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Assessing the Black Sea Mesozooplankton Community Following the Nova Kakhovka Dam Breach

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Abstract: In June 2023, following the breach of the Nova Kakhovka Dam during the Ukraine-Russia war, a comprehensive study was conducted along the Romanian Black Sea coast to assess water quality and mesozooplankton communities. Surface water analyses revealed significant gradients in nutrient levels and salinity, particularly from north to south, influenced by the influx of freshwater and nutrients from riverine sources and the dam breach. Flooding was found to significantly impact nutrient dynamics and species distributions, with increased concentrations of SiO_4 and NO_3 in flooded stations. A strong relationship was observed between environmental factors and biological assemblages, with silicates identified as a key driver. Biodiversity patterns varied across regions, with the Shannon–Wiener Index indicating lower zooplankton diversity in transitional waters, reflecting environmental stress. Statistical methods, including correlation analysis, multidimensional scaling, *t*-tests, and canonical analysis, were employed to investigate the links between mesozooplankton communities and environmental variables. These findings underscore disruptions in trophic dynamics and ecosystem balance, emphasizing the need for integrated environmental management strategies to mitigate further degradation and foster the ecological recovery of the Black Sea.

Keywords: nutrient imbalances; biodiversity; mesozooplankton; water quality; environmental management

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1. Introduction

Zooplankton communities are highly influenced by physical processes within the water column, making them reliable biological indicators of climate change and pollution [1–4]. Mesozooplankton, a size-based fraction of the zooplankton community, encompass taxa and developmental stages, with body lengths ranging from 0.2 to 20 mm [5]. Changes in the abundance and structure of zooplankton communities are particularly sensitive to environmental variations [5], and the distributions and abundances of these organisms in aquatic environments provide valuable insights into water pollution levels and the health of marine ecosystems [6]. Beyond their critical role in the food chain and their sensitivity to climate change, zooplankton are also used to evaluate the impact of global change [7,8]. The species composition, biomass, and diversity of zooplankton groups indicate the strength and stability of biological systems. Zooplankton organisms have significant potential as bioindicators due to their development and distribution being influenced by various abiotic factors (e.g., temperature, salinity, stratification, and pollutants) and biotic factors (e.g., food availability, predation, and competition) [6,9,10].

The dynamics of zooplankton populations, including their reproductive cycles, growth, and survival rates, are key factors influencing the recruitment of fish stocks, making zooplankton ecology a vital area of research [6]. Many marine organisms rely on plankton at some point in their life cycle or throughout their lives, underscoring the importance of plankton in transferring energy to higher trophic levels through various food chains. As the foundation of the marine food web, plankton plays a vital role in supporting fisheries. Additionally, primary productivity and plankton growth are closely linked to the physicochemical parameters of seawater. Any alterations in zooplankton community structure can have implications for fisheries and ecosystem services [11]. Eutrophication, which leads to changes in the qualitative and quantitative structure of zooplankton communities, highlights the importance of using zooplankton as indicators of trophic level changes and ecological conditions driven by nutrient dynamics [12].

The northwestern shelf of the Black Sea, primarily influenced by significant European rivers like the Danube, Dniester, and Dnieper, has experienced gradual improvement in its eutrophication status over the past two decades [13–15].

The breach of the Nova Kakhovka Dam in June 2023 on the Dnieper River had consequences for the Black Sea environment, highlighting the interconnectedness of infrastructure, ecosystems, and regional stability [16]. The dam, which was crucial in regulating water flow and sediment transport to the Black Sea, collapsed on 6 June, releasing a torrent of water that carried debris, pollutants, and sediments [16]. This sudden influx, especially during the early summer when agricultural activity and related pollutant runoff were high, posed a significant threat to the fragile marine ecosystem [17,18]. Floodwater introduced industrial waste, fertilizers, pesticides, and other contaminants into the river, all leading to pollution and worsening eutrophication in the region [19,20]. The increased nutrient load could trigger algal blooms, leading to hypoxic conditions that stress marine life on the northwestern shelf. Additionally, the disruption of sediment transport patterns may alter the seabed, impacting habitats and the overall ecological balance. The dam's breach underscores the serious risks posed by such environmental disturbances, potentially reversing years of progress in safeguarding the Black Sea's marine environment [19].

Moreover, altering freshwater flow into the Black Sea can impact the salinity balance and nutrient levels, further stressing marine ecosystems. The Black Sea is already a vulnerable body of water, with limited exchange with the Mediterranean Sea, making it particularly susceptible to environmental disruptions [13]. The Nova Kakhovka dam breach thus not only caused immediate destruction but also set off a chain of ecological consequences that could have long-term impacts on the health and sustainability of the Black Sea environment [16].

The study aims to evaluate the impact of the Nova Kakhovka Dam breach on the mesozooplankton community in the Black Sea by analyzing the diversity, composition, and abundance of taxa following the event. To achieve this, the study also employs a systems-based approach using Mental Modeler to better understand the complex effects of the dam breach on mesozooplankton, identifying key environmental drivers that most influence community structure. Additionally, the study evaluates the Black Sea environmental status through mesozooplankton indicators, including copepod biomass, mesozooplankton biomass, and *Noctiluca scintillans* biomass. These findings offer valuable guidance for developing effective management and conservation strategies to mitigate the ongoing environmental impacts in the region.

2. Materials and Methods

2.1. Description of the Study Area

The Black Sea is a semi-enclosed water body linked to the global oceans solely through the narrow Bosphorus Strait, which connects it to the Mediterranean. It spans between latitudes 40°55′ to 46°32′ N and longitudes 27°27′ to 41°32′ E, bordered by six countries—Bulgaria, Georgia, Romania, Russia, Turkey, and Ukraine. The basin, which supports about 160 million people, is impacted by inflows from the Danube, Dnieper, and Don rivers, covering almost a third of Europe's landmass [21]. A comprehensive study of Romania's Black Sea coast [22] categorized marine reporting units (MRUs) into four areas based on physical characteristics and chlorophyll-*a* concentration:

- RO-TT03 (transitional waters): Northern coastal waters influenced by the Danube, at depths up to 30 m.
- RO-CT01 (coastal waters): Central to the southern coastal zone from the shoreline, to a depth of 30 m.
- RO-MT01 (marine waters): Inner and outer shelf, from depths of 30 m to 100 m.
- RO-MT02: Offshore waters beyond a depth of 100 m.

An oceanographic cruise was carried out from 6 to 11 June 2023 along the Romanian Black Sea coast, within three marine reporting units (MRU)—transitional (TT03), coastal (CT) and marine (MT01)—with bottom depth stations between 6 m and 57 m (Figure 1).

