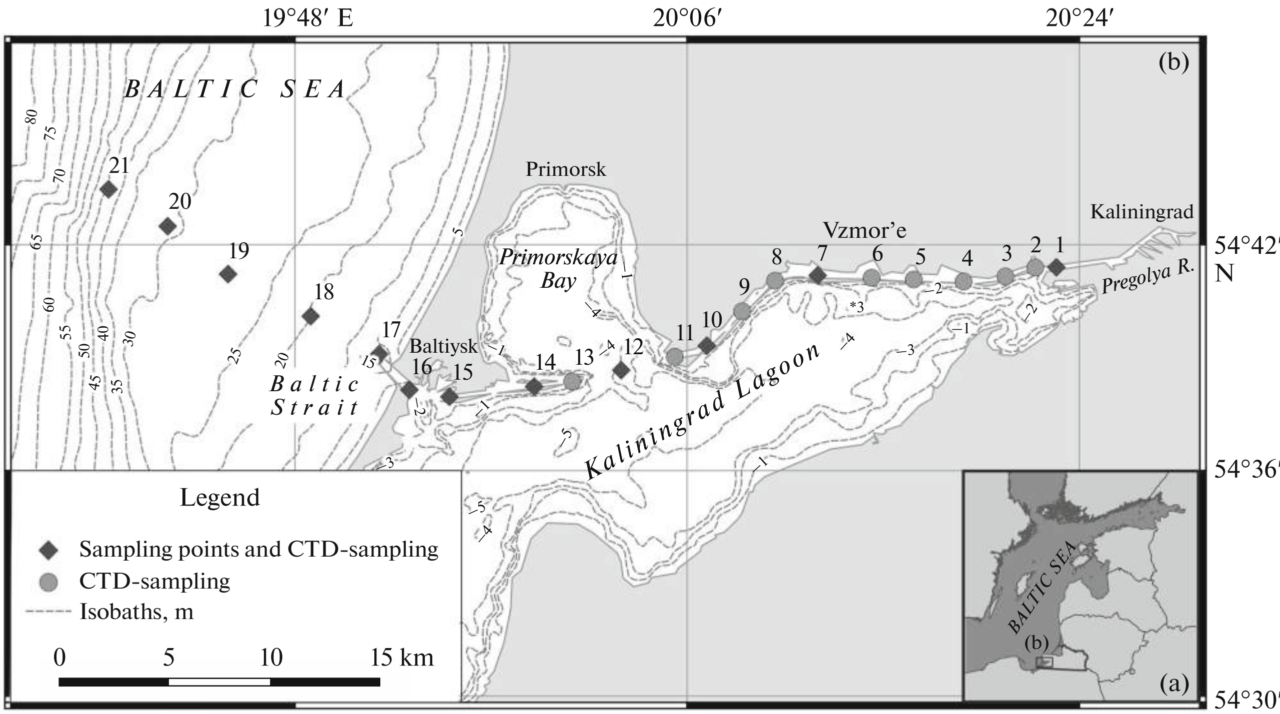

Fig. 1. Map of stations.

analysis maps from the Bracknell meteorological center (https://www.metoffice.gov.uk/).

Salinity and water temperature were determined by Sea&Sun CTD90M and CastAway multiparameter hydrophysical probes. Water samples to study the chlorophyll *a* content were taken with 5- and 10-L Niskin bottles in the KMC from the subsurface (0–1 m) and bottom horizons, and additionally in the coastal zone of the sea at the 10- and 20-m horizons. To determine the chlorophyll *a* concentration, water samples with a volume of 0.04–0.50 L were filtered through MFAS-MA-6 membrane filters (pore diameter 0.3 μm). A membrane filter with concentrated phytoplankton along with an acetone extract was placed in a test tube, homogenized, and centrifuged for 10 min at 7000 rpm to remove light-scattering particulates. The acetone extract with pigments was transferred to a quartz cell and measurements were taken on a spectrophotometer at four wavelengths: 750, 664, 647, and 630 nm in accordance with GOST 17.1.04.02–90. When describing spatial and seasonal variability, data obtained for the subsurface layer were used, which reflect the development of phytoplankton in the photic layer.

Water with zooplankton samples were taken with 5-, 10-, and 30-L Niskin bottles in the KMC from the subsurface (0–1 m) and bottom horizons, and additionally in the coastal zone of the sea at the 10- and 20-m horizons. After sampling, samples were concentrated using a net from gas no. 70 (mesh size 68 μm) [11, 19]. To assess the proportion of dead individuals in zooplankton, immediately after collection, zooplankton samples were stained with 0.05% neutral red dye [26, 30, 35, 36, 41], which was added to the water sample at the rate of 2 mL of dye per 100 mL of water, thus the final concentration dye when staining was 1 : 100000. The zooplankton sample was kept for 1–1.5 h for staining and fixed according to the standard method with 40% formalin with sucrose [45] to a final concentration in the sample of 2–4%. Desk processing of samples was done under a binocular in a Bogorov counting chamber according to standard methods [11, 18, 46, 53]. In order to take into account the most numerous species, subsamples with a volume of 1–5 mL (depending on the number of organisms) were taken from the main sample in three replicates; the obtained abundance values were averaged and recalculated for the entire sample volume. Small and rare species were taken into account in their entire volume (totally). When processing samples, most organisms were identified to species; if not possible, to a larger taxon. When calculating biomass, to calculate weight characteristics, formulas for the length–mass relationship were used or the figure of the organism was equated to a similar geometric figure. The taxonomic affiliation of the identified invertebrates was given in accordance with the World Register of Marine Species [55] and the Integrated Taxonomic Information System [47].

RESULTS AND DISCUSSION

Hydrometeorological conditions. Wind direction and speed play a decisive role in water exchange in the

Table 1. Typical wind conditions on survey dates

Year	Date of survey	Season	Wind characteristics		Surge
			direction, rumb	speed, m/s	
2021	August 29	Summer	SE → E	2–5	Outflow
	October 19	Autumn	W → NW → SE	5–10	Inflow
2022	March 2	Winter	SW → W → SW	2–7	Inflow
	May 25	Spring	NW → N → SE → W	2–7	Inflow
	October 13	Autumn	S → W → SW	2–7	Inflow

KMC [24, 37]. When the influence of the Scandinavian anticyclone spread in early March 2022, weak winds with a southern component prevailed (Table 1). For spring and summer surveys 2021–2022 the wind changed from the western direction to the southern and eastern ones. At the end of summer (August 29, 2021), moderate easterly winds prevailed under the influence of not deep Atlantic cyclones. For autumn survey 2021–2022 the wind changes from the west to the south. Analysis of seasonal wind conditions from 2021 to 2022 showed that the greatest wind activity was observed in the autumn period (October 2021 and 2022), which is associated with the restructuring of atmospheric processes and increased westerly transport. Wind gusts from the western directions reached speeds of 10–11 m/s.

