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Water Quality of the Odra (Oder) River before and during the Ecological Disaster in 2022: A Warning to Water Management

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Abstract: Aquatic ecosystems are under pressure due to human activity. In the summer of 2022, the Odra River (Central Europe) suffered a massive death of fish and mollusks. This paper aims to show selected water quality parameters before and during the ecological disaster and find which parameters may have been crucial to the development of this disaster. We used the Kruskal–Wallis test and Spearman's correlation to check the water parameters' spatial and temporal diversification. In addition, non-metric multidimensional scaling was performed. The water quality parameters of the Odra system were analyzed in sections: middle Odra, lower Odra, transitional waters, and Szczecin Lagoon. Human activity has led to the formation of a system with unusual characteristics, disturbing the river's natural continuum and related processes. The year 2022 in the middle Odra differed from the previous years in having a high water temperature (>24 °C), high ammonium concentrations (>4 mg/L), and relatively low nitrate concentrations (<6.5 mg/L). At the same time, salt pollution in the river was very high (maximum 1.4 g/L). In June and July 2022, we observed low chlorophyll *a* concentrations in the middle Odra (on average 2.3 µg/L and 4.4 µg/L, respectively), presumably due to salinity stress and high temperatures, suppressing freshwater phytoplankton taxa. This circumstance has created the appropriate conditions for developing euryhaline and thermophilic *Prymnesium parvum*. Because of decaying organisms, hypoxia occurred in the lower Odra (0.26 mg/L of dissolved oxygen in surface waters), and oxygen conditions worsened in the transitional waters (<4 mg/L). The zonal deaths of fish and mollusks result from multiple stressors induced by human activity. This disaster has proven that it is necessary to improve selected water quality parameters to reduce the risk of such disasters. The most urgent recommendations are to reduce the salt pollution of the upper section of the Odra, reduce nutrient inputs, and improve the condition of smaller rivers feeding the main course of the Odra.

Keywords: chlorophyll *a*; fish kill; human impact; hypoxia; large river; multiple stressors; river continuum; salt pollution; sustainable water management; water parameters

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1. Introduction

Anthropogenic modifications of water bodies and improper management in the catchment area deprive the natural self-regulatory mechanisms of ecosystems [1–3]. Additionally, disruptions in hydrological cycles caused by climate change are becoming a significant stress factor for aquatic ecosystems [4,5]. Inland waters are at great risk of decreasing water quality and quantity, leading to the eutrophication of waters with consequences such as algae blooms and hypoxia [6–8]. These events can negatively affect entire ecosystems. Such disturbance of ecosystems brings substantial financial losses and can contribute to a decline in the standard of living [9].

Algae blooms have become more frequent recently [10]. An example of harmful algae is *Prymnesium parvum*, which causes the death of fish and mollusks and can also negatively affect other animal groups [11,12]. Extensive bloom of *Prymnesium parvum* occurred in the Odra River in the summer of 2022, contributing to the massive death of fish and mollusks [13].

Despite the regulations in the European Union (Water Framework Directive) obligating the monitoring of water quality [13], we do not have all the relevant data to determine the state of the Odra River before the catastrophic event in the summer of 2022. Fortunately, additional surveys on the Odra River in 2022 before and during the ecological disaster were conducted, which improved our knowledge of the spatial variation in the selected parameters [14,15]. Our presented paper fills some gaps in the state of knowledge on selected water quality parameters during summers in the Odra River from 2019 till the ecological disaster, supplementing this information with additional data on phenological changes in water parameters in the Odra based on data from 2015. Knowledge about the water quality parameters of the Odra River before the ecological disaster in 2022 will help to understand the factors that led to the bad ecological state and help to prevent such events in the future.

2. Methods

2.1. Study Area

The Odra (Oder) River is one of the major rivers (854 km) in Central Europe. Springs feeding the river are located in the Czech Republic, and the outlet reaches the Baltic Sea in northwestern Poland. The river is transboundary (Polish–German border) in the middle and lower sections. The size of the basin is approximately 118,861 km^2.

This study was conducted in the Odra River at 20 sampling stations (Figure 1). The measurement sites are ordered from the springs of the Odra River toward the Baltic Sea. To describe the parameters of the Odra system, we divided it into four sections: middle Odra, lower Odra, transitional waters, and Szczecin Lagoon. The middle Odra begins in Nowa Sól (430 km of the river) and ends in Górzyca (604 km) (6 sampling sites); the lower Odra begins 6 km downstream of the influx of the Warta River (623 km) (the largest tributary of the Odra River) in Kaleńsko and ends in Szczecin (741 km) (Western Odra) (8 stations); the transitional waters include Dąbie Lake (749 km from the springs of the river) and Roztoka Odrzańska (764 km) (3 stations); and the Szczecin Lagoon includes Zatoka Skoszewska (777 km), the Dziwna strait, and the Świna strait (794 km) (3 stations). One station in the lower Odra (station No. 11) refers to a canal that collects water from a discharge of cooling water from a power plant.

A system of dams modifies the Odra River in the upper section. There is no damming in the studied sections of the Odra system. Instead, the Odra River has a system of spurs in almost the entire studied section of the middle Odra and part of the lower Odra.

2.2. Data Collection

Water quality parameters were measured in the years 2015 and 2019–2022. In 2015, measurements were made in the lower Odra section on two branches of the river (Western Odra and Eastern Odra). In 2019, measurements were made in the lower Odra, transitional waters, and Szczecin Lagoon, while in 2020–2022, measurements were made at all 20 sites. The exact dates of the measurements are included in the Supplementary Materials. Measurements immediately before the disaster occurred on 20–21 July 2022 and those during the disaster on 20–21 August 2022 when the fish kill was heavy in the lower section of the Odra River. In addition, on 22 and 25 August 2022, depth profiles were investigated at the interface between the lower Odra and transitional waters.

A map of sampling sites was prepared in QGIS (version 3.20) with the plugin "Wody Polskie—Baza WMS" and based on the Copernicus Land Monitoring Service data set (https://land.copernicus.eu (accessed on 25 April 2023)).

The values of ammonium (mg/L), chlorophyll *a* (μg/L), conductivity (mS/cm), dissolved oxygen concentration (mg/L), nitrate (mg/L), pH, salinity (g/L), temperature (°C), and total dissolved solids (TDS) (g/L) were measured with a Hydrolab DS5 probe (Hach, Loveland, CO, USA). Turbidity was measured using a colorimeter DR/890 (Hach). Transparency (m) was measured with a Secchi disc (Limnos, Komorów, Poland). The same survey tools were used in all years of the study. The measurements made with the multiparametric probe are subject to error due to the specifics of the tool, so the actual values of the parameters (especially those measured with ion-selective sensors) may differ from the real values measured with other methods [16,17]. Salinity and total dissolved solids are based on electrolytic conductivity measurements; however, we chose to report these three parameters at the reader's convenience. Raw data of measurements and coordinates are attached in the supplementary file (Supplementary Materials).

At each site associated with flowing waters, water was taken from the current with a 12 L bucket, and measurements were taken immediately. For other stations, water for measurements was taken from the open water near the shoreline. In addition, measurements of depth profiles were taken from the central part of the current from the motorboat.

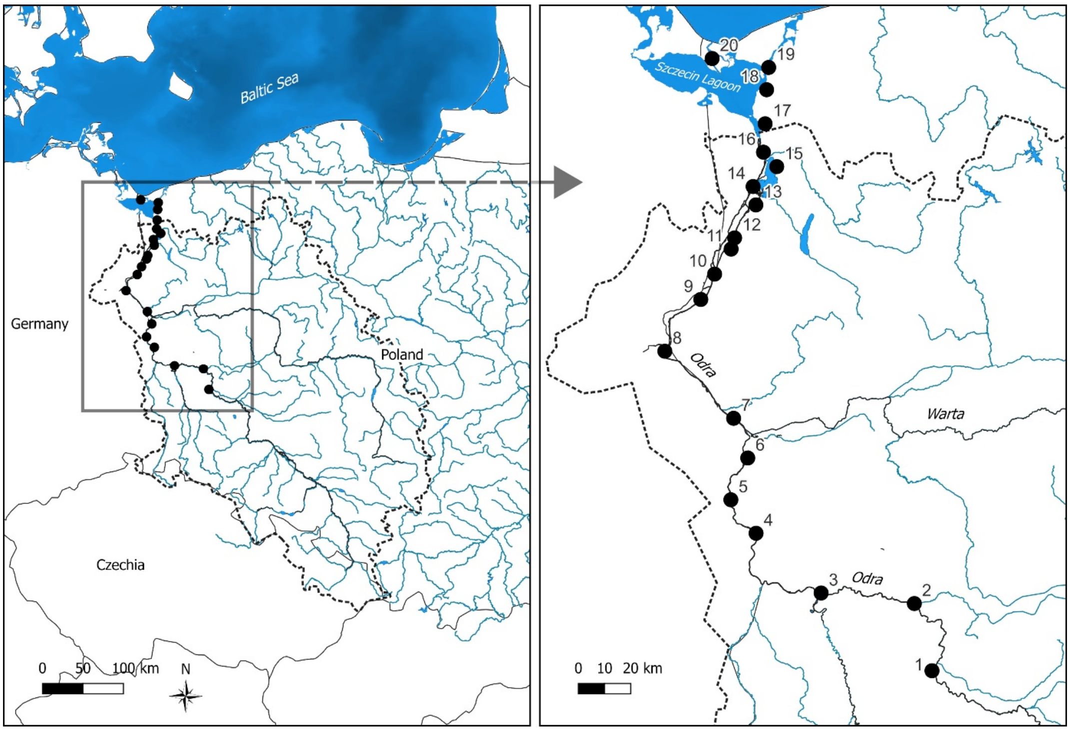

Figure 1. Map of sampling locations. The dashed line presents the drainage of the Odra River. Stations from 1 to 6 represent middle Odra, from 7 to 14 lower Odra, from 15 to 17 transitional waters, and from 18 to 20 Szczecin Lagoon.