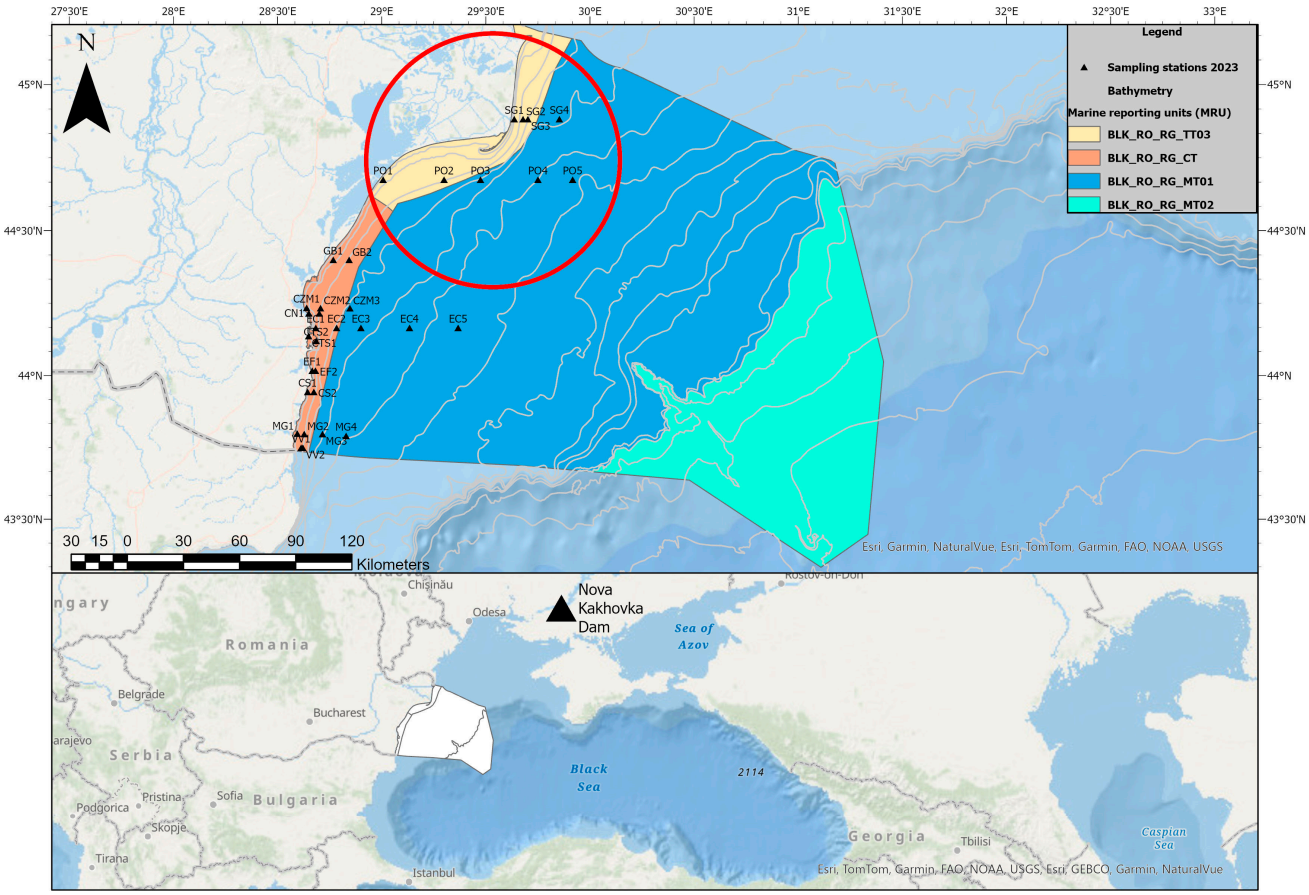

Figure 1. Map of the study area and Romanian EEZ (white) in the Black Sea region, stations affected by the floodwaters (red circle), and the Nova Kakhovka Dam location (black triangle).

Romania has a coastline that stretches for 245 km, with its territorial sea (extending 12 nautical miles from the coastal baseline) covering an area of 3202 km^2 [23]. The country's exclusive economic zone (EEZ) spans approximately 22,485 km^2 [23] (Figure 1).

A total of 33 zooplankton and water samples for evaluating the physicochemical parameters were collected and analyzed in the National Institute for Marine Research and Development "Grigore Antipa" laboratories.

2.2. Mesozooplankton Sampling and Analysis

Zooplankton samples were collected in the entire water column by vertical tows with a Juday net (0.1 m^2 mouth opening, 150 µm mesh size) equipped with a flow meter to estimate the filtered water volume [24]. These samples underwent both quantitative and qualitative assessments under an Olympus SZX10 stereomicroscope (Evident Corporation, Tokyo, Japan). Taxonomic identification of zooplankton species was guided by relevant manuals and references [25,26], with classification aligned with the World Register of Marine Species (WoRMS). Not all organisms could be identified at the species level; meroplanktonic components were classified only at the group level. In the Bogorov chamber, organisms in the subsample(s) were counted until at least 100 individuals from each of the three dominant taxonomic groups were recorded. For larger organisms, the entire sample was examined in a Petri dish. Density (ind/m^3) and biomass (mg/m^3 of wet weight) were calculated using the count of individuals and mean individual weights, respectively, based on standard tables for Black Sea zooplankton [24,27].

2.3. Environmental Parameters

The environmental variables were analyzed from the sea surface, as surface waters are the most impacted by inputs from events like the Nova Kakhovka Dam breach. While mesozooplankton samples were collected from the entire water column to capture vertical distribution patterns, the surface analysis of environmental parameters provides critical insights into how these changes influence mesozooplankton populations and their habitat, particularly in the context of the dam breach's impacts.

Temperature and salinity measurements were conducted using a reversible thermometer, the titration method, and a CastAway CTD multiparameter probe (SonTek, San Diego, CA, USA) (YSI CastAway model). Dissolved nutrient concentrations were determined according to standard seawater analysis methods [28], using spectrophotometric techniques validated in the laboratory. For nitrate determination, the method of Mullin and Riley (1955) was employed [29], where nitrate is reduced to nitrite with hydrazine sulphate, and the nitrite reacts with sulphanilamide in an acid solution to form a diazonium compound. This compound is coupled with N-(1-Naphthyl)-ethylenediamine dihydrochloride to produce a colored azo dye, which is measured spectrophotometrically.

Ammonia concentrations were determined using the indophenol blue method [28], where ammonia reacts in a moderately alkaline solution with hypochlorite to produce monochloramine. In the presence of phenol, catalytic amounts of nitroprusside ions and excess hypochlorite monochloramine forms indophenol blue, which is measured spectrophotometrically.

For inorganic phosphate analysis, phosphate ions react with ammonium molybdate in an acidic medium to form a yellowish phosphomolybdenum complex. This complex is then reduced to a blue-colored compound, the intensity of which is measured at 885 nm and correlates with the phosphate ion concentration [28].

Silicon ions were quantified by reacting them with ammonium molybdate in an acidic medium to form a yellowish silicomolybdenum complex. This complex is reduced to an

intensely blue-colored compound in the presence of ascorbic acid, with the color intensity measured at 810 nm reflecting the silicon concentration [28].

2.4. Data Analysis

Data analyses were conducted using PRIMER v. 7.0 [30], and statistical analyses were performed using Statistica® 14.0.1.25 (TIBCO Software Inc., Palo Alto, CA, USA) [31].

Various diversity indices highlight different aspects of diversity, focusing on species richness or evenness. Among the most used indices are the Shannon–Wiener diversity index (H'), species richness, and Pielou's evenness index (J') [32].

The Shannon–Wiener diversity index (H') is calculated as follows:

$$H' = -\text{å}Pi(\ln Pi)$$

where Pi represents the proportion of each species in the sample, and å is the abundance of the i-th species.

Pielou's evenness index (J') is determined as follows:

$$J = \frac{H'}{H'max} = \frac{H'}{\log S}$$

where $H'max$ is the maximum possible value of the Shannon diversity index, which occurs when all species are equally abundant, and S is the natural logarithm of the total number of species (S).

Shade plots, generated using PRIMER v. 7.0 [30], were employed to represent species abundance variation across marine reporting units. The plots were designed to illustrate the density and diversity of mesozooplankton taxa, providing an overview of spatial patterns, correlations within the dataset, and the distribution of the mesozooplankton fodder component.

To assess the differences in mesozooplankton composition between species and marine reporting units, we performed a non-parametric analysis of similarities (ANOSIM). ANOSIM is based on rank similarities and calculates an R statistic that measures the separation between groups relative to the variation within groups. The analysis was conducted with 999 permutations to determine the statistical significance of observed differences. A significance level of 0.05 was used to evaluate the results.

We conducted a similarity percentage analysis (SIMPER) to further investigate individual taxa's contributions between marine reporting units. This analysis decomposes the overall dissimilarity into contributions from each taxon or variable. SIMPER identifies which species are the most responsible for differences between groups and provides a detailed breakdown of the average dissimilarity between each pair of groups. Results were interpreted to understand the key drivers of community structure and variation across the study sites.

Non-metric multidimensional scaling (nMDS) plots were used to assess the similarities in taxa density (ind/m^3) and taxa biomass (mg/m^3) between flooded (F) and non-flooded (NF) stations. This technique visually represents the relative dissimilarities in community composition based on the selected metrics, allowing for a comparison of the ecological patterns between the two station types.

To evaluate differences in environmental parameters and species abundances between flooded (F) and non-flooded (NF) stations, an independent two-sample t-test was performed, and statistical significance was determined at a significance level of $p < 0.05$.

Canonical analysis investigated the relationships between environmental variables and mesozooplankton community structure. This multivariate statistical method facil-

itated the identification of key ecological drivers influencing species composition and distribution patterns. Canonical correspondence analysis (CCA) was specifically applied, allowing for the direct association of mesozooplankton species abundances with measured environmental parameters such as temperature, salinity, dissolved oxygen, and nutrient concentrations.

Semi-quantitative modeling was conducted using open-source Mental Modeler software (https://www.mentalmodeler.com/) [33] (accessed on 30 October 2024), with significant correlation coefficients indicating the strength of linkages between components. Fuzzy cognitive mapping (FCM) generated qualitative static models [34], which were later converted into quantitative dynamic models. A correlation analysis was performed to evaluate the relationships between mesozooplankton species across marine reporting units and environmental factors, including temperature, salinity, oxygen, and nutrients (phosphate, silicate, nitrite, nitrate, and ammonium). Statistical significance was assessed at a threshold of $p < 0.05$, identifying the environmental gradients that influence species distributions and responses to changing conditions. This approach captured system knowledge by defining three key attributes: the system components (mesozooplankton and abiotic parameters), the positive or negative relationships between them, and the degree of influence one component has over another [12,34,35]. These influences were categorized qualitatively as high, medium, or low, based on significant ($p < 0.05$) Pearson correlation coefficients. Pearson correlation coefficients between physicochemical parameters and mesozooplanktonic species were input into Mental Modeler using data from marine reporting units to build the model [12,34,35]. Positive correlations were visualized with blue arrows and negative correlations with orange arrows, with the weightings reflecting the corresponding coefficient values [12,34,35].