During the survey period in 2021–2022, Pregolya River runoff was not measured. According to previous studies for the period 1990–2020 [35], river flow is characterized by significant intra-annual variability. The maximum flow rate is observed in the winter–spring period (January–April), the minimum in the summer–autumn period (June–October) (Fig. 2). The average long-term water flow of the Pregolya, according to various sources, is 62 m^3/s or 1.53 [39]–1.96 km^3/year [40].

Most of the surveys (August 29, October 19, 2021; May 25, October 13, 2022) were carried out during the low-water period, during which the influence of river runoff on the estuary of the Pregolya is less significant and the role of seawater inflow increases.

The nature of water level variability in the estuary significantly depends on the water level in the receiving reservoir—the Kaliningrad Lagoon (correlation coefficient 0.62)—and has a time variability more similar to fluctuations in sea level than rivers (the distribution is close to normal, with weak asymmetry [35].

Hydrological conditions. The water temperature distribution in the surface layer was uniform; at the Pregolya estuary and in the KMC, the values varied within 1–2°C (Fig. 3). At the end of spring, the surface waters in the coastal part of the sea warm 3–4°C less than the canal waters, and in the autumn, conversely, the seaward part is warmed up several degrees more than the canal and the estuarine zone. At the end of summer, the surface was uniformly heated and the temperature of the subsurface water layer averaged 18.8°C.

The salinity of the subsurface water layer (up to the 1-m horizon) naturally increased from the Pregolya estuary to the coastal part of the Baltic Sea in all seasons of the year (see Fig. 3). Minimum salinity values (0.2–0.5 PSU) were noted at the end of the winter hydrological period [9] (March 2022) in the river estuarine zone (stations 1–3), which is due to an increase in water flow during the flood period. This paper does not provide a quantitative analysis of the river runoff

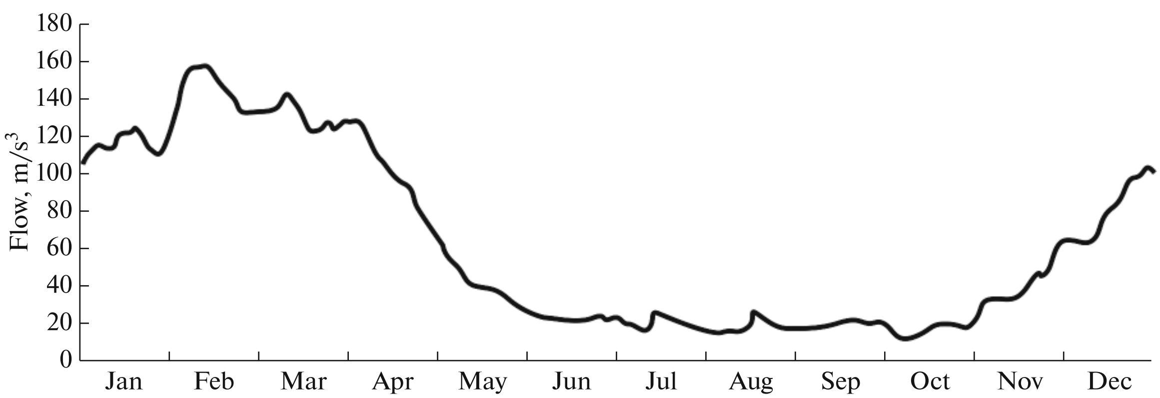

Fig. 2. Model calculation of seasonal water flow of Pregolya (estuary part) for 1980–2009 [40].