2.3. Statistical Analysis

A low number of records, high skewness of the data, and non-normal distribution of data (Shapiro–Wilk test) in most sets of the variables made us use the non-parametric Kruskal–Wallis test to check the differences in the water quality parameters between sections, months, and years (computed using Statistica 13, StatSoft). In addition, the non-parametric Spearman's rank correlation was used to test the relationships between distance from springs and water quality parameters. Finally, multivariate data analysis (non-metric multidimensional scaling with principal component analysis rotation) was performed using Canoco 5.1 software for Windows [18].

3. Results

3.1. Water Quality Parameters

3.1.1. Ammonium and Nitrate

In the Szczecin Lagoon, we recorded the highest values (median = 5.05 mg/L) of ammonium among all considered sections of the Odra system ($p < 0.05$) (Figure 2). In the middle Odra (median = 1.87 mg/L) and transitional waters (median = 1.71 mg/L), the ammonium concentration was lower than in the Szczecin Lagoon. However, the lowest values of ammonium were noted in the lower Odra (median = 1.33 mg/L) ($p < 0.05$). In all sections of the Odra system, the concentrations of ammonium were the highest in 2022 ($p < 0.05$) (Figure 3). The middle Odra was heterogeneous ($p < 0.05$). In contrast, other sections were homogeneous in each year of the survey.

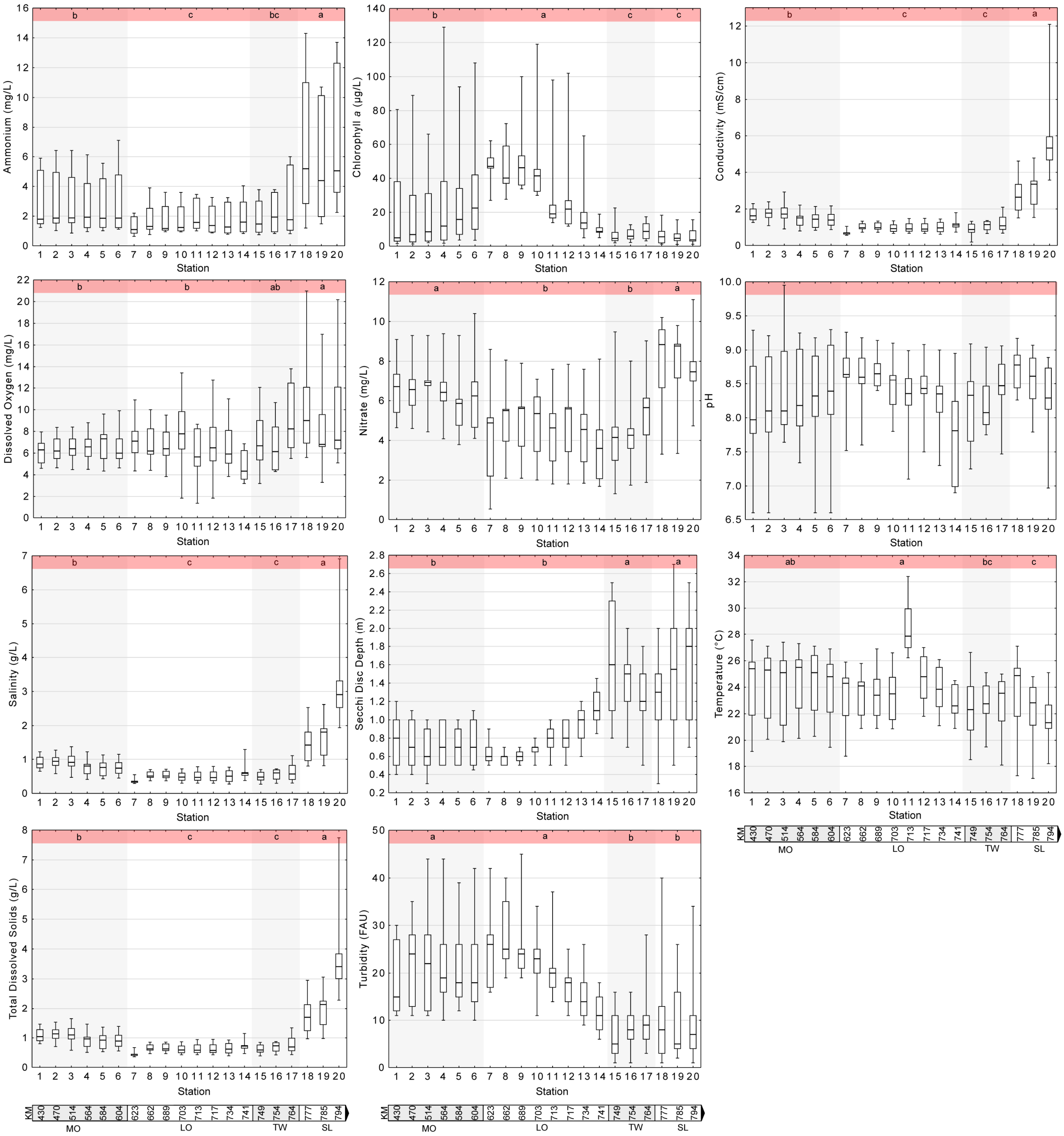

Figure 2. Comparison of water quality parameters in summer from 2019 to 2022 at twenty stations from the middle section of Odra River to Szczecin Lagoon. Different letters indicate significant differences between sections of Odra system (Kruskal–Wallis test, $p < 0.05$). KM—distance from the spring of Odra River in course of the river (km); MO—middle Odra; LO—lower Odra; TW—transitional waters; averaged values for a given section are given in the Results section; SL—Szczecin Lagoon. The central horizontal bar in box plots depicts the median. The lower and upper limits of the box are the first and third quartiles, respectively; whiskers represent maximum and minimum values; dots are outliers.