To evaluate the environmental status of the Black Sea using mesozooplankton indicators and determine good environmental status (GES), reference periods were established to set thresholds through descriptive statistics. In Romania, these reference conditions rely on long-term data from 1960 to 2002, divided into two distinct reference periods: 1960–1969, which indicates good conditions, and 1977–2002, which reflects less favorable conditions. The reference conditions and limits were assessed for defining GES using statistical analyses of the data from 1960 to 2002, supplemented by expert judgment. GES was calculated by determining the 90th percentile of values for each marine reporting unit. The resulting values were then compared to the averages for the two reference periods: 1960–1969 (very good condition) and 1977–2002 (poor condition). This comparative method facilitated the establishment of threshold values for each marine reporting unit and indicator which were further utilized in the subsequent analysis (Table 1) for evaluating the Black Sea environmental status.

Table 1. Threshold values for defining ecological status in the Black Sea.

MRU	Ecological Status	Copepoda Biomass (mg/m^3)	Mesozooplankton Biomass (mg/m^3)	*Noctiluca scintillans* Biomass (mg/m^3)
Transitional Waters (TT03)	GES	>45	>240	<240
	Non-GES	<45	<240	>240
Coastal Waters(CT)	GES	>65	>210	<350
	Non-GES	<65	<210	>350
Marine Waters (MT01)	GES	>45	>70	<240
	Non-GES	<45	<70	>240

Green—GES; red—Non-GES.

The integrated Index of Ecological Status (IES) [36] was calculated based on the three mesozooplankton indicators, assessed across the three MRUs. Each indicator in each zone was classified as either achieving GES (good environmental status) or Non-GES, following established ecological assessment criteria. The counts of GES (NG) and Non-GES (NB) cases were tallied to quantify the ecological status across the zones.

The IES value was then derived using the formula:

$$\mathrm{IES} = \frac{\mathrm{NG} - \mathrm{NB}}{\mathrm{NG} + \mathrm{NB}},$$

where NG represents the total number of cases with GES status and NB represents the total number of Non-GES cases. The IES value ranges from −1 to +1, where −1 indicates a completely degraded ecological status and +1 signifies a fully healthy ecosystem [36].

NASA's high-resolution satellite imagery [37], sourced from sensors such as MODIS and VIIRS, was used to monitor environmental changes in marine ecosystems, focusing on the Black Sea. Data were acquired from NASA's Earthdata platform [37], with images filtered by location and time to capture the specific event and key environmental parameters such as chlorophyll-a concentrations. These high-resolution images offer a comprehensive view of oceans, seas, and coastlines, allowing scientists to track real-time water quality, sediment movement, and ecological disturbances. With advanced sensors, NASA satellites can detect events such as algal blooms, pollution spread, and the impacts of natural disasters like floods or dam breaches. These data are essential for evaluating environmental impacts, guiding disaster response, and supporting conservation efforts in sensitive areas like the Black Sea.

3. Results

3.1. Environmental Parameters

The surface temperature ranged from 19.53 °C to 22.32 °C (Table S1). A temperature gradient was shaped from north to south and from coast to shelf. Thus, in transitional waters, the temperature was the highest, with a relatively small range of variability. The coastal region had slightly lower temperatures than the transitional region, with a moderate range, while marine waters were measured with the lowest temperatures and the greatest variation, possibly due to less uniformity in sea conditions compared to nearshore environments (Figure 2).

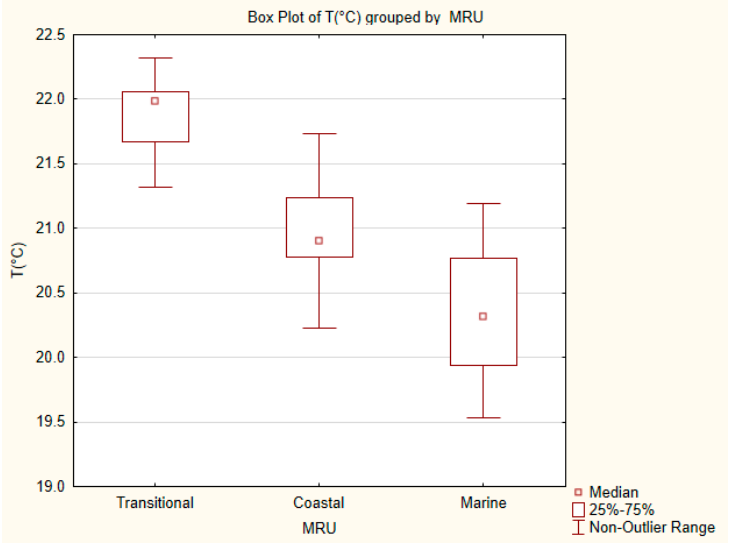

Figure 2. Seawater temperature plot by marine reporting units, surface of the Black Sea, June 2023.

Following the same gradient pattern, salinity oscillated within 6.34–18.25 (Table S1). Thus, salinity was lowest in the transitional region, the area receiving the Danube's waters, showing a wide range with a low median and significant variation. The coastal region had higher salinity with less variability, though a few outliers indicated local deviations. Salinity was the highest and most stable in marine waters, at distances from rivers and coastal sources, with a narrower range and a higher median than the other two marine reporting units (Figure 3).

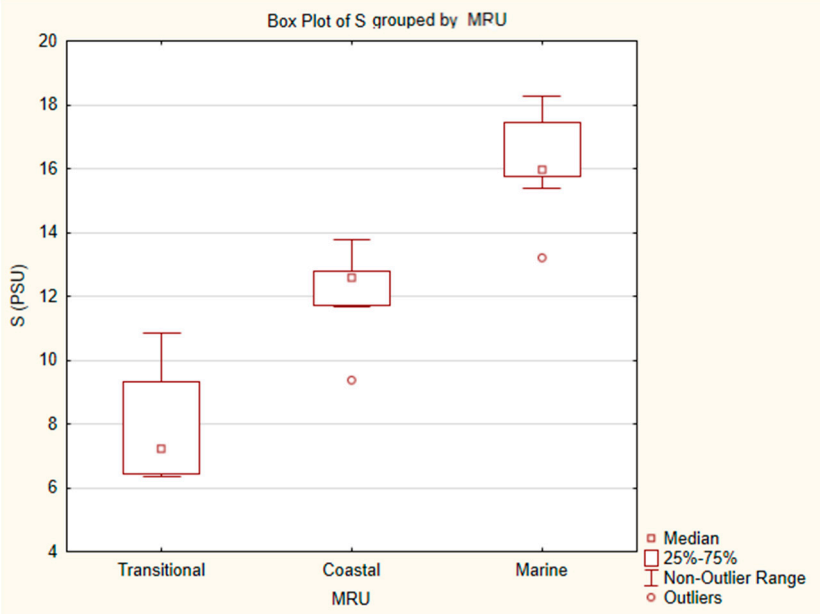

Figure 3. Salinity box plot by marine reporting units, surface of the Black Sea, June 2023.

In terms of nutrients, coastal waters had the widest range of dissolved inorganic phosphorus (phosphate) concentrations, with several outliers above 0.40 µM in the Constanta port area. Transitional waters showed a moderately wider distribution with no extreme values but constant high levels, while the marine area had the smallest range and lower concentrations (Figure 4).

As for silicate, the marine unit showed the greatest variability, with a wide spread of concentrations and extreme values in the northern part, indicating significant fluctuations in silicate levels due to the dam's breach. Transitional waters, by contrast, exhibited more consistent silicate concentrations, suggesting a more uniform distribution of silicate. The coastal zone showed the lowest silicate concentrations overall, with values clustered near the lower limit and a few extreme outliers, indicating minimal silicate presence and lack of coastal sources (Figure 5).

The spatial distribution of dissolved inorganic nitrogen (DIN), comprising the sum of nitrate (NO_3), nitrite (NO_2), and ammonium (NH_4), indicated two primary sources: the Danube River (in transitional waters) and the coastal waters near Constanta, the largest city in the coastal region. Nitrogen speciation varied across locations, suggesting differences in sources or local environmental conditions. The nutrient gradient showed that the transitional region was the most enriched, while offshore areas experienced dilution, reducing the impact of land-based nutrients with distance from the coast. Nitrate predominated in the transitional zone, whereas ammonium levels were higher in more urbanized coastal areas (Figure 6).