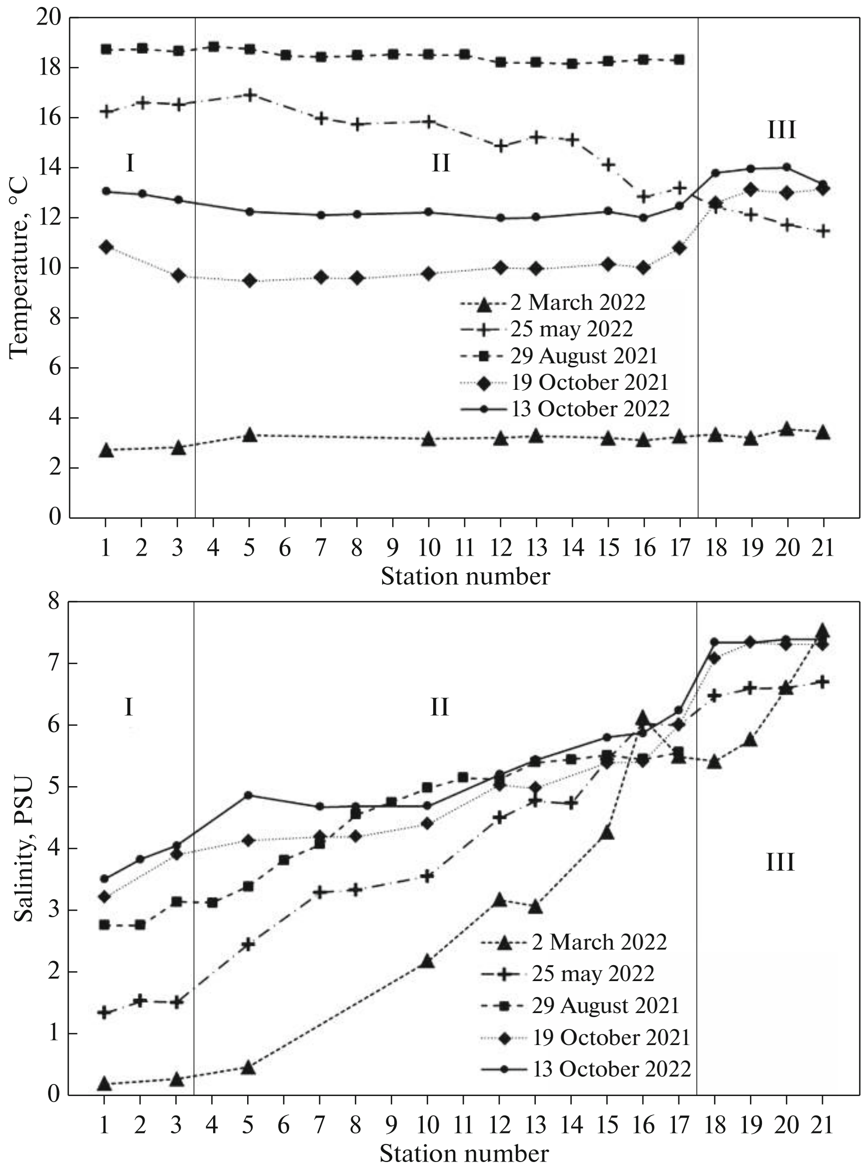

Fig. 3. Temperature and salinity profiles in surface layer in different seasons (averaged hydrological zones: I, estuarine; II, mixed; III, marine).

and discharge during the period under study due to the lack of reliable data. However, according to the distribution curve of the seasonal variation of the Pregolya discharge (see Fig. 2), the discharge in March is quite high. Near the Primorskaya Bay area, the salinity increased to 3.2 PSU. Then the salinity increased sharply to 6 PSU before the Baltic Strait (station 15), which is associated with the prevailing southwestern winds, forming inflow phenomena. In the strait and coastal zone, salinity values decreased slightly (5.4 PSU) and increased in the seaward part up to 7.6 PSU.

In May, salinity values at the river estuary were 1.3 PSU and increased to 6.7 PSU in the coastal part of the sea. At the end of summer, the general pattern of salinity distribution in the surface layer is similar to that in spring; minimum values were noted in the estuarine zone (2.7 PSU) and increased towards the Baltic Strait (5.6 PSU). In autumn (October 2021 and 2022), salinity values were higher throughout the entire section in the subsurface layer (from 3.5 PSU at the estuary to 7.4 PSU at the exit from the Baltic Strait). During this period of the year, westerly winds dominated, which favor the formation of inflow phenomena.

The vertical and spatial distributions of temperature and salinity are presented in Fig. 4. Mixing in the KMC of waters of different origins is characterized by the presence of pronounced salinity gradients: in the zone of mixing of river waters with canal waters—between stations 1–3; mixing of seawater with canal water—in the area of stations 15–18. Based on the

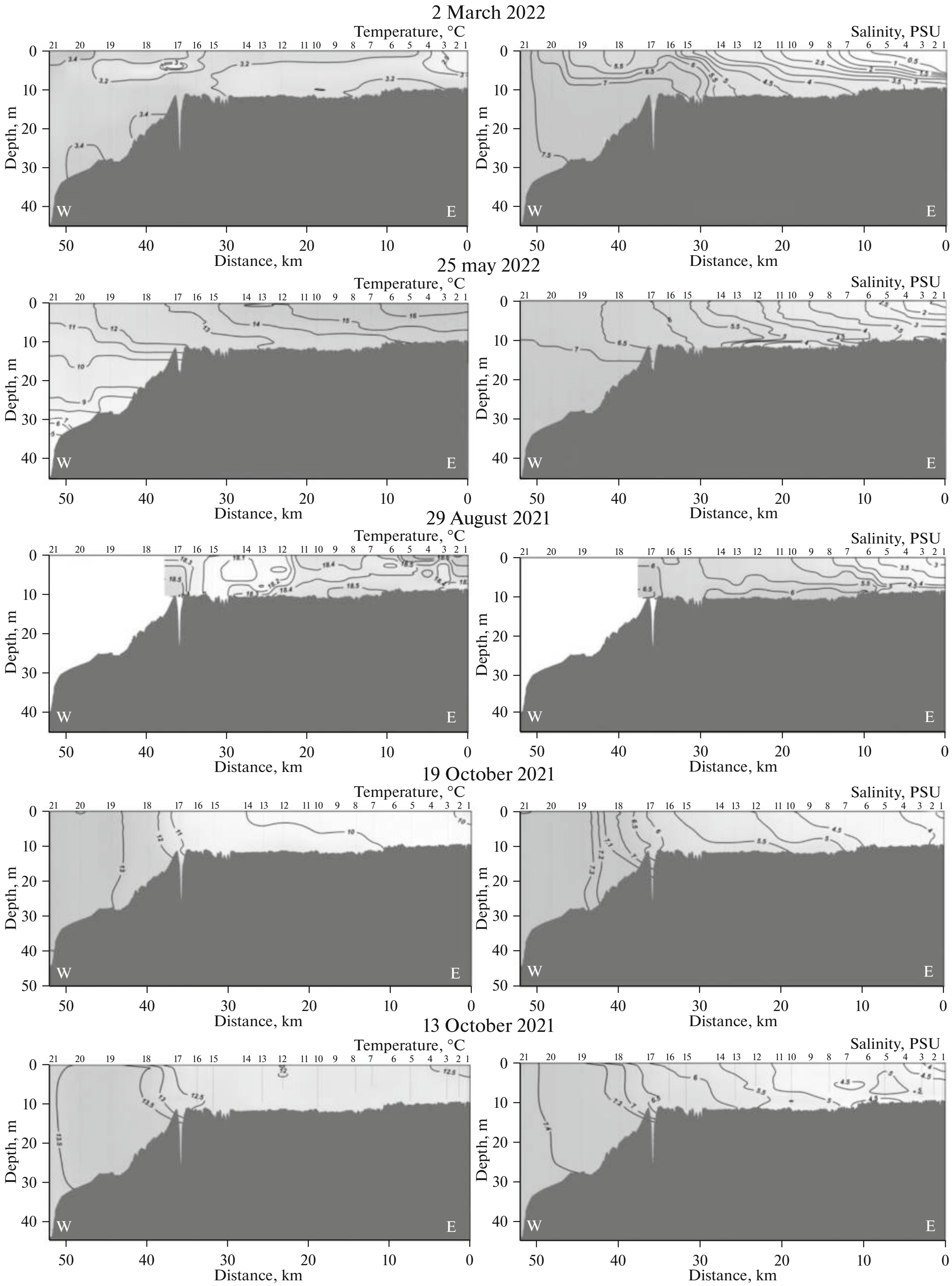

Fig. 4. Distribution of temperature and salinity of water in different seasons from Pregolya estuary (right) to coastal zone of Baltic Sea (left).