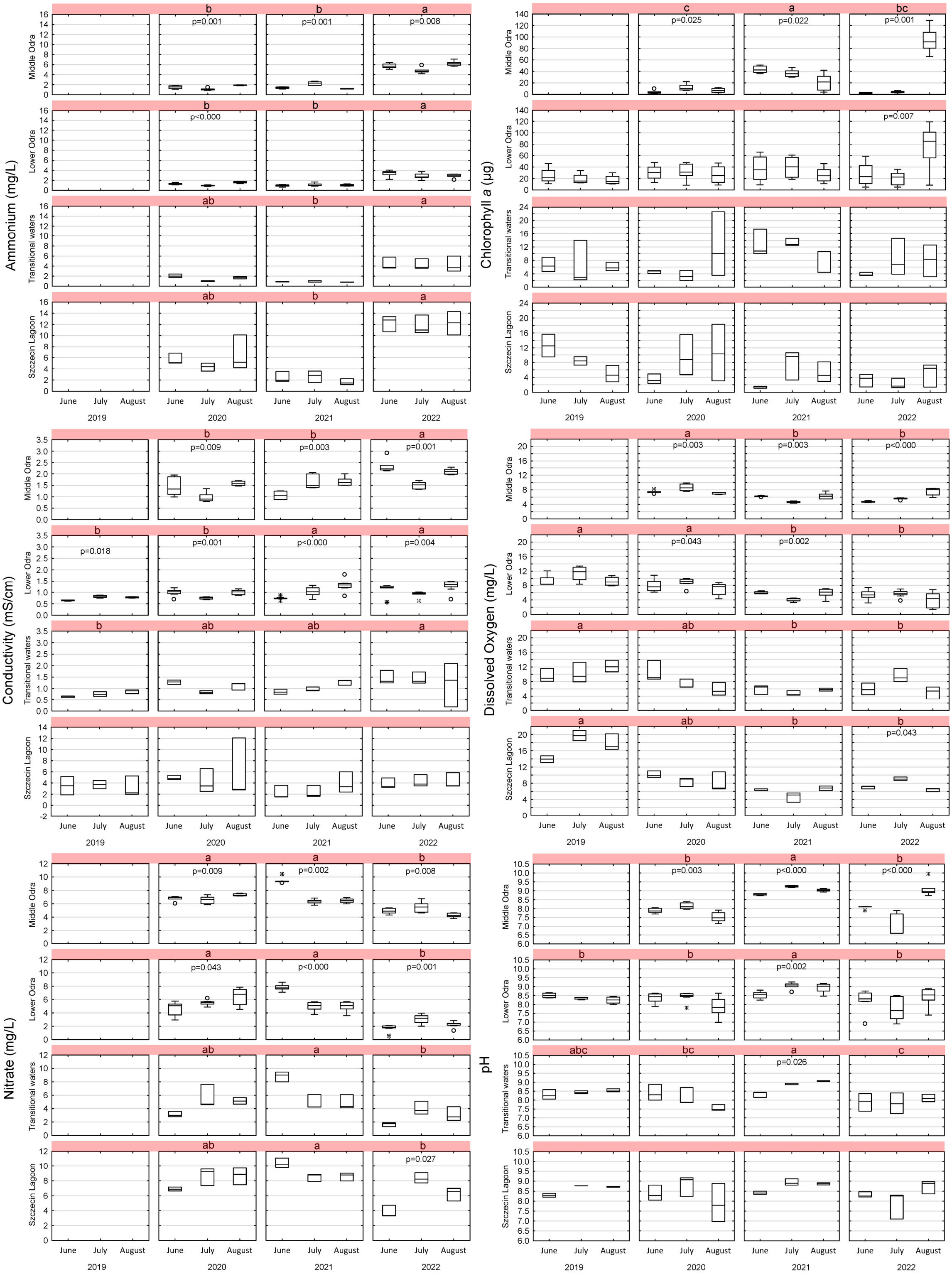

Figure 3. Comparison of water quality parameters (ammonium, chlorophyll *a*, conductivity, dissolved oxygen, nitrate, pH) among months and years in Odra River sections. Significant differences among months are indicated with an exact *p*-value. Different letters indicate significant differences between years in each section of the Odra system (Kruskal–Wallis test, $p < 0.05$). The central horizontal bar in box plots depicts the median. The lower and upper limits of the box are the first and third quartiles, respectively; whiskers represent maximum and minimum values; dots are outliers; asterisks are extreme values.

The highest values of nitrate were recorded in the Szczecin Lagoon (median = 7.98 mg/L) and middle Odra (median = 6.46 mg/L) ($p < 0.05$) (Figure 2). Significantly lower values were noted in the lower Odra (median = 4.90 mg/L) and transitional waters (median = 4.28 mg/L) ($p < 0.05$). The middle and lower Odra were homogenous regarding this parameter ($p < 0.05$) (Figure 3). In 2022, we observed the lowest nitrate concentrations in all sections of the Odra system ($p < 0.05$).

3.1.2. Chlorophyll *a*

The highest values of chlorophyll *a* were recorded at the stations of the lower Odra (median = 27,5 µg/L) ($p < 0.05$); however, the variation in this parameter in this section was very high (minimum value = 4.9 µg/L; maximum value = 119 µg/L) (Figure 2). In general, the highest chlorophyll *a* concentrations occurred in the initial reaches of the lower Odra and decreased toward the transitional waters. Lower concentrations were recorded in the middle Odra (median = 10.1 µg/L), but here, the range of this parameter was even more significant than in the previous section (minimum value = 1.3 µg/L; maximum value = 129 µg/L). In the middle Odra, we noted an increase in chlorophyll *a* concentration downstream of the river (Figure 2). In August 2022, very high chlorophyll *a* concentrations were recorded at the middle and lower Odra (Figure 3), which was the highest observed fluctuation between months in this survey. The lowest chlorophyll *a* concentrations were recorded in the transitional waters (median = 5.4 µg/L) and Szczecin Lagoon (median = 4.7 µg/L).

3.1.3. Conductivity, Salinity, and Total Dissolved Solids (TDS)

The highest conductivity, salinity, and TDS values were noted in the Szczecin Lagoon (median = 3.48 mS/cm; 1.89 g/L; 2.23 g/L, respectively) ($p < 0.05$) (Figure 2). The conductivity, salinity, and TDS values in the middle Odra (median = 1.55 mS/cm; 0.83 g/L; 0.99 g/L, respectively) were significantly higher than those at the stations of the transitional waters (median = 0.96 mS/L; 0.54 g/L; 0.65 g/L, respectively) and at the stations of the lower Odra (median = 0.93 mS/cm; 0.49 g/L; 0.60 g/L, respectively) ($p < 0.05$). The highest values of conductivity, salinity, and TDS in the middle Odra were noted on June 2022 (maximum value = 2.92 mS/cm; 1.38 g/L; 1.65 g/L, respectively) (Figures 3 and 4). In the middle and lower Odra, in every year of the survey, we observed high heterogeneity of this parameter ($p < 0.05$).

3.1.4. Dissolved Oxygen

In general, concentrations of dissolved oxygen increased downstream of the river ($p < 0.05$), reaching the highest values in the Szczecin Lagoon (median = 7.27 mg/L) (Figure 2). Dissolved oxygen values did not differ between the middle (median = 6.35 mg/L) and lower Odra (median = 6.25 mg/L) ($p > 0.05$); however, there is a noticeable decrease in oxygen concentration in the lower Odra from site No. 11 to site No. 14. In 2021 and 2022, we observed the lowest values of dissolved oxygen concentration ($p < 0.05$) (Figure 3). The middle Odra was the most heterogeneous, which means that the values differed between months. We observed the lowest single dissolved oxygen value in August 2022 in the lower Odra (1.38 mg/L). This alarming signal was additionally investigated; data are presented in the next section of the paper.

3.1.5. pH

The pH values most commonly did not exceed 9.0 and were not lower than 7.5. The median value for the middle Odra was 8.15; for the lower Odra, 8.47; for the transitional waters, 8.36; and for the Szczecin Lagoon, 8.60. No significant differences between sections of the Odra system were recorded in the case of this parameter ($p > 0.05$). In 2021, the values of pH were the highest ($p < 0.05$). In the middle of the Odra, we observed the most heterogeneous pH values. In 2022, fluctuations in this parameter in the middle Odra were very high. The most stable pH values were at the Szczecin Lagoon stations.