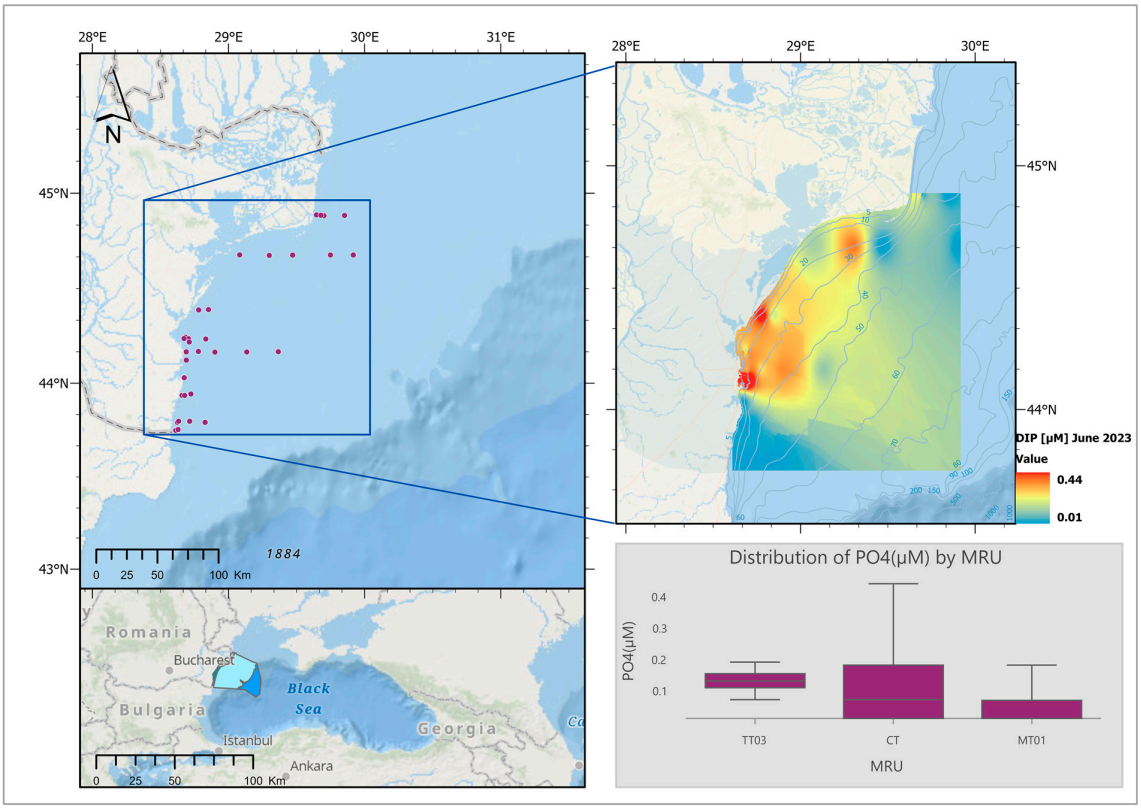

Figure 4. Spatial distribution of dissolved inorganic phosphorus (DIP) and box plot by marine reporting units, surface of the Black Sea, June 2023.

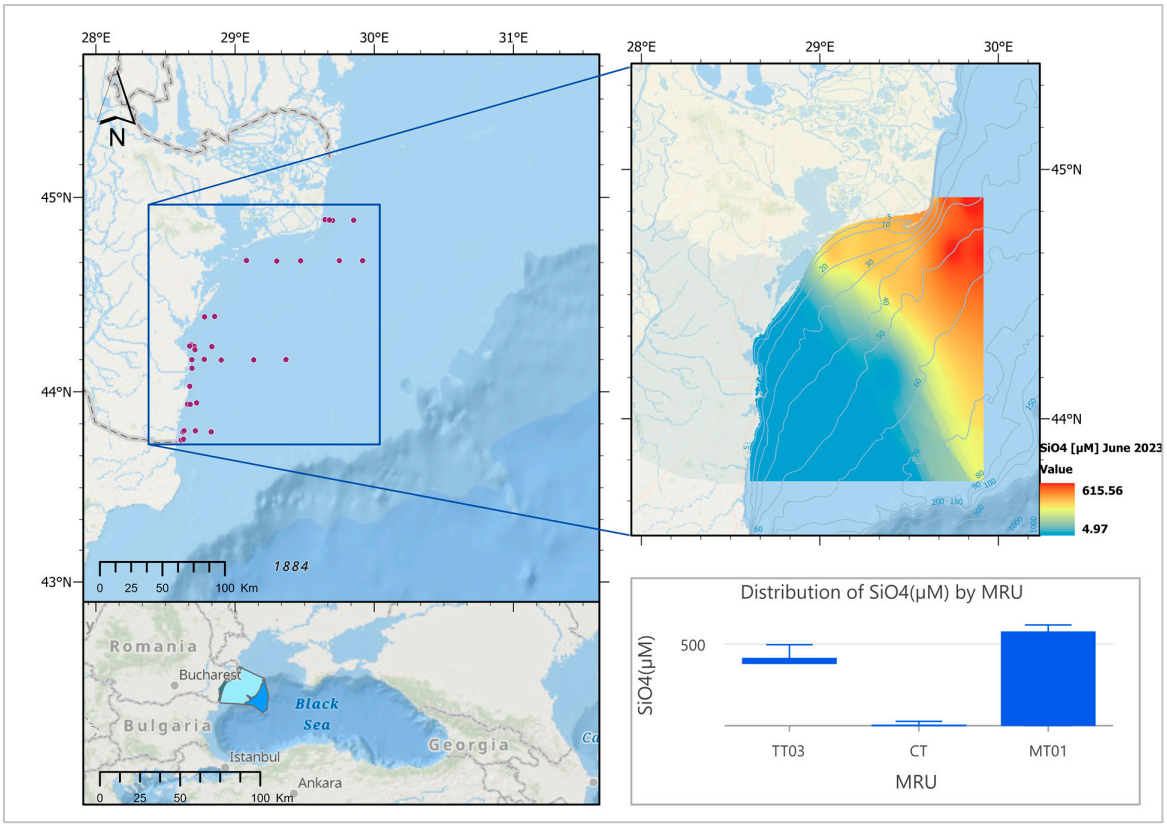

Figure 5. Spatial distribution of dissolved silicate and box plot by marine reporting units, surface of the Black Sea, June 2023.

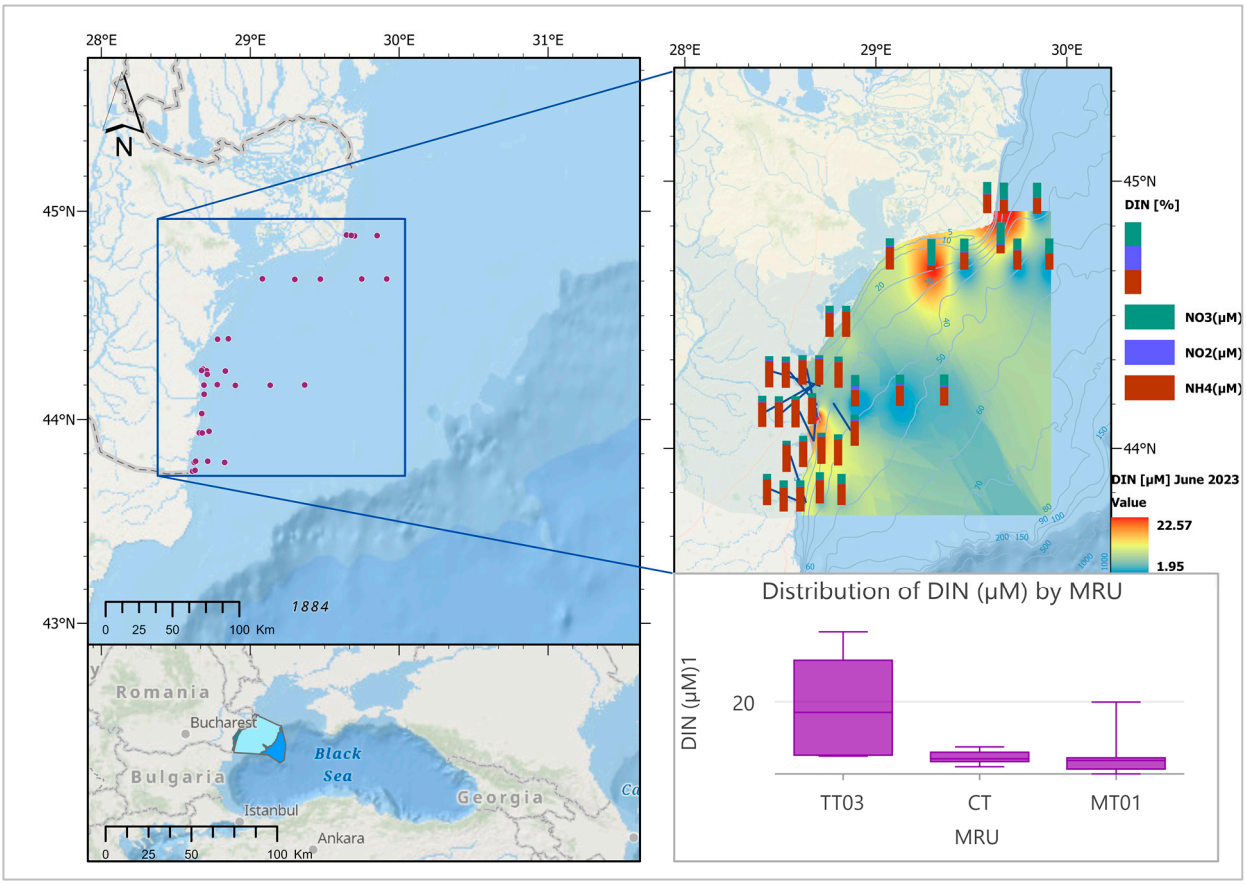

Figure 6. Spatial distribution of dissolved inorganic nitrogen and box plot by marine reporting units, surface of the Black Sea, June 2023.