obtained hydrological data and the results of previous works [17, 47], we can conditionally divide the estuary of the Pregolya into three zones: the estuarine zone (stations 1–3), the mixing zone (stations 4–17), and the marine zone (stations 18–21) (see Fig. 2). *The estuarine zone* is understood as the area where the river flows into the receiving reservoir (Kaliningrad Lagoon and KMC), which is conventionally considered freshwater, but during periods of strong inflow phenomena, penetration of brackish-waters upstream of the river is observed. *The mixing zone* is characterized by the presence of river, lagoon and transformed waters of the Baltic Sea, which, during surge winds, enter the KMC (and, during strong and prolonged inflows, further into the Pregolya estuary). *The marine zone* is understood as the area to the west of the Baltic Strait, in which, during outflows events, the waters of the canal and lagoon are mixed with seawater. The identification of zones in this study was carried out by salinity, since the spatial gradient is most pronounced for this parameter. The boundaries of the selected zones vary depending on the season of the year, the prevailing wind direction and speed, and the volume of river flow. It is known [38] that a surge event is stable when the water level rises at a speed of more than 0.8 cm/h. River flow in spring ensures a shift in the equilibrium of water exchange towards outflow (by 10% in duration). The average inflow-outflow rate is 3.14 and 3.16, the maximum is 8.00 and 8.31 million m^3 per hour. The average inflow-outflow volumes are 37 and 31 million m^3.

At the end of the **winter hydrological period**, the water column was thermally homogeneous and characterized by a gradual increase in temperature from the estuary to the exit from the Baltic Strait (from 2.9°C at station 1 to 3.4°C at station 17). Stratification of the water column is determined solely by the vertical distribution of salinity. Minimum salinity values (0.2–0.5 PSU) in the Pregolya estuary is explained by an increase in water discharge during the flood period. The influence of river flow extends far into the sea in the surface layer and is clearly visible up to station 20. Between stations 3 and 10, strong two-layer stratification with a significant spatial gradient is established. The salinity of the seawater wedge has lower values (6–7 PSU).

In the **spring**, by the end of May, with increasing air warming, the water temperature in the surface layer in the river estuarine zone, KMC and the Baltic Strait increased significantly: to 15–17°C. In the sea, the temperature of the upper layer to the depths of 5–10 m was 11–12°C. The thermocline, which had a stepped structure, lay deeper. The first step was located in the depth range of 10–15 m, then a relatively homogeneous layer with a temperature of 9–10°C was observed, and deeper (25–35 m) the second step was located. The minimum salinity was noted in the surface layer of the Pregolya estuary (stations 1–3) and amounted to 1.3–1.7 PSU. The lens of fresh river water (<2.4 PSU) on the surface extended to station 5. The wedge of cold seawater with a salinity of 6.3–5.6 PSU reached Primorskaya Bay. Salinity values increased with depth along the study area, and the 7 PSU isohaline coincided with the first stage of the seasonal thermocline. Deeper down, salinity increased uniformly to 7.4 PSU in the bottom layer in the open sea.

In **summer**, the water column is well heated, and the horizontal and vertical temperature distribution is uniform throughout the entire profile. The maximum temperature values(18.8°C) were observed in the surface layer of the canal. The difference in surface and bottom temperatures was less than 1°C. Salinity in the surface layer of the Pregolya estuary varied within 2.8–3.2 PSU at stations 1–3. An area with stratification formed by the interaction of the waters of the canal and the Pregolya estuary, located east of station 8, the gradient between the salinity values at the surface and at the bottom here was up to 2.2 PSU. The bottom salinity here decreased from 6.3 to 4.7 PSU in an easterly direction. The western part of the canal and the area of the Primorskaya Bay (stations 10–14) were weakly stratified. The difference between salinity at the surface and at the bottom here was up to 1 PSU.

During the **autumn**, atmospheric cooling processes developed, leading to comparative thermal homogeneity of the water column. Minimum temperature values (9.8°C) were observed in the surface layer near the Pregolya estuary (stations 1–2). The water from station 3 to 7–8 is thermally homogeneous; the difference between the values at the surface and at the bottom varied within 0.5–0.8°C. In the coastal part of the Baltic Sea, the vertical temperature distribution is uniform down to a depth of about 40 m, where the upper boundary of the seasonal thermocline is located. In the coastal zone of the sea (stations 18–19), a significant spatial gradient was observed. Warmer water spread along the bottom of the canal to the east in the shape of a wedge (up to station 7) with a thickness of about 3–4 m. The salinity distribution is similar to the temperature distribution. Salinity values increased westward from 3.2–3.8 PSU in the surface layer of the river estuary to 7.3 PSU in a homogeneous layer of coastal seawater to a depth of 40 m. A sharp spatial gradient was observed throughout the study area. The strongest vertical stratification was noted above the wedge of seawaters (stations 7–14) and in the area of the river estuary (stations 1–3). The salinity value in the inflow water wedge decreased from 6 PSU at station 17 to 5 PSU at station 7.

Depending on the season of the year and the prevailing wind direction and speed, which are characteristic of a particular season, the type of Pregolya estuary changes by the nature of vertical mixing and stratification [20] and the position of the high-gradient zone, which is formed when water mixes. In autumn and winter, there is a sharp stratification in the estuarine zone and a wedge of saline waters, which practically

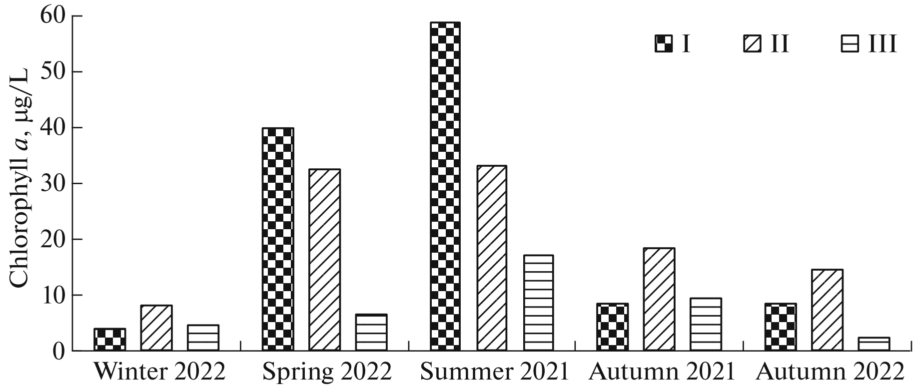

Fig. 5. Seasonal dynamics of chlorophyll *a* concentration in surface layer (conventional zones: I, estuarine; II, mixing; III, marine).

disappears by the end of spring, and the water is well stratified. In summer, the channel and estuarine zone are weakly stratified. Seasonal changes in abiotic factors (temperature and salinity) affect the composition and quantitative development of plankton and the concentrations of chlorophyll *a* in the studied system.