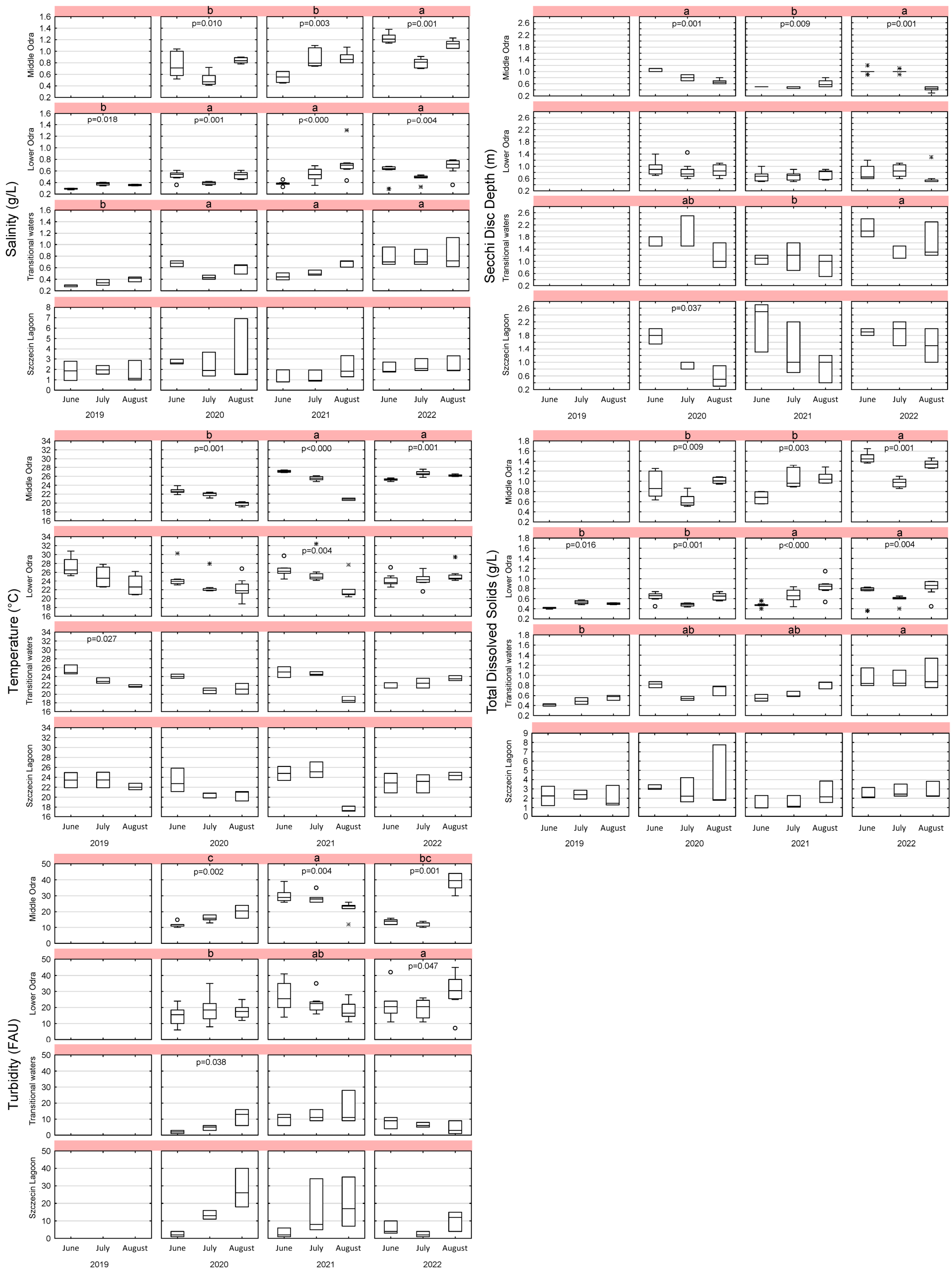

Figure 4. Comparison of water quality parameters (salinity, Secchi disc depth, temperature, total dissolved solids, turbidity) among months and years in Odra River sections. Significant differences among months are indicated with an exact p-value. Different letters indicate significant differences between years in each section of the Odra system (Kruskal–Wallis test, $p < 0.05$). The central horizontal bar in box plots depicts the median. The lower and upper limits of the box are the first and third quartiles, respectively; whiskers represent maximum and minimum values; dots are outliers; asterisks are extreme values.

3.1.6. Secchi Disc Depth and Turbidity (Transparency Indicators)

The highest values of Secchi disc depth and the lowest values of turbidity were recorded in the transitional waters (median = 1.5 m and 8 FAU, respectively) and Szczecin Lagoon (median = 1.5 m and 7 FAU, respectively) (Figure 2). Lower transparency was noted in the middle (median = 0.7 m and 18.5 FAU) and lower sections of the Odra River (median = 0.7 m and 20 FAU) ($p < 0.05$). In the lower Odra, the transparency of the water increases downstream. In 2022, we noticed a higher transparency of the water ($p < 0.05$). However, the heterogeneity of those parameters was also the highest this year (Figure 4). The transparency in the middle Odra in June (median = 1 m and 14 FAU) and July (median = 1 m and 11 FAU) 2022 was uncommonly high. In contrast, in August (median = 0.45 m and 39.5 FAU), we noticed a significant decrease in water transparency ($p < 0.05$). In summer, the water transparency in the lower Odra was controlled by the development of algae, as suggested by the high correlation between chlorophyll *a* concentration and turbidity (Spearman's correlation, r = 0.77; $p < 0.0001$), likewise between chlorophyll *a* concentration and Secchi disk depth (Spearman's correlation, r = −0.86; $p < 0.0001$) (see also Figure 5).

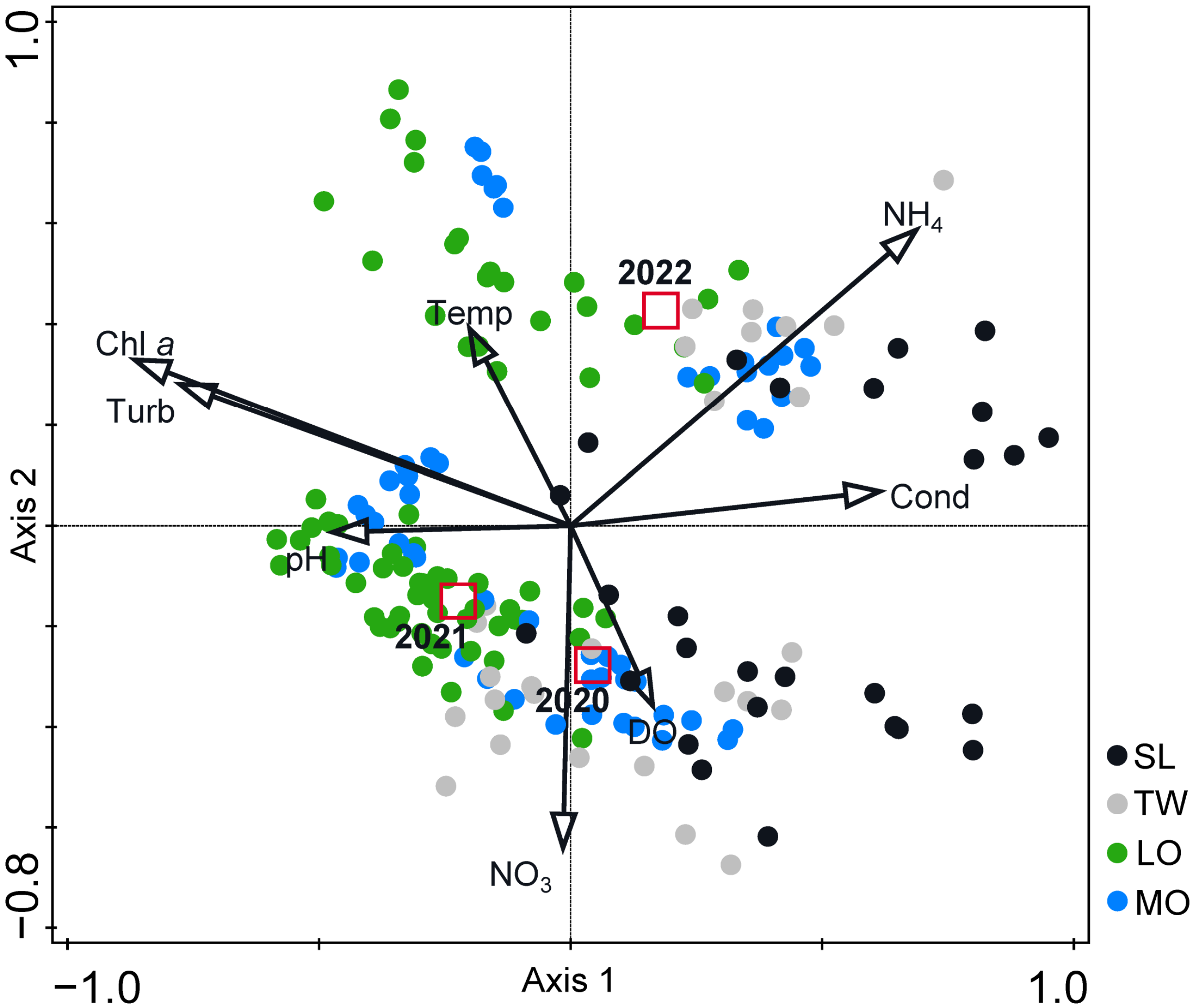

Figure 5. Non-metric multidimensional scaling (NMDS) for the distribution of sampling stations of Odra River in order of water parameters and year of survey (stress criterion value = 0.10). Sections of Odra River: MO—middle Odra; LO—lower Odra; TW—transitional waters; SL—Szczecin Lagoon. Variables: Chl *a*—chlorophyll *a*; Cond—conductivity; NH_4—ammonium; NO_3—nitrate; Temp—temperature; Tur—turbidity.

3.1.7. Temperature

Temperature decreased downstream of the river ($p < 0.05$) except for the stations in the lower Odra that were under the influence of the discharge of warm waters from the power plant (PGE Elektrownia Dolna Odra) (Figure 2). The highest noted temperature in the warm canal was 32.4 °C. The median temperature value in the middle Odra was 25.1 °C; in the lower Odra, 24.3 °C; and in the transitional waters and Szczecin Lagoon, 22.8 °C. In 2021 and 2022, the water temperature was at a similar level; however, in 2022, in the middle Odra, we noticed temperatures higher than 24 °C every month of the survey (Figure 4).

3.2. Water Quality Parameters along the River Continuum

In the gradient of the river system continuum, the concentration of chlorophyll *a* showed a decreasing trend (r = −0.39; $p < 0.0001$) (Table 1). The largest significant decrease in chlorophyll *a* concentration was observed in the lower Odra (r = −0.76; $p < 0.0001$), but in 2022, this trend was the weakest (r = −0.54; $p < 0.05$). Conductivity slightly increased (r = 0.16; $p < 0.05$) in the gradient of the entire system (including the Szczecin Lagoon). However, considering the middle and lower Odra sections, the trend was significantly negative (r = −0.50; $p < 0.0001$). The same patterns were found for salinity and TDS. In the gradient of the entire Odra system, dissolved oxygen content increased (r = 0.20; $p < 0.05$), but for the lower Odra section, the trend was negative (r = −0.25; $p < 0.05$). Transparency (Secchi disc depth and turbidity) in the gradient of the entire Odra system increased ($p < 0.0001$), but the trend was most pronounced in the lower Odra section ($p < 0.0001$).