3.2. Qualitative and Quantitative Structure of Mesozooplankton

Copepoda represented the most dominant taxonomic group across all MRUs, followed by meroplankton, and Cladocera, the least abundant group (Figure 7). Taxa richness was highest in marine waters, followed by a slight reduction in transitional waters, and lowest in the coastal region (Figure 7).

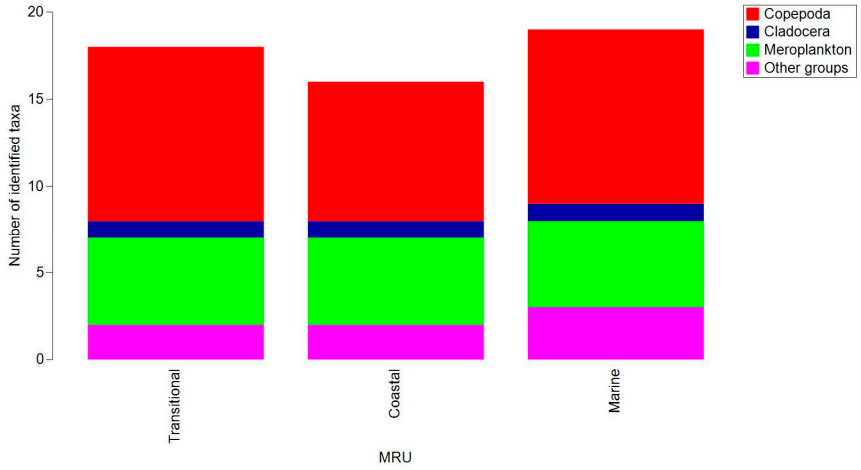

Figure 7. Composition of identified taxa across different MRUs.

The shade plot displays the spatial distribution of mesozooplankton taxa in terms of density (ind/m^3) and biomass (mg/m^3) across transitional, coastal, and marine reporting units (MRUs). The taxa, categorized into functional groups (e.g., copepods, meroplankton,

and nonfodder component—represented by *N. scintillans*), showed varying abundances across these environments. Taxa density (individuals/m^3) showed the highest values for *N. scintillans* and Balanus (Cirripedia larvae) at certain coastal and marine stations, reaching up to 200 individuals/m^3. Biomass (mg/m^3) followed a similar distribution pattern but with lower overall values, peaking at 60 mg/m^3 (Figure 8).

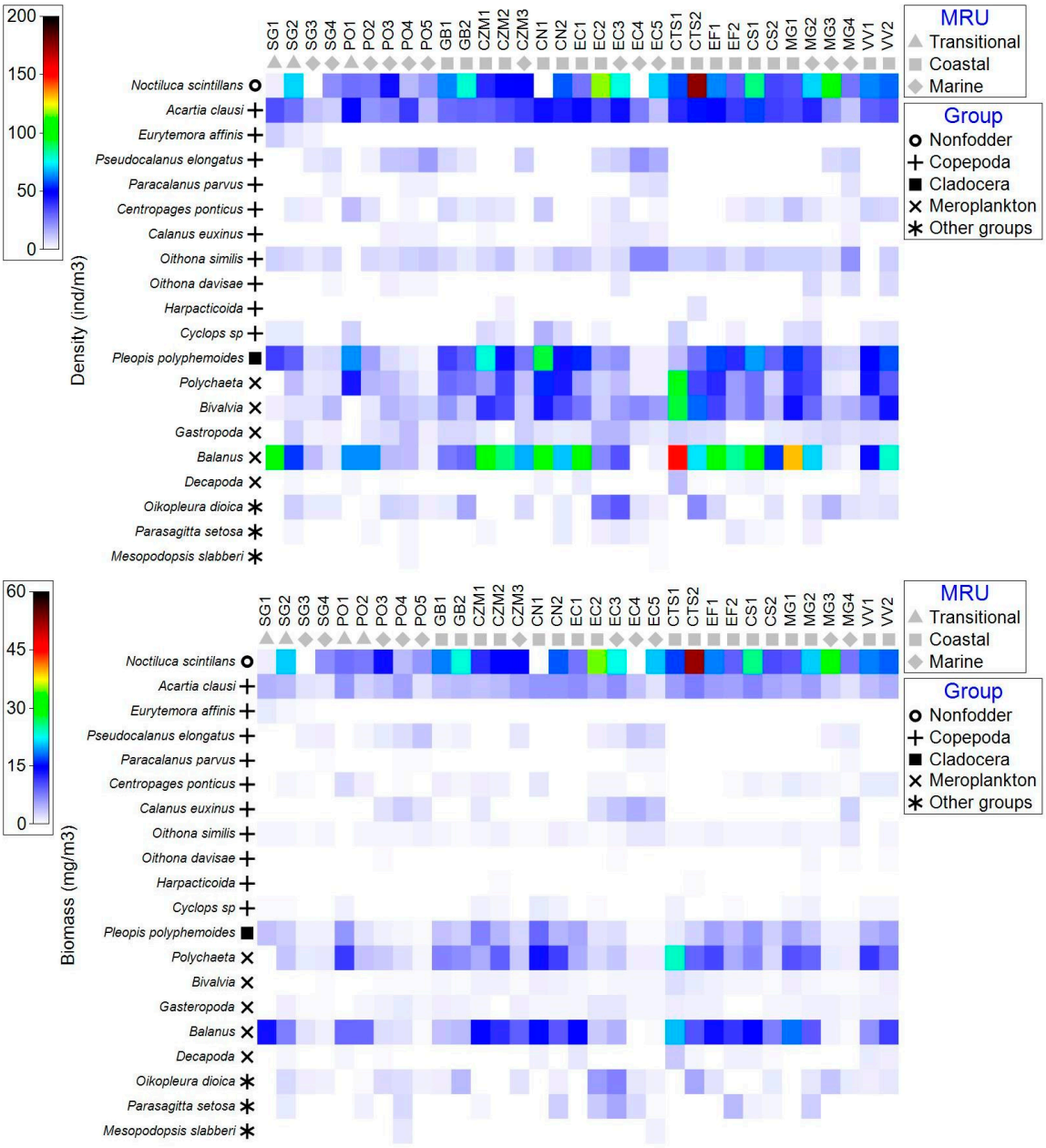

Figure 8. Shade plot of taxa density and biomass across various sampling stations within transitional, coastal, and marine reporting units (MRUs).

The species composition across transitional, coastal, and marine waters revealed distinct patterns of dominance, as suggested by the ANOSIM results, with an R value of 0.652 (Figure 9).

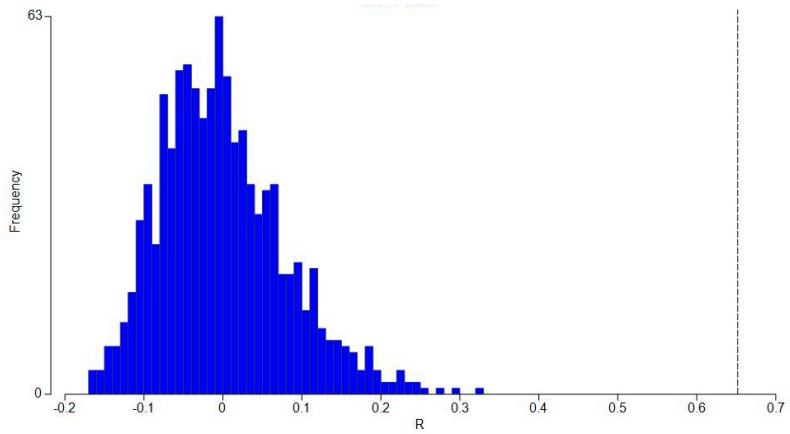

Figure 9. Histogram representing the distribution of the test statistic R from the MRU test.

The results of the species similarity and dissimilarity analyses across MRUs revealed notable patterns in community composition. Transitional waters had the highest average similarity (61.85%), driven primarily by dominant species like Balanus larvae (39.81% contribution) and *Pleopis polyphemoides* (22.73%). Coastal waters showed the highest average similarity (70.59%), with strong contributions from Balanus larvae (25.29%) and *N. scintillans* (17.89%). Marine waters, with a lower average similarity (54.92%), were marked by significant contributions from *N. scintillans* (21.71%) and *Acartia clausi* (18.01%). The dissimilarity analysis indicated that the largest differences occurred between transitional and marine waters (56.25%), particularly due to contrasting abundances of Balanus larvae and *N. scintillans*. Transitional and coastal waters showed moderate dissimilarity (34.53%), with Balanus larvae and *P. polyphemoides* being key differentiators. Finally, marine and coastal waters also exhibited significant dissimilarity (52.06%), largely driven by differences in Balanus larvae and *P. polyphemoides* abundances (Table 2).

Species richness (S) ranged from 8 (e.g., SG1 and PO1) to 16 (e.g., PO4 and EC5), indicating varying levels of biodiversity, while evenness (J′) varied from 0.1676 (MG3) to 0.7479 (PO1), reflecting differences in distribution. High species richness did not always correspond to high evenness, as seen in PO4 (high richness, moderate evenness) and PO1 (low richness, high evenness). Notably, MG3 stood out with very low evenness despite moderate richness (Figure 10).