Photosynthetic Pigments of Phytoplankton. At the end of the **winter** hydrological period (March 2, 2022), weak development of phytoplankton was observed (Fig. 5), the biomass of which is indicated by the concentrations of chlorophyll *a* [8, 10]. In the estuarine zone and near the Baltic Strait, low concentrations of chlorophyll *a* (3–4 µg/L) were noted, which increased significantly in the water mixing zone in the Primorskaya Bay (up to 13 µg/L at the surface). In the marine zone, with distance from the coast, the values of chlorophyll *a* decreased from 10 to 2 µg/L.

In the **spring**, with the beginning of active phytoplankton growing season, the chlorophyll *a* concentrations increased sharply. At the end of spring 2021, in the estuarine zone, the value of chlorophyll *a* was 40 µg/L and was also high in the adjacent eastern part of the water mixing zone (61–62 µg/L at stations 7 and 10), after which it decreased significantly in western (up to 13 µg/L at station 15) due to the inflow of significantly less productive seawaters [29]. In the marine zone, with distance from the coast, chlorophyll *a* decreased from 9 to 4 µg/L, reflecting a decrease in eutrophication of waters from the coastal zone to the open sea [14].

In the **summer**, the development of phytoplankton in the Kaliningrad Lagoon regularly reaches the level of water "blooming" [3]. At the end of the summer of 2021, the chlorophyll *a* concentrations reached their maximum values, while their spatial distribution corresponded to that in spring. In the estuarine zone, the average chlorophyll *a* value was 58 µg/L. To the east, at the boundary of the water mixing zone (station 7), a maximum value (72 µg/L) was noted, which corresponded to the boundary state between eutrophic and hypertrophic [49], as a result of water "blooming". In the water mixing zone, there was a rapid decrease in the concentration of chlorophyll *a* to 18–20 µg/L in the western part. In the coastal marine zone, the maximum for the period 2021–2022 the concentration of chlorophyll *a* was 17 µg/L, which may be associated both with the runoff of highly productive waters of the lagoon, and, possibly, with a more intensive level of phytoplankton development in the Baltic Sea under the influence of increased heating of the waters in the summer of 2021 [5].

In the **autumn**, a seasonal decrease in chlorophyll *a* concentrations was observed in the Kaliningrad Lagoon, which is characterized by a summer maximum in primary plankton production and chlorophyll *a* concentrations [1]. As a result, the concentrations of chlorophyll *a* in the surface layer in the water mixing zone (on average 18 and 15 µg/L in 2021 and 2022, respectively) were two times lower than in summer (33 µg/L in August 2021). Just like in previous seasons, the chlorophyll *a* values decreased significantly from the eastern part to the Baltic Strait (from 25–30 to 8 µg/L) due to the influx of seawater. The river flow had a significant influence on the Pregolya estuarine zone, where the development of phytoplankton in river water during this period was weak. As a result, in October 2021 and 2022 in the estuarine zone a low chlorophyll *a* value (8 µg/L) was observed, comparable to the Baltic Strait. In the marine zone, the survey on October 19, 2021, coincided with the autumn peak in phytoplankton development in the Baltic Sea, which is observed when the seasonal thermocline is destroyed and nutrients enter the photic layer [13, 15]. In the coastal zone, the chlorophyll *a* concentrations in the subsurface layer reached 12 µg/L and gradually decreased to 6 µg/L at the 30-m isobath. Conversely, in October 2022, the chlorophyll *a* values were significantly lower: from 3 µg/L near the coast up to 1 µg/L at the 40-m isobath, which can be explained by significant warming of the water preceding the beginning of active autumn development of cold-water phytoplankton species in the Baltic Sea.

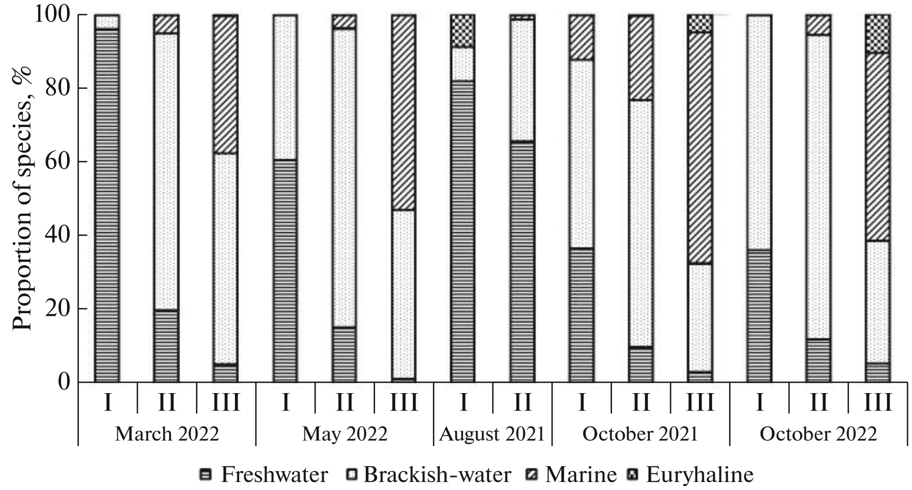

Fig. 6. Proportion of zooplankton species different in relation to salinity in different seasons of the year (conventional zones: I, estuarine; II, mixing; III, marine).