Table 1. Spearman's correlations between the distance from springs of Odra (km) and water parameters in sections and years. MO—middle Odra; LO—lower Odra; x—lack of data. Only significant correlations presented: * $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$. Different n-values are due to lower number of measurements for ammonium, nitrate, Secchi disc depth, and turbidity.

	All Sections	**MO + LO**	**MO**	**MO 2020**	**MO 2022**	**LO**	**LO 2019**	**LO 2020**	**LO 2021**	**LO 2022**
	n = 208/180	n = 138/126	n = 54	n = 18	n = 18	n = 84/72	n = 12	n = 24	n = 24	n = 24
Ammonium		−0.25 **					x			0.44 *
Chlorophyll *a*	−0.39 ***			0.72 **		−0.76 ***	−0.89 **	−0.82 ***	−0.88 ***	−0.54 *
Conductivity	0.16 *	−0.50 ***	−0.28 *			0.24 *			0.51 *	
Dissolved Oxygen	0.20 *			0.54 *		−0.25 *		−0.67 **	−0.50 *	−0.42 *
Nitrate		−0.43 ***			−0.47 *		x			
pH						−0.47 ***		−0.41 *	−0.58 *	−0.76 ***
Salinity	0.15 *	−0.51 ***	−0.28 *						0.51 *	
Secchi Disc Depth	0.56 ***	0.30 **				0.73 ***	x	0.84 ***	0.87 ***	0.63 **
Temperature	−0.22 *									
TDS	0.16 *	−0.51 ***	−0.28 *			0.23 *			0.51 *	
Turbidity	−0.51 ***	−0.19 *				−0.66 ***	x	−0.64 **	−0.73 ***	−0.69 **

3.3. Multivariate Analyses

The computed NMDS was interpretable, as the stress criterion value was low (=0.10). The computed NMDS was plotted on the PCA axis. Principal component analysis rotation of the NMDS accounts for 96% of the variation. Sections of the Odra River grouped vaguely along the gradients of conductivity, chlorophyll *a*, and turbidity (axis 1), as expected in the case of natural or semi-natural systems (Figure 5). In consequence, the water characteristics of the middle Odra were sometimes very similar to the water characteristics of the Szczecin Lagoon. The analysis also revealed the distinctiveness of the water quality parameters in 2022 compared to those in 2021 and 2020, which mainly differed regarding temperature, nitrate, ammonium, and dissolved oxygen concentrations (axis 2).

3.4. Hypoxia of the Lower Section of the Odra River

Because of the observation on 20 August 2022 of deficits in oxygen concentration in the lower Odra, we investigated the stations of the lower Odra and transitional waters on 22 and 25 August. On 22 August 2022, we recorded low concentrations of dissolved oxygen in the surface waters at stations No. 13 (0.26 mg/L) and No. 14 (1.6 mg/L), while the mean temperature was 25 °C (Figure 6). On 22 August, we also noticed very high values of salinity at station No. 16 (1.37 g/L), which were due to the north wind and the input of saltwater from the Szczecin Lagoon into the transitional waters, which impeded the migration of deoxygenated waters downstream into the Szczecin Lagoon. On this day, we also observed very high concentrations of ammonium (from 2.92 mg/L at station No. 15 to 6.62 mg/L at station No. 16). At station No. 14, the oxygen concentration did not exceed 2 mg/L in the entire depth profile (Figure 7). On 25 August, the depth profile at station No. 13 showed higher concentrations of dissolved oxygen. In contrast, station No. 14 was without significant change. On that day, we observed a decline in dissolved oxygen concentration in the transitional waters, but this decline was not as severe as that at the stations in the lower Odra. However, the oxygen concentration in the transitional waters was affected later. At site No. 15, low oxygen concentrations (<4 mg/L) were recorded on 14 September, despite a decrease in water temperature (18 °C).

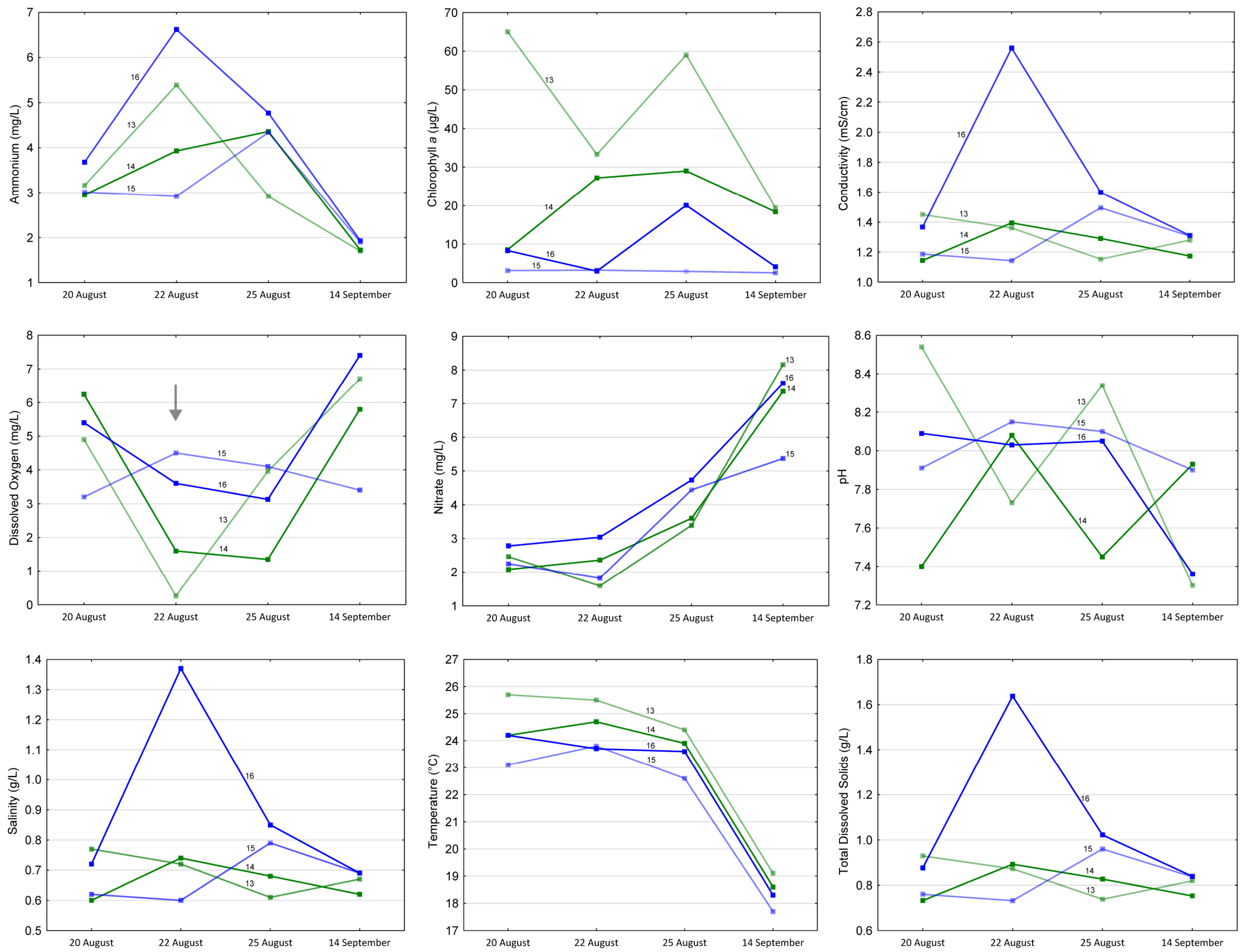

Figure 6. Water quality parameters from 20 August to 14 September 2022 in the lower section of the Odra system. Green lines—lower Odra; blue lines—transitional waters; arrow indicates hypoxia.