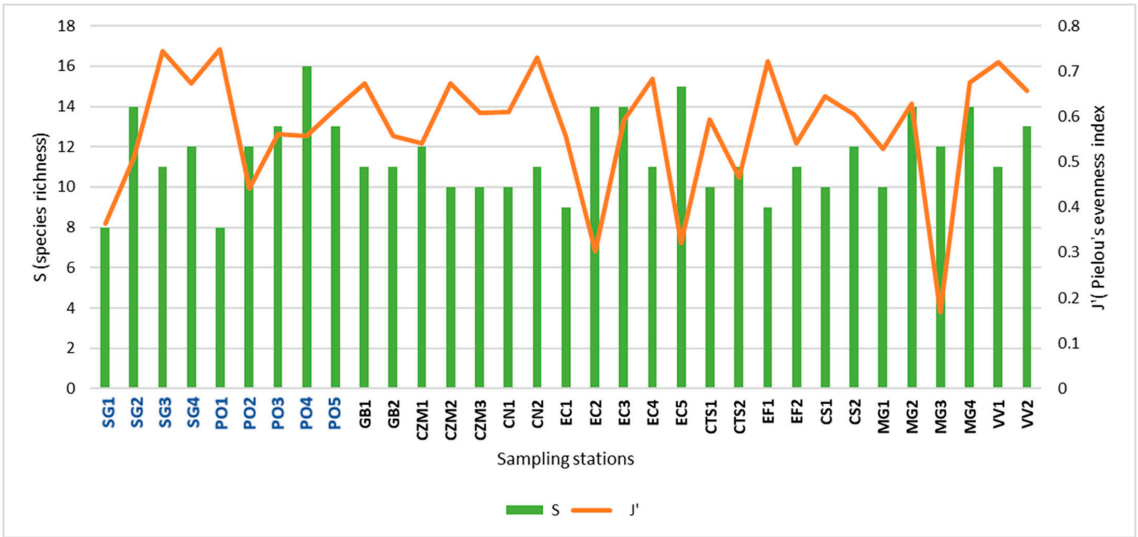

Figure 10. Species richness (*S*) and evenness (*J*′) across sampling stations, blue stations represent flooded sampling sites, June 2023.

Table 2. Simper analysis for mesozooplankton taxa in June 2023.

Group Transitional						
Average similarity: 61.85						
Taxa	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%	
Balanus larvae	71.45	24.62	8.27	39.81	39.81	
Pleopis polyphemoides	43.69	14.06	7.35	22.73	62.54	
Acartia clausi	35.94	12.49	6.31	20.19	82.73	
Group Coastal						
Average similarity: 70.59						
Taxa	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%	
Balanus larvae	80.33	17.85	2.33	25.29	25.29	
Noctiluca scintillans	60.73	12.63	1.9	17.89	43.19	
Pleopis polyphemoides	46.22	10.85	2.48	15.37	58.56	
Acartia clausi	38.37	10.48	6.1	14.84	73.4	
Group Marine						
Average similarity: 54.92						
Taxa	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%	
Noctiluca scintillans	40.62	11.92	1.23	21.71	21.71	
Acartia clausi	23.52	9.89	2.79	18.01	39.72	
Bivalvia larvae	13.92	6.29	2.3	11.45	51.17	
Oithona similis	10.34	4.52	1.52	8.23	59.4	
Pseudocalanus elongatus	9.62	4.28	1.33	7.79	67.2	
Balanus larvae	22.05	4.2	0.72	7.65	74.85	
Groups Transitional & Marine						
Average dissimilarity = 56.25						
	Group Transitional	Group Marine				
Taxa	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Balanus larvae	71.45	22.05	14.45	1.53	25.68	25.68
Pleopis polyphemoides	43.69	11.36	8.59	1.87	15.27	40.96
Noctiluca scintillans	33.76	40.62	8.55	1.27	15.21	56.17
Acartia clausi	35.94	23.52	4.45	1.47	7.91	64.07
Polychaeta larvae	18.86	9.14	4.2	1.14	7.47	71.54
Groups Transitional & Coastal						
Average dissimilarity = 34.53						
	Group Transitional	Group Coastal				
Taxa	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Noctiluca scintillans	33.76	60.73	7.43	1.24	21.53	21.53
Balanus larvae	71.45	80.33	6.02	1.47	17.44	38.97
Bivalvia larvae	3.02	34	5.23	1.94	15.15	54.12
Polychaeta larvae	18.86	33.51	4.3	1.46	12.45	66.57
Pleopis polyphemoides	43.69	46.22	3.47	1.42	10.05	76.61
Groups Marine & Coastal						
Average dissimilarity = 52.06						
	Group Marine	Group Coastal				
Taxa	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Balanus larvae	22.05	80.33	13.09	1.74	25.14	25.14
Noctiluca scintillans	40.62	60.73	8.68	1.22	16.67	41.81
Pleopis polyphemoides	11.36	46.22	7.67	1.72	14.72	56.54
Polychaeta larvae	9.14	33.51	5.24	1.53	10.06	66.6
Bivalvia larvae	13.92	34	4.26	1.36	8.19	74.79

Shannon–Wiener legislation of the aquatic environment classifies water quality as >4 = very good quality, 3–4 = good quality, 2–3 = moderate quality, 1–2 = poor quality, and <1 = very poor quality [32]. Most of the sampling stations in June recorded low index values

within 1–2, implying poor quality, with some stations having very poor quality, indicating low biodiversity (Figure 11).

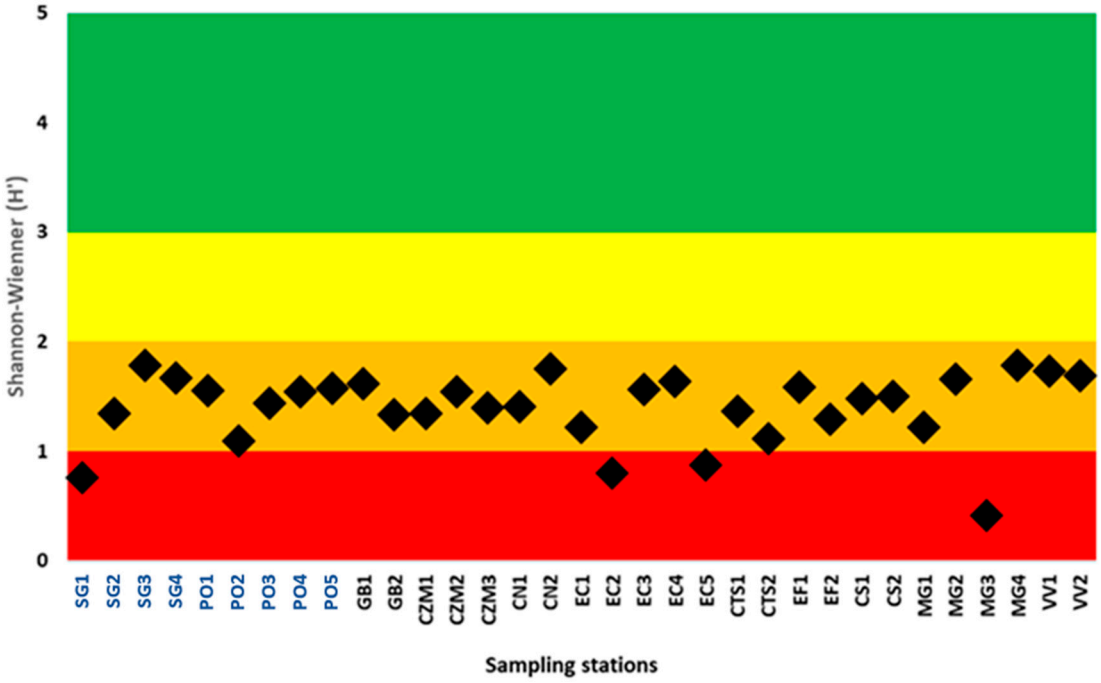

Figure 11. Shannon–Wiener diversity index (H') values for zooplankton in June 2023, blue stations represent flooded sampling sites. Red—very poor quality, orange—poor quality, yellow—moderate quality, green—good quality.

Transitional, coastal, and marine waters exhibited varying levels of biodiversity, as indicated by the Shannon diversity index (H'). Transitional waters showed the lowest H' value (1.8, orange) and were classified as poor quality, likely due to environmental stressors such as pollution or freshwater inputs. Coastal waters had a slightly higher H' value (1.98, orange), reflecting a mix of influences from both transitional and marine zones but were still classified as poor quality. Marine waters displayed the highest H' value (2.04, yellow), indicating moderate ecological quality, with more stable conditions (Figure 12).