Intensive mixing of river and seawaters affects the development of plankton and determines the spatial heterogeneity of the distribution of chlorophyll *a* from the estuary of the Pregolya River to the open part of the Baltic Sea. The highest chlorophyll *a* values were noted in the most desalinated parts – in the estuarine zone and at the beginning of the mixing zone (stations 1, 7, 10). This water area is under the influence of a significant supply of nutrients from the catchment area, including wastewater from the city of Kaliningrad with a population of half a million [2, 7]. In particular, the eastern part of the Kaliningrad Lagoon is characterized by the highest concentrations of nitrogen and phosphorus in the lagoon, which stimulates the development of phytoplankton [1, 6]. In the mixing zone itself, there is a significant decrease in the chlorophyll *a* values under the influence of seawater inflow. The removal of highly productive waters through the strait affects the coastal zone of the Baltic Sea, where during the studied seasons of 2021–2022. Increased concentrations of chlorophyll *a* were observed. With distance from the coast and increasing depth, the amount of chlorophyll *a* decreased, reflecting the previously established long-term pattern of decline in productivity and abundance of plankton from the coastal zone to the open sea [4, 5, 14].

Chlorophyll *a* concentrations as an indicator of phytoplankton abundance are the most important criterion in modern classifications of water eutrophication. Assessment of the level of water eutrophication in 2021–2022 was carried out according to the classification of water trophicity [48], which is applicable to relatively shallow waterbodies, which include the Kaliningrad Lagoon. The highest level of eutrophication is characteristic of the estuarine zone, where very high values of chlorophyll *a* were observed in spring and summer. The average value of chlorophyll *a* was 27 μg/L, which corresponds to the transition state between eutrophic and hypertrophic types of water (conventional limit 25 μg/L [48]). In the mixing zone, the concentrations of chlorophyll *a* decreased significantly from the estuarine zone to the sea strait, but on average corresponded to the eutrophic type of water (8–25 μg/L). For the Baltic Sea, including coastal waters, a different classification of trophic status is used [41], which takes into account the greater depth of the water area and the thickness of the photic layer. According to this classification, in the studied marine zone of the Baltic Sea, the average value of chlorophyll *a* corresponded to the eutrophic type of water (4–10 μg/L). The noted level of water eutrophication and its spatial distribution corresponds to long-term data obtained for the Kaliningrad Lagoon and the southeastern Baltic Sea, including in 2021 [1, 3–5].

Zooplankton. In the mixing zone, salinity is one of the main factors influencing the distribution of zooplankton. The estuarine zone is dominated by freshwater species, mainly carried out from the river (Fig. 6). In the mixing zone, as salinity increases, brackish-water species begin to predominate, and marine species are also found, which during inflow periods can make up a significant proportion (October 2021).

During the hydrological **winter**, minimal species diversity was observed (22 taxa). In the estuarine zone, freshwater species predominated (96%), in terms of numbers and biomass, the rotifers *Polyarthra vulgaris* and *Keratella quadrata*, the crustaceans *Cyclops vicinus*, as well as nauplii and juveniles of Cyclopoida dominated. In the mixing zone, there were brackish-water species (75%), and the brackish-water species *Eurytemora affinis* (Calanoida) dominated here in terms of abundance and biomass. The marine zone was also dominated by brackish-water species (57%), most of which were represented by the rotifer *Syn-*

chaeta baltica, nauplii of copepods of the genus *Acartia*, and there was also a large proportion of the marine copepod *Temora longicornis*. Freshwater species could have been carried out by the canal water plume, which is clearly visible in the salinity profile (see Fig. 4). The quantitative development of zooplankton during this period decreased from the estuary to the marine zone and in all zones was at the minimum level for intra-annual dynamics (number 3.6–11.5 thousand ind./m^3 and biomass 31–136 mg/m^3).

In the **spring**, zooplankton was represented by the maximum number of species (44), mainly due to an increase in the species diversity of rotifers and cladocerans. At the river estuary, freshwater species dominated (60%), but approximately 40% brackish-water species were also present, which may be due to increased salinity due to decreased river flow and the two-layer stratification of temperature and salinity in the area. The zooplankton was dominated by the freshwater rotifer *Asplanchna priodonta* and the brackish-water copepod *E. affinis*. In the coastal part of the sea, marine (53%) and brackish-water (46%) species predominated. In terms of abundance and biomass, the brackish-water rotifer *S. baltica* and the marine cladoceran *Evadne nordmanni* and the copepod *T. longicornis* predominated in this zone. The abundance and biomass of zooplankton in all zones increased significantly compared to the winter period (14–60 times) and reached their maximum values (64–172 thousand ind./m^3 and 971–1885 mg/m^3). The abundance of zooplankton was maximum in the estuarine zone, while the biomass was maximum in the marine zone, due to the dominance of larger individuals.

In the **summer**, the total number of zooplankton species decreased slightly, but remained at a high level (33). In the estuarine zone, up to 82% of freshwater species were recorded; freshwater rotifers *K. quadrata*, *Acanthocyclops trajani* and nauplii Cyclopoida were dominant. In the mixing zone, freshwater species (66%), also dominated in numbers by the rotifer *K. quadrata*, prevailed over brackish-water species (33%), which is explained by the weak stratification of the entire water column and the removal of surface water from the estuarine zone. The abundance and biomass of zooplankton decreased slightly compared to the spring period (1.5–2.5 times), but remained at a high level (85–108 thousand ind./m^3 and 621–642 mg/m^3). The maximum quantitative development of zooplankton was observed in the most desalinated estuarine zone.

In the **autumn** period of different years, a similar number of species (31–35) was found in zooplankton, comparable to the summer period. Under inflow conditions and a significant spatial salinity gradient, the strongest vertical stratification was observed above the seawater wedge (stations 7–14). In the estuarine zone, with a salinity of 3.2–3.8 PSU in the surface layer and 4.6 PSU at the bottom, the species composition was represented by 36% freshwater species and more than 50% brackish-water species. In this zone, the brackish-water copepod *E. affinis* dominated in abundance and biomass (Table 2). In the mixing zone (stations 4–17), as salinity increased, the proportion of freshwater species decreased to 9–12% and brackish-water species predominated; marine species were also noted (up to 5%), which is associated with inflow through the Baltic Strait and distribution along the bottom of the KMC seawaters In the conventionally marine zone (stations 18–21), marine species of zooplankton (*E. nordmanni*, *T. longicornis*) dominated and brackish-water species (*E. affinis*, etc.) were numerous. Freshwater species were also present, in particular the rotifer *K. quadrata*, which accounted for up to 3–5%), which could be carried out with runoff from the canal (see Table 2). The quantitative development of zooplankton in the autumn of both years, when averaging data, was comparable to the spring-summer period (85–86 thousand ind./m^3 and 723–1093 mg/m^3), but at the same time there was a sharp (3–12 times) decrease in abundance and zooplankton biomass from the estuarine zone (140–164 thousand ind./m^3 and 1182–2321 mg/m^3) to the marine zone (15–28 thousand ind./m^3 and 197–351 mg/m^3).