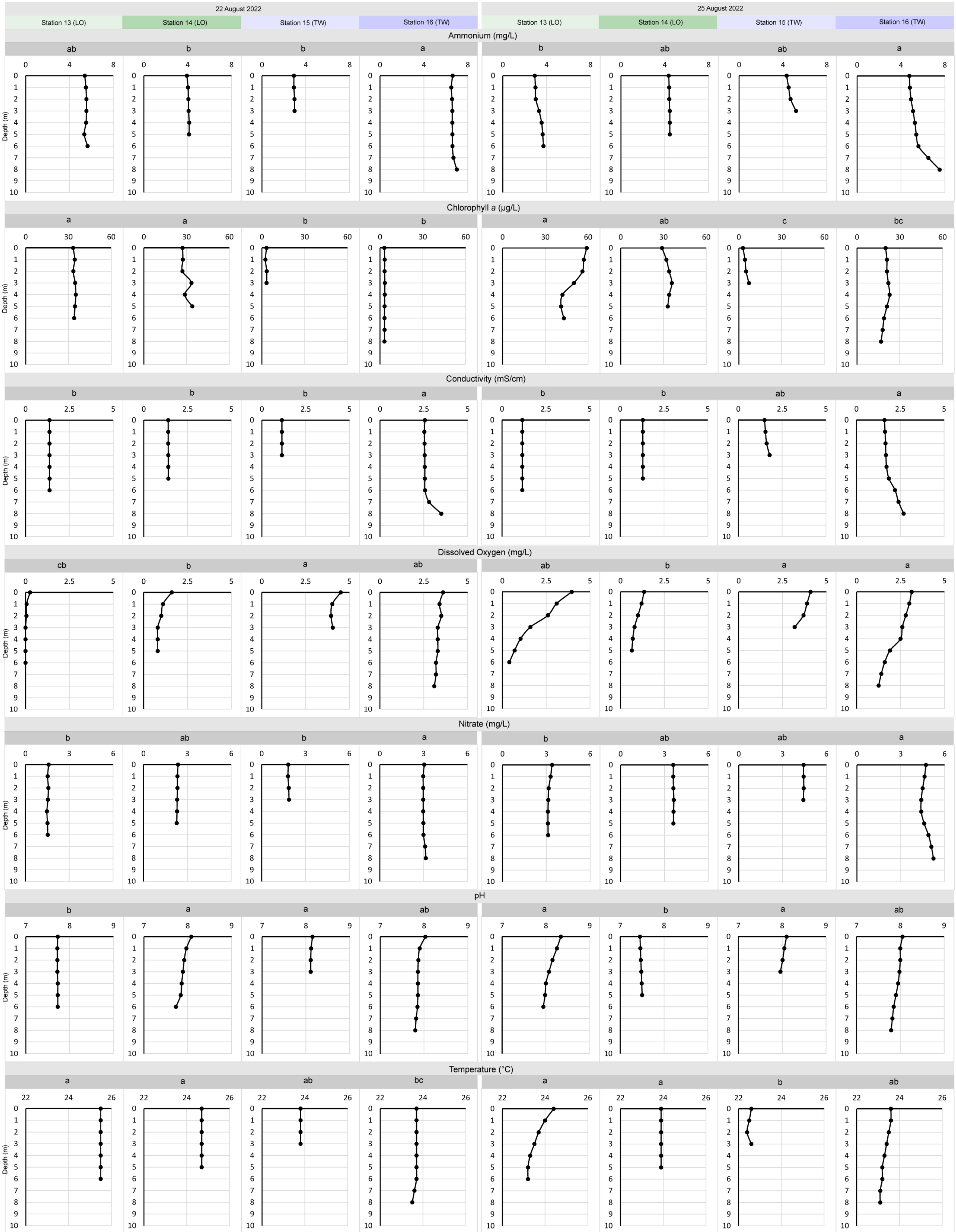

Figure 7. Profiles of water quality parameters during deoxygenation of the lower section of Odra River in 2022. LO—lower Odra; TW—transitional waters. Different letters indicate significant differences between sampling stations of the Odra system (Kruskal–Wallis test, $p < 0.05$); each date presented separately.

3.5. Phenological Variability in the Parameters

Monitoring the water parameters in the lower Odra at monthly intervals in 2015 showed natural temperature fluctuations, with the highest temperature in August (average 24.9 °C) (Figure 8). A low concentration of dissolved oxygen in the water was observed during the summer (2.32 mg/L in August in Eastern Odra). We also noted a gradual increase in electrolytic conductivity values this year. While in January 2015, the average conductivity value was 0.71 mS/cm, in December 2015, this value averaged 0.99 mS/cm. The highest chlorophyll *a* concentrations were recorded in the spring when the average values were 55.8 µg/L in March, 51.6 µg/L in April, and 46.5 µg/L in May. During the summer, we recorded a considerable decrease in chlorophyll *a* concentrations, with an average of 25.7 µg/L in June, 19.0 µg/L in July, and 16.9 µg/L in August.

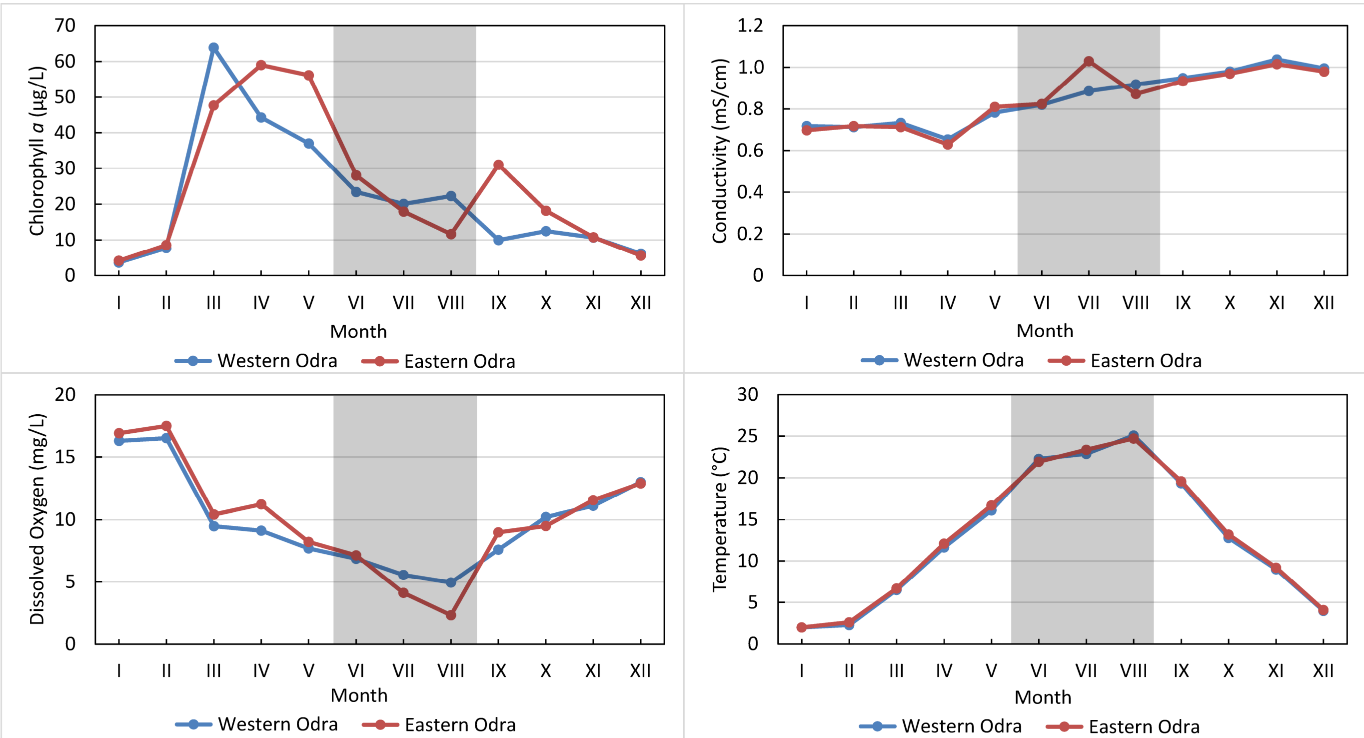

Figure 8. Phenological variability (monthly) of selected water parameters in lower Odra in 2015. Eastern Odra is station No. 13 (Podjuchy) and Western Odra (Ustowo; 53°22′55.7′′ N 14°32′11.8′′ E) is a homologous station on the west section of Odra (not indicated in Figure 1). Gray area refers to the summer period.

3.6. Other Remarks

During an inspection of the sampling sites in June and July 2022 (before the massive death of fish and mollusks), we noticed low water levels that led to the death of mussels, mainly *Dreissena* spp., in sections of the middle and lower Odra. At many sites, we noted decaying patches of *Dreissena* spp. located on a newly exposed stretch of shore. In addition, during the ecological disaster (August 2022), we recorded high abundances of microinvertebrates (Rotifera and Copepoda). Detailed research results on microinvertebrates will be published.

4. Discussion

4.1. Zonation and Disruption of the River Continuum

The waters of the Odra system were divided into four different sections: middle Odra, lower Odra, transitional waters, and Szczecin Lagoon. The middle Odra was characterized by high salinity of anthropogenic origin [13,19], high variability in parameters over time, and high similarity of water parameters between sites. The lower Odra was characterized by high variability between sites and a gradient of parameters (chlorophyll *a*, water transparency) that was inverted regarding the river continuum concept [20]. The lower Odra and downstream waters were characterized by greater parameter stability associated with higher water volume. Thus, meteorological changes and changes due to the supply from upstream did not affect the variation in the studied parameters to such a large extent. The transitional waters were characterized by a significantly lower chlorophyll *a* concentration than that in the previous two sections and were also temporarily influenced by waters from the Szczecin Lagoon. Finally, the Szczecin Lagoon was characterized by high salinity of marine origin [21] and high variability in this parameter.