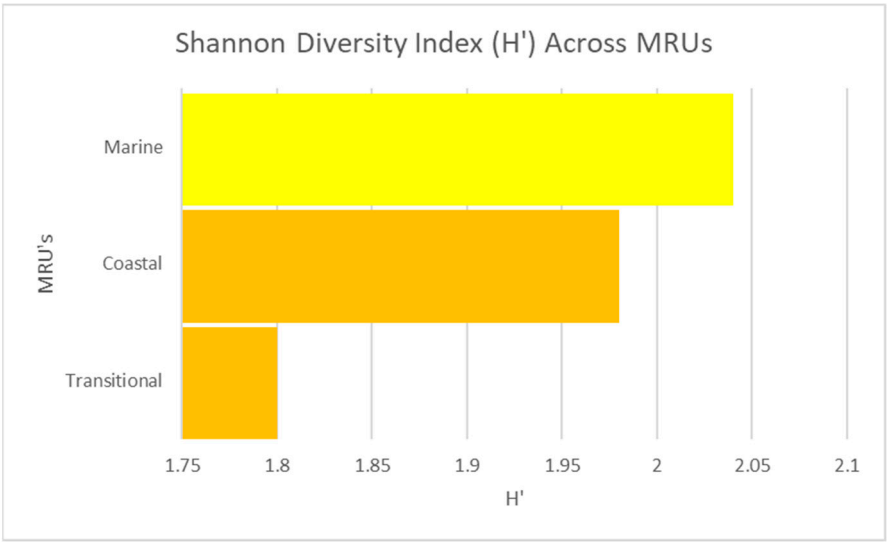

Figure 12. Shannon–Wiener diversity index (H') values for zooplankton across MRUs in June 2023. Orange—poor quality, yellow—moderate quality.

In transitional waters, zooplankton densities were comparatively low, with nonfodder zooplankton and fodder zooplankton exhibiting reduced abundances, accompanied by moderate variability in biomass (e.g., copepod biomass displayed a broad range). By contrast, the coastal zone exhibited the highest zooplankton densities, characterized by high fodder zooplankton and copepod abundances, along with relatively stable yet elevated biomass (e.g., meroplankton biomass peaked significantly). The marine zone displayed intermediate zooplankton densities, with nonfodder zooplankton and copepods showing moderate abundances but with pronounced variability in biomass (e.g., meroplankton biomass fluctuated widely) (Table S2).

The highest concentrations of fodder zooplankton were observed near the coast, where elevated nutrient levels enhanced phytoplankton growth, thereby supporting dense zooplankton populations. As the distance from the coast increased, zooplankton concentrations progressively declined, with moderate concentrations observed in mid-range zones and the lowest concentrations occurring in offshore areas where nutrient availability diminishes and oceanic conditions dominate (Figure 13).

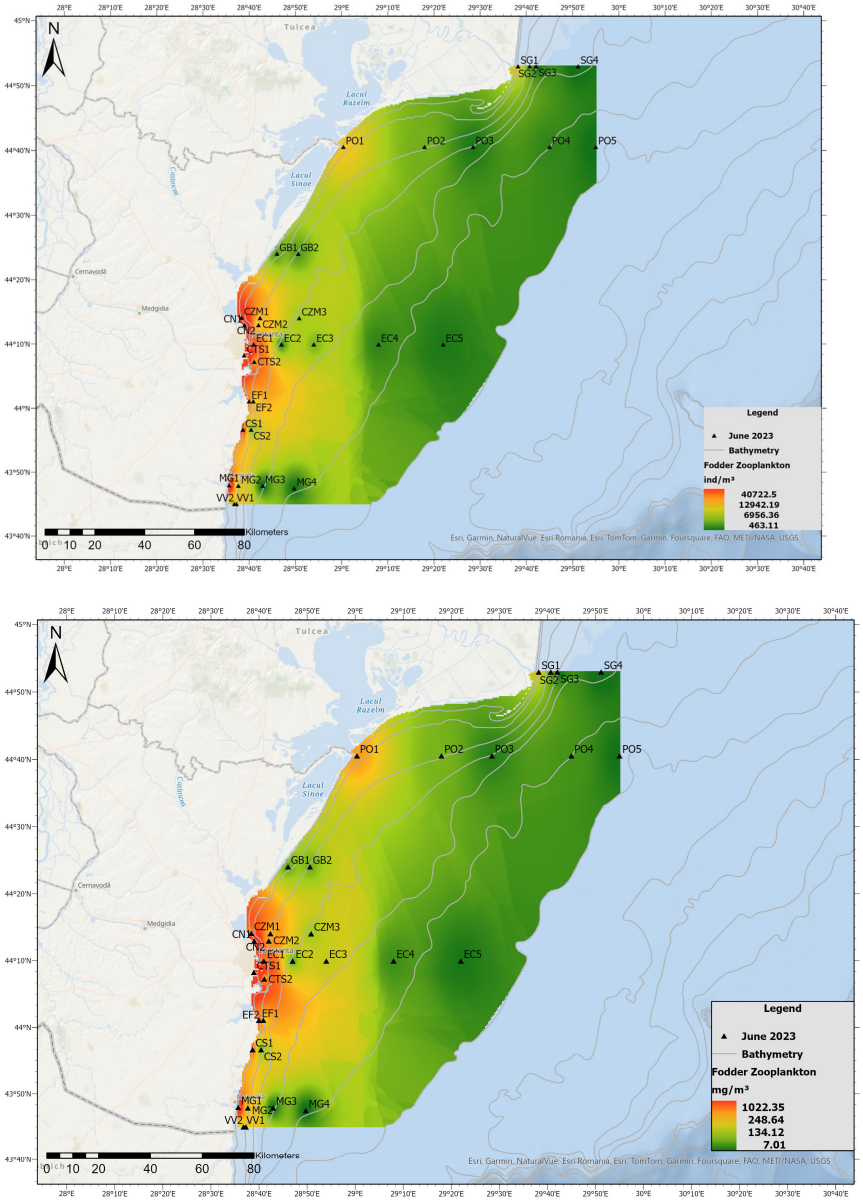

Figure 13. Spatial distribution of fodder zooplankton density (**upper**) and biomass (**lower**) along the coastal region in June 2023.

The heatmap analysis demonstrated distinct patterns in the density and biomass distribution of fodder zooplankton groups across sampling stations. Meroplankton exhibited prominent peaks in density and biomass in specific sampling sites while Copepoda maintained consistent moderate density and biomass (Figure 14). The Cladocera group showed moderate density and a contribution to biomass, influenced by *Pleopis polyphemoides* relatively larger size; however, its overall impact appears less prominent compared to meroplankton. In contrast, Other groups consistently show low density and biomass, indicating a limited role in community structure. The clustering patterns in the heatmaps reveal spatial or temporal trends, with meroplankton dominating localized hotspots, while Copepoda and Cladocera exhibited broader, more stable distributions (Figure 14).

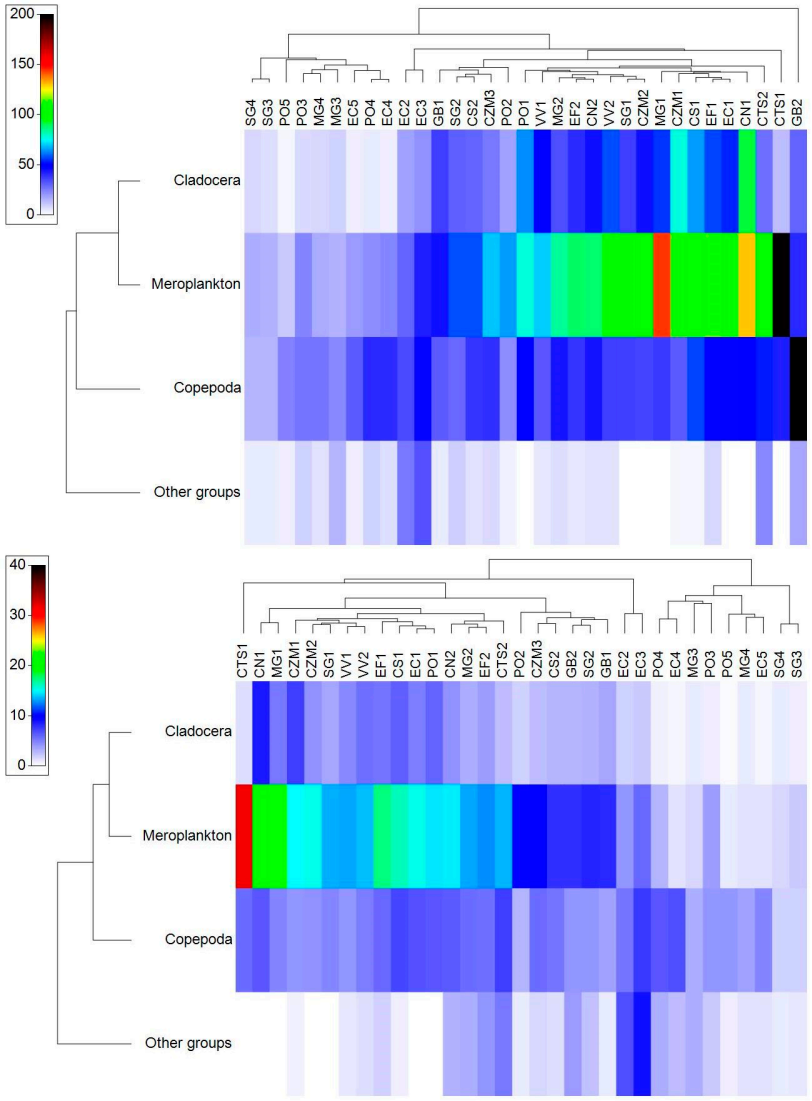

Figure 14. Shade plots showing the distribution of fodder zooplankton in June 2023 across sampling stations. Upper—density (ind/m^3), lower—biomass (mg/m^3).