Proportion of dead individuals in zooplankton. Due to changes in hydrological conditions (mainly salinity), a number of species not adapted to a certain salinity may die. A salinity of 5–8 PSU is critical for many aquatic organisms [33]. During the winter hydrological period, freshwater and euryhaline species died in the marine zone, the proportion of dead individuals among them increased to 9–33% of the number (Fig. 7). They got there when the waters of the lagoon were carried out through the Baltic Strait, which spread into the sea in the surface layer. At the end of May, marine species died in the estuarine zone: the proportion of dead individuals among them increased from 4–8 to 33% of the number. During the same period, the proportion of dead individuals among brackish-water and euryhaline species in the marine zone increased, up to 21 and 29%, respectively. Marine species could have entered the estuarine zone with the influx of seawater along the bottom due to western winds with gusts of up to 10 m/s (see Table 1), which were observed two days before the survey. Brackish-water and euryhaline species could have been transported through the strait to the sea when south-easterly winds prevailed. At the end of the summer period in the mixing zone, compared to the estuarine zone, the proportion of dead individuals among freshwater and euryhaline species increased two to six times, from 5–7 to 10–33%. During this period, weak stratification of the waters of the canal and the estuarine zone was observed, and the area with a salinity gradient, when river waters mixed with canal waters, was located to the west of station 7. In the autumn of 2021, a large number of freshwater species died in the mixed and marine zones (up to 11–20% of numbers), which were carried out by surface runoff during the

Table 2. Proportion (%) of dominant zooplankton species by abundance/biomass (conventional zones: I, estuary; II, mixing; III, marine

Group	Species/taxon	Attitude to salinity	March 2022			May 2022			August 2021		October 2021			October 2022		
			I	II	III	I	II	III	I	II	I	II	III	I	II	III
Proportion of abundance/biomass, %																
Cladocera	*Bosmina* (*Eubosmina*) *coregoni*	Euryhaline	0/0	0/0	0/0	0/0	0/0	0/0	9/31	0/0	0/0	0/1	5/6	0/0	0/0	10/17
	Evadne nordmanni	Marine	0/0	0/0	0/2	0/0	1/8	15/67	0/0	0/0	0/0	0/0	5/53	0/0	0/0	4/39
Copepoda	*Acanthocyclops trajani*	Freshwater	0/0	0/0	0/0	0/0	0/0	0/0	9/26	11/31	1/3	0/0	0/0	2/2	0/0	0/0
	Acartia sp.	Brackish-water	0/0	23/14	4/6	0/0	1/2	4/1	0/0	12/15	0/0	2/1	12/9	3/2	4/3	5/3
	Cyclopoida	Freshwater	15/19	10/3	0/0	2/1	0/0	0/0	9/7	11/8	1/0	0/0	0/0	5/1	1/0	0/0
	Cyclops vicinus	Freshwater	4/30	0/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Eurytemora affinis	Brackish-water	0/0	34/71	3/34	12/36	30/62	2/11	0/0	9/15	34/87	28/74	0/1	34/88	25/65	1/7
	Nauplia *Acartia*	Brackish-water	0/0	0/0	24/3	0/0	0/0	3/0	0/0	0/0	0/0	0/0	8/1	0/0	0/0	3/0
	Nauplia Calanoida	Brackish-water	4/2	2/0	0/0	21/4	27/3	0/0	6/2	7/2	17/4	21/3	0/0	8/1	27/3	0/0
	Nauplia Cyclopoida	Freshwater	22/3	4/0	0/0	20/2	7/0	0/0	15/1	10/1	26/2	4/0	0/0	9/0	2/0	0/0
	Nauplia *Temora*	Marine	0/0	0/0	5/1	0/0	0/0	4/0	0/0	0/0	0/0	1/0	32/3	0/0	0/1	16/1
	Temora longicornis	Marine	0/0	1/1	14/25	0/0	0/0	18/5	0/0	1/1	0/0	1/1	14/11	0/0	5/5	20/14
Polychaeta	Larvae Polychaeta	Marine	0/0	4/1	13/8	0/0	0/0	0/0	0/0	0/0	12/2	21/7	0/0	0/0	0/0	0/0
	Ova Polychaeta	Marine	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	18/2	3/1	0/0
Rotifera	*Asplanchna priodonta*	Freshwater	0/0	0/0	0/0	12/32	1/2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Keratella quadrata	Freshwater	11/2	6/0	5/0	7/1	3/0	1/0	15/2	22/2	1/0	3/0	3/0	5/0	6/0	5/0
	Polyarthra vulgaris	Freshwater	12/1	0/0	0/0	2/0	0/0	0/0	0/0	0/0	2/0	0/0	0/0	0/0	0/0	0/0
	Synchaeta baltica	Brackish-water	0/0	12/1	21/7	1/0	19/5	35/6	0/0	2/0	0/0	15/4	8/2	0/0	23/6	22/5
Others			36/14	5/10	10/32	24/29	9/25	17/16	37/33	15/29	4/9	5/23	13/20	15/7	4/27	13/20
Number of species																
			11	11	14	25	33	19	23	22	15	27	17	18	18	16
Number, thousand specimens/m^3																
			11.4	11.5	3.6	171.6	165.1	63.6	107.5	84.6	139.8	90.4	28.5	164.4	76.2	15.1
Biomass, g/m^3																
			0.04	0.14	0.03	0.97	1.55	1.88	0.64	0.62	1.18	0.64	0.35	2.32	0.76	0.20