Anthropogenic changes in the catchment of the Odra River have led to the formation of a system with unusual characteristics. According to the theory of the river continuum, downstream and depending on the river size, the contribution of planktonic primary producers becomes more important [20], whose indicator is the concentration of chlorophyll *a* in the water. Disturbance of the Odra system caused the highest activity of autotrophs (or mixotrophs) to be observed at the beginning of the lower section of the Odra River and sometimes in the middle section, as exemplified in August 2022. This condition is mostly influenced by the supply of nutrients along the entire length of the catchment [13], which supports algae development. Another factor is low competition for resources from riparian or benthic vegetation, which could limit resources for phytoplankton [22].

4.2. Trophic State Indicators

High chlorophyll *a* concentrations in the lower Odra were reported previously [13,23]. For example, in 1994–1996, in the lower Odra (station No. 9 in our survey) during the summer, the average concentrations of chlorophyll *a* ranged from 109 to 145 µg/L [24]. In turn, the maximum chlorophyll *a* concentrations in the lower Odra (site No. 10 in our study) reported by IOŚ PIB [13] were 176.3 µg/L in May 2019 and 171.4 µg/L in July 2021. These values are higher than those observed in our study. The content of chlorophyll *a* has a high fluctuation due to seasonality. The high chlorophyll *a* concentrations reported in our study in 2015 agree with previous studies conducted in the lower Odra in 1993–1996 which reported the highest fluctuations in chlorophyll *a* in spring [23]. The spring peak is a natural response of phytoplankton communities to phenological changes, i.e., longer time with photosynthetically active radiation, higher temperatures, and available nutrient resources. This high chlorophyll *a* concentration in spring also indicates that the waters of the Odra are very fertile (nutrient-rich).

On average, the highest chlorophyll *a* concentrations were recorded in the upper reaches of the lower Odra. The chlorophyll *a* concentrations decreased in a stretch of about 120 km in the lower Odra. There are a few possible explanations for that phenomenon. First, the lower Odra is fed by the Warta River (Poland's third-longest river). The Warta River itself largely contributes to the chlorophyll *a* concentration in the lower Odra. Average chlorophyll *a* concentrations during the vegetation season (March–October) in the middle Warta River were 78.0 µg/L in 2003, 44.3 µg/L in 2009, 26.5 µg/L in 2010, and 82.0 µg/L in 2016 [25]. Our measurements in April 2023 of the chlorophyll *a* concentrations of the outfall of the Warta to the Odra showed 50% higher chlorophyll *a* concentrations in the Warta than in the Odra (station No. 7) (unpublished data). A certain share of phytoplankton from the Warta probably dies off because of changes in physicochemical conditions (salt pollution). Studies on the effects of salinity on freshwater phytoplankton communities have shown that even subtle changes in the salinity decrease chlorophyll *a* concentration and cause a taxonomic shift into cyanobacteria and green-algae dominance [26]. Another explanation is the higher grazing rate of phytoplankton by zooplankton, which develop more effectively in slow-flowing rivers [27]. The next factor contributing to the decrease in chlorophyll *a* concentration downstream of the lower Odra section is the competition for resources between phytoplankton and macrophytes in the network of canals and branches of the inter-basin. At the local scale, elevated temperatures due to discharge from the power plant locally decrease phytoplankton abundance [28].

In contrast to the report presented by IOŚ PIB (p. 59) [13] showing no abnormalities in chlorophyll *a* concentrations in 2022, we observed the highest concentrations in 2022 in two sections of the Odra (middle Odra and lower Odra). This discrepancy is due to the spatial variation in parameters that were not included in the IOŚ PIB Report and to the fact that we did not capture bloom peaks in previous years in our study (as the resolution of our data was limited).

The relatively low level of chlorophyll *a* in the middle section of the river (median largely below 20 μg/L at stations from No. 1 to No. 6) is due to the excessive salinity of the river, which is an inhibitor for many phytoplankton species [26]. Therefore, it seems that the level of chlorophyll *a* (excluding the 2022 bloom) does not reflect the actual trophic state of this section of the river. A decrease in salinity could restore the phytoplankton communities typical of large lowland rivers to the Odra system and increase chlorophyll *a* concentrations. This should increase competition among algae and hamper toxic algal blooms.

Experimental studies of phytoplankton communities in the Guadiana estuary (Portugal–Spain border) [29] showed that an increase in ammonium relative to nitrate favored the growth of cyanobacteria and green algae, in contrast to diatoms that used nitrate as a nitrogen source. The lower nitrate concentration in the lower section than in the middle section is due to the dilution of the Odra River with the waters of the Warta River. A change in available forms of nitrogen may lead to a taxonomic shift in phytoplankton communities. It may also be a stress factor for phytoplankton communities from the middle Odra that encounter new environmental conditions in the lower Odra.

Despite many measures to reduce the doses of nutrients entering the waters, the trophic status of the Odra and other rivers of Central Europe is still very high, as evidenced by the observed chlorophyll *a* concentrations [30]. Nevertheless, such a tragic fish kill was recorded only in the Odra. This suggests that other additional factors led to the harmful algae bloom.

4.3. Excessive Salinity

An unusual characteristic of the Odra system is the salinity in the upper section of the Odra River [13,31], which results in high salt concentrations in the middle section of the Odra that are much higher than those observed in the lower section. In an undisturbed river system, the waters located lowest topographically are the most saline [32]. In the case of the Odra River, the Warta River's tributary dilutes the salt concentration in the Odra River by approximately 50% (average salinity at station No. 6 is 0.77 g/L and at station No. 7 is 0.37 g/L). An inverted gradient of river salinity due to industrialization is observed in other large rivers in Europe [33,34]. In the case of the Odra River, saline water is mainly derived from mine water [19]. However, agriculture, industrial wastes, and wastewaters contribute to the Odra's water salinization.

An increase in common ions associated with anthropogenic salinization decreases water's natural processes of self-purification [35]. As a result, this increase disrupts the functions of ecosystems and, ultimately, can negatively affect human health [36].

Salinity is one of the main factors on a global scale that, along with thermal changes, affects the spread of organisms and the formation of communities [37,38]. Salinization of freshwaters induces physiological stress in biota, resulting in a shift in communities [39]. The increase in salinity of the Odra River system has a significant impact on ecosystem changes, including the expansion of alien and invasive species that tolerate or prefer salty waters [19,31,40,41]. In the case of the ecological disaster in the Odra River, salinity was an important factor favoring the growth of the euryhaline species *Prymnesium parvum* [42].

4.4. Temperature

Global temperature changes due to human activities contribute to rising water temperatures [43]. Rising temperatures that accelerate evaporation and inadequate catchment management because of water draining too quickly from the upper reaches of the catchment lead to water deficits [44]. The observed low water levels in the Odra in 2022 may have been one of the factors supporting water blooms and fish deaths. In addition, in 2022, we observed high temperatures, which could have supported algal blooms. In those conditions, thermophiles such as cyanobacteria and toxic haptophytes (e.g., *Prymnesium parvum*) grow fast [7,11,12].

However, high temperatures or local thermal shock can harm plankton growth. Thermal pollution was one factor that locally disturbed the continuum of the Odra River. The plume of a warm channel from the power plant is a refugium for invasive exotic species [45] and causes thermal stress for local fauna [46,47]. With the high temperatures of the Odra River and higher temperatures predicted in the future [43], this refugium may play an essential role in the dispersion of undesirable species. This dispersion could be accelerated along with ballast waters from ships [48].

4.5. Ecological Disaster and Consequences

Before the disaster in June and July 2022, we observed low concentrations of chlorophyll *a* in the middle section because salinity and temperature suppressed the development of the phytoplankton communities typical of large rivers (Figure 9). However, once salty and thermophilic species appeared in the system, massive growth occurred—*Prymnesium parvum* did not have sufficient competition, nor was it efficiently limited by other filter feeders (as a result of mussel death in June and July 2022). After the population of mussels was reduced, abundant zooplankton in the Odra River in August 2022 were a component in the trophic network that contributed to purifying the water but not effectively suppressing algae bloom. The factor that amplified the toxic effects of the *Prymnesium parvum* bloom was the shock of the drastic reduction in salinity levels with the influx of water from the Warta River. Studies have shown that low salinity shock increases the toxicity of *Prymnesium parvum* [49]. Therefore, in the initial section of the lower Odra, very high mortality of fish and mollusks was observed.

Fish kill occurred heterogeneously in the system of the Odra River (zonation of fish kill), which suggests that different factors were responsible for fish death in different sections. In addition to the harmful effects of *Prymnesium parvum* and hypoxia, it could have been other unrecognized factors locally amplifying stress on aquatic organisms, such as local sediment agitation and the release of contaminants due to hydro-technical activities [50,51], that caused their death. Therefore, the zonal deaths of fish and mollusks resulted from multiple stressors of mainly anthropogenic origin.