The coastal areas exhibited significantly higher *N. scintillans* densities, likely driven by nutrient-rich waters that support their growth. As distance from the shore increases, concentrations progressively decrease, with moderate levels observed in mid-range zones and the lowest concentrations found in offshore waters. This gradient highlights the strong influence of coastal nutrient inputs on N. scintillans distribution. High con-centrations are seen near stations such as CZM1, CZM2, and MG3, likely affected by nutrient runoff from the cities of Constanța and Mangalia, as well as nearby ports. In contrast, stations

located further offshore, like EC4 and PO4, show much lower con-centrations, likely due to reduced nutrient availability and dilution in deeper waters (Figure 15).

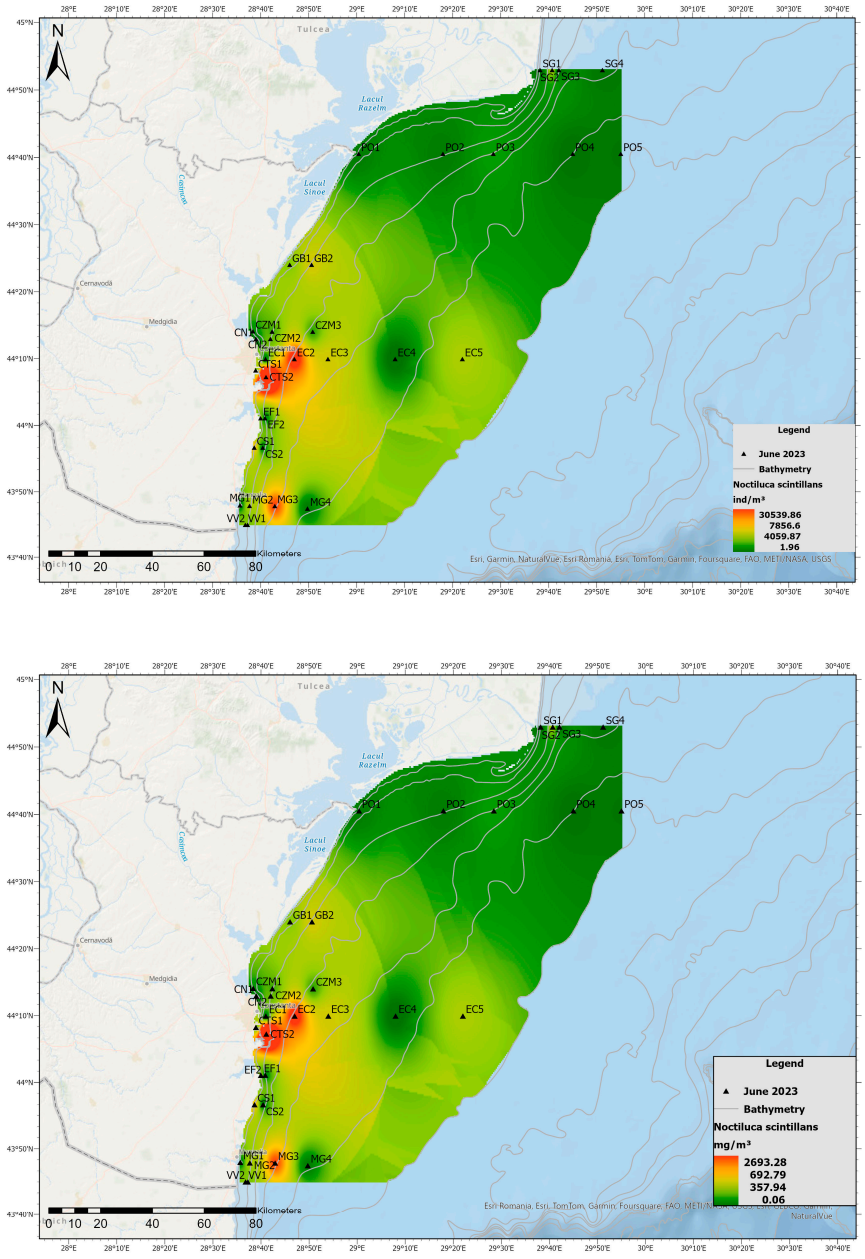

Figure 15. Spatial distribution of nonfodder zooplankton density (**upper**) and biomass (**lower**) along the coastal region in June 2023.

3.3. Variability in Environmental Parameters and Mesozooplankton Between Flooded and Non-Flooded Stations

The analysis revealed distinct differences in mesozooplankton composition between flooded (F) and non-flooded (NF) sampling stations. Flooded stations exhibited moderate similarity (50.06%), with *A. clausi*, Balanus larvae, and *N. scintillans* as key contributors, reflecting variability likely driven by altered hydrological conditions. By contrast, non-flooded sites showed higher similarity (61.84%), dominated by *N. scintillans* and Balanus larvae (Table 3). The dissimilarity (49.81%) between the two groups was primarily driven by higher abundances of Balanus larvae and *N. scintillans* in non-flooded sites, while *A. clausi* and other taxa were more characteristic of flooded conditions (Table 3).

Table 3. Simper analysis for mesozooplankton taxa in June 2023, flooded (F) and non-flooded (NF) sampling stations.

Group F						
Average similarity: 50.06						
Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%	
Acartia clausi	24.66	10.8	3.12	21.57	21.57	
Balanus larvae	35.93	9.3	1.04	18.58	40.16	
Noctiluca scintillans	25.45	8.3	1.15	16.58	56.74	
Pleopis polyphemoides	19.58	4.86	1.31	9.7	66.44	
Oithona similis	6.58	3.73	1.57	7.45	73.89	
Group NF						
Average similarity: 61.84						
Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%	
Noctiluca scintillans	59.7	13.75	1.61	22.24	22.24	
Balanus larvae	64.3	12.27	1.25	19.84	42.08	
Acartia clausi	35.17	9.86	3.53	15.95	58.03	
Pleopis polyphemoides	37.01	7.76	1.58	12.55	70.58	
Groups F & NF						
Average dissimilarity = 49.81						
	Group F	Group NF				
Species	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib%	Cum.%
Balanus larvae	35.93	64.3	11.08	1.41	22.24	22.24
Noctiluca scintillans	25.45	59.7	9.96	1.26	19.99	42.23
Pleopis polyphemoides	19.58	37.01	6.34	1.39	12.73	54.96
Bivalvia larvae	7.24	29.29	4.62	1.54	9.27	64.24
Polychaeta larvae	11.33	26.8	4.55	1.33	9.13	73.37

The non-metric multidimensional scaling (nMDS) plots illustrated the similarities in taxa density (ind/m^3) and taxa biomass (mg/m^3) between flooded (F) and non-flooded (NF) stations. For both metrics, flooded stations (blue triangles) exhibited greater spatial dispersion, indicating variability in community composition. Conversely, non-flooded stations (red inverted triangles) generally clustered together, particularly in taxa density, suggesting higher similarity within this group (Figure 16). The 2D stress values (0.10 for density, 0.09 for biomass) confirmed that the plots reliably represented the data's multivariate relationships, highlighting the influence of flooding on taxa distributions.

The data revealed considerable variability in density across most mesozooplankton groups at flooded stations (Table 4). Fodder mesozooplankton had the highest mean density but exhibited a wide range of values, as reflected in its substantial variability. Similarly, meroplankton showed a high mean density but was accompanied by significant variability, indicating large differences across samples. Nonfodder mesozooplankton (*N. scintillans*) also displayed notable variability in density, suggesting substantial differences in organism counts. Other groups, such as Copepoda and Cladocera, demonstrated moderate variability but still exhibited a broad range in their densities.

For biomass, fodder mesozooplankton again stood out with the highest mean value, though it showed considerable spread in mass concentration (Table 5). Nonfodder meso-

zooplankton followed closely, also characterized by substantial variability. Meroplankton, while having a slightly lower mean biomass, reflected high variability, underscoring wide differences in its biomass concentration. Copepoda and Cladocera had moderate mean values with varying degrees of variability, highlighting differences in biomass among groups.

The *t*-test analysis comparing flooded (F) and non-flooded (NF) stations revealed several significant differences in environmental parameters and species abundances (Table S3). Key findings include significantly higher mean concentrations of SiO_4 ($p = 0.000000$) and NO_3 ($p = 0.009581$) in flooded stations, suggesting that flooding may have influenced nutrient levels in these areas. Additionally, *Eurytemora affinis* showed significantly higher abundance in flooded stations ($p = 0.040417$). However, no significant differences were observed for species like *N. scintillans* and *A. clausi*, nor for PO_4 ($p = 0.482187$), indicating similar concentrations across both station types. Variance comparisons also revealed significant differences for some variables, such as SiO_4 and NH_4, suggesting varying degrees of fluctuation in