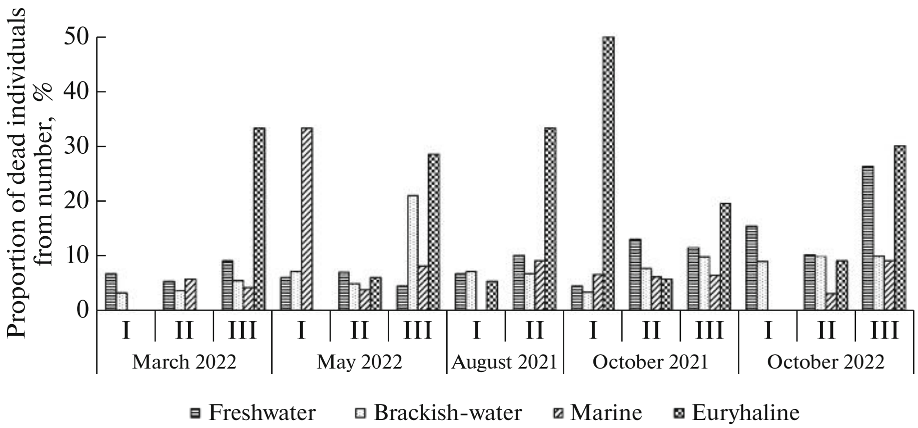

Fig. 7. Proportion of dead zooplankton individuals from number (conditional zones: I, estuarine; II, mixing; III, marine).

windy periods. In the autumn of 2022, freshwater species died already at the estuary, where the proportion of dead individuals among them was 15% of the number, this was facilitated by an increase in salinity in this zone to 5 PSU when the canal waters entered into the estuarine zone along the bottom. In October 2021, the maximum for the estuarine zone during the study period was the proportion of dead euryhaline zooplankton individuals (50%).

In general, in zooplankton in the mixing zone during the research period in 2021–2022 64 taxon was found with a rank below Rotifira, Cladocera, and Copepoda; also in zooplankton were meroplakton larvae of Cirripedia, and mollusks Astropoda, Bivalvia and Polychaeta, as well as Mysida. The mentioned zooplankton species belonged to both the freshwater complex of species, and to brackish-water species, but also living in conditions of significant desalination, as well as to marine species that are typical of the Baltic Sea. Some species (euryhaline) were observed in a wide range of salinity from fresh to seawaters. The species encountered were typical of the Pregolya River, Kaliningrad Lagoon, KMC, and the Baltic Sea [21–23, 28, 38, 52]. Approaching the sea strait and the Baltic Sea, the abundance and biomass of freshwater species decreased, and the quantitative indicators of brackish-water and marine species increased. Species diversity, as well as the quantitative development of zooplankton, were at a minimum level at the beginning of the growing season in March 2022; by May, both the number of species and the abundance and biomass of zooplankton increased, remaining at a high level in the summer, and decreased slightly by autumn. The increase in zooplankton species diversity in the spring-summer period was associated with an increase in the species diversity of rotifers (Rotifera) and cladocera (Cladocera). The zooplankton abundance decreased from the estuarine to the marine zone in all studied seasons, while biomass decreased from the estuarine to the marine zone only in autumn of both 2021 and 2022 (see Fig. 4). In winter, the maximum values of zooplankton biomass were noted in the water mixing zone; in spring, in the marine zone; and in summer, the biomass indicators varied slightly between zones.

Comparison of the obtained data with the results of [43, 44, 51–54] in other estuaries and lagoons of the Baltic Sea (the Neva River estuary, the northern part of the Curonian Lagoon, the Darß-Zingster Boddenkette lagoon system) revealed a general pattern of the influence of salinity changes on the composition and quantitative development of zooplankton. For example, in the estuary of the Neva River, with an increase in salinity above 3 PSU, freshwater copepods of the genera *Mesocyclos* and *Thermocyclos* were partially replaced by species of the genus *Acartia* living in brackish water.

The proportion of dead individuals for groups different in relation to salinity was studied earlier in the Kaliningrad Lagoon, and an increased proportion of dead organisms was also observed in the water mixing zone, which is associated with the hydrodynamic features of the study area [12]. Received in 2021–2022 data for the Pregolya estuary showed an increase in the proportion of dead individuals for zooplankton groups different in relation to salinity in different zones, associated with changes in salinity as a result of surge phenomena.

CONCLUSIONS

One of the main factors influencing the mixing of river and seawaters in the non-tidal estuary of the Pregolya River are the direction and speed of the wind. The dominant winds for the study area are western and northwestern, causing inflow phenomena in the KMC. Four out of five surveys took place under inflow conditions, one—during outflow conditions. At the end of March 2022, weak winds with a southerly component prevailed. Spring and summer surveys 2021–2022 were characterized by a change in the wind from the western direction to the southern and eastern, forming inflow–outflow conditions.

Based on the data obtained and analysis of literary sources, we can talk about the existence (with some degree of convention) in the area of interaction of river, canal, lagoon and seawaters of three zones (estuary, mixing and marine), identified by salinity. The presence of pronounced salinity gradients is characteristic: in zones of mixing of river waters with canal waters and their further mixing with the water of the Baltic Sea. The wind regime and river flow influence the spatial position of gradient zones.

The composition and quantitative development of zooplankton and the abundance of phytoplankton (based on the chlorophyll *a* concentration) are governed by the seasonal dynamics, and their spatial distribution within the selected zones is influenced by river runoff and seawater inflow.

The highest chlorophyll *a* values were noted in the most desalinated parts: in the estuarine zone and at the beginning of the mixing zone, which is under the influence of the influx of nutrients. In the mixing zone, there is a significant decrease in the values of chlorophyll *a* under the influence of seawater inflow. The removal of highly productive waters through the strait affects the coastal zone of the Baltic Sea, where increased chlorophyll *a* values were observed. The quantitative development of zooplankton, especially its abundance, generally corresponded to the distribution of phytoplankton abundance, reaching its greatest values in the estuarine zone and decreasing in the water mixing zone; the opposite picture was observed in the distribution of biomass during calving periods.

Formed as a result of inflow and outflow in the river–seawater mixing zone, hydrological conditions affect the composition of zooplankton, in which the proportion of species different in relation to salinity changes, and the number of dead species not adapted to a given salinity increases sharply. The estuarine zone was dominated by freshwater species, mainly carried out from the river. In the water mixing zone with increasing salinity, brackish-water species predominated and marine species were also found, which during periods of inflows can make up a significant proportion. An increase in the proportion of dead individuals in zooplankton groups different in relation to salinity was established, associated with changes in hydrological conditions as a result of inflow–outflow phenomena. With strong westerly winds and, as a consequence, an inflow of seawater into the KMC and the lagoon, dead individuals of lagoon waters, an increased proportion of dead individuals of freshwater zooplankton species was observed in the mixing zone and marine zone.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This work does not contain any studies involving human and animal subjects.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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