The heavy algal bloom observed in August 2022 and the massive death of fish and mussels at the time led indirectly to a significant deterioration in oxygen conditions in the lower section of the Odra River, temporarily creating a zone unsuitable for most aquatic animals. Algal blooms and dead fish are subject to decay by microbes that consume oxygen, causing hypoxia (oxygen shortage) and generating dead zones [52]. Additionally, reductions in dissolved oxygen to concentrations below 3 mg/L inhibit nitrifying bacteria that convert ammonia, which is toxic to fish [53].

A harmful dose of oxygen dissolved in water for most species of fish, crustaceans, and bivalves is <3–4 mg/L [52,54]; however, some microinvertebrates can survive hypoxia [55]. Juveniles are usually more sensitive to low oxygen concentrations than adults [52]; therefore, juvenile specimens are at greater risk of hypoxia. Concentrations below 2 mg/L are lethal [54] for most fish species recorded in the Odra River [56,57]. The concentration of oxygen observed in the Odra River (minimum 0.26 mg/L at surface water) created a zone where fish could not survive. However, some fish had a chance to escape to the more oxygenated transitional waters, tributaries, or canals. Fish kill and especially the loss of fish predators can cascade into a long-term deterioration in the trophic state of the water, which can be amplified by the loss of filter feeders in the water [58]. Therefore, we expect a deterioration in the ecological status of the Odra, especially in the lower section where hypoxia has occurred.

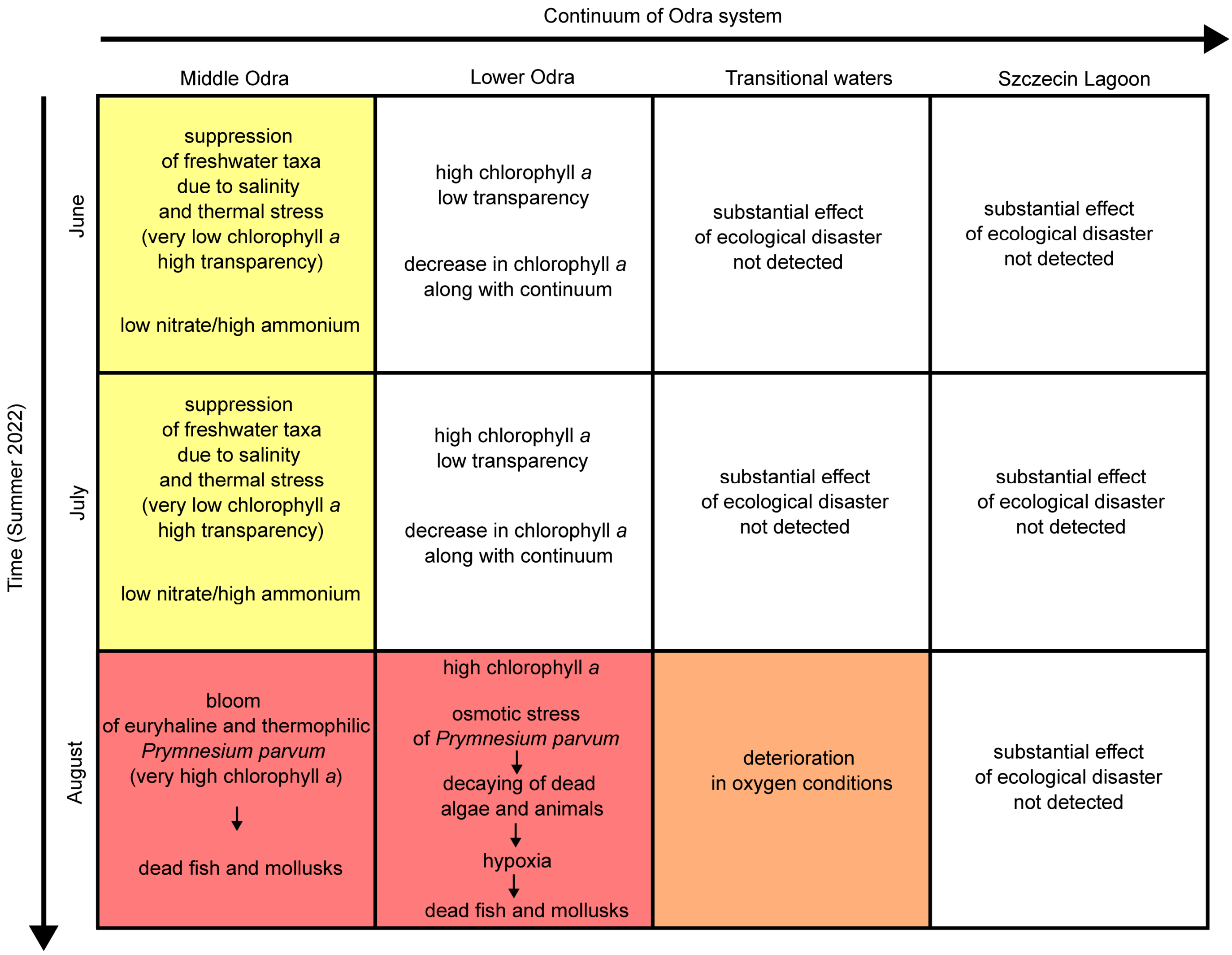

Figure 9. The simplistic diagram shows the run of the disaster in individual sections in the Odra system. The presumed lack of adverse effects on Szczecin Lagoon is based on the lack of significant changes in the parameters studied at the research stations. However, such an impact should not be excluded.

The hypoxia of the lower-Odra zone has led to a deterioration in oxygen conditions in the transitional waters. The problem with low oxygen concentrations in the lower Odra River also occurred during the survey in 2015 but was not as lethal as in August 2022. This suggests that there are temporal deficits in oxygen in the lower Odra River and suggests the need to accelerate changes to reduce the factors contributing to the deterioration in oxygen conditions.

The waters of the Odra system are the crucial migratory road for salmonids that use the Drawa River (tributary to the Noteć that supplies the Warta River) for breeding [59]. Therefore, the parameters of the Odra River system directly impact the ecological status of the entire river basin. The poor condition of the lower Odra can thwart revitalization efforts in the Noteć River basin and other rivers in the upper section of the Odra catchment.

During the deoxygenation of the lower Odra River section, authorities (using fire-fighter pumps and bubble diffusers) and local communities (using pumps and motorboats) attempted to aerate selected river sections to create a refugium for aquatic organisms. However, the volume of water hindered adequate aeration. The problem of low oxygen concentrations in the lower Odra was already occurring before 2022, so it is reasonable to assume that such situations will happen in the future. To protect the populations of fish and other aquatic organisms, mechanical or chemical aeration measures could be implemented in case of a decrease in the oxygen level below 3 mg/L for the creation of refugia for water biota. Such measures were proposed after the fish kill caused by hypoxia in the Darling River, Australia [60]. Nevertheless, as a priority, the supply of nutrients should be reduced to strengthen the resilience of ecosystems to oxygen deficits.

4.6. Recommendations

The most critical threats to the ecosystem perceived on the basis of the above analyses arise from excessive salinity and excessive enrichment of nutrients while limiting the ability of self-purification (limiting the biologically active coastal zone, shortening the course of the river, and homogenizing the morphology of the riverbed). The first action should be to reduce the influx of saltwater into the Odra system in the river's upper reaches. In order to improve the state of the water quality in the Odra River, it is necessary to take measures in upstream watercourses, stabilize decreasing temperatures and the outflow of water from drainage, and limit the amount of suspended solids and nutrients entering the main channel of the Odra River (see [44]). Water quantity shortages, if possible, should be regulated by measures at the catchment level and not in the Odra riverbed only. Research has shown that the construction of dams on large rivers has negative ecological and social consequences [61]. In addition, revitalization measures are recommended for the Odra to improve the river's ability to recover fish and mollusk populations. Area-based protection is a good solution for strengthening the Odra ecosystem. The use of the Międzyodrze zone (system of canals in the lower Odra) for strengthening the self-purification capacity should be reconsidered. This would reduce the impact of the bad-quality waters on the quality status of the transitional waters and the Szczecin Lagoon. Additional surveys of the biota and continuous monitoring of water quality parameters can provide information about changes in the ecosystem of the Odra River.

5. Conclusions

As a result of anthropogenic modifications, the Odra River is characterized by water quality parameters that are atypical in particular zones. The high trophic state of the Odra waters (nutrient pollution), salinity pollution, high temperature (global warming to which human activity contributes plus local thermal pollution), and anthropogenic modifications of the river (lowering the self-purification abilities of the system) have led to the creation of the specific environmental conditions in Summer 2022. Those circumstances favored the bloom of *Prymnesium parvum*. This bloom triggered a cascade of consequences, such as hypoxia of the lower Odra sections, and hindered the decomposition of harmful forms of nitrogen. All of the causes mentioned above and their effects will hinder ecosystem restoration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15118594/s1.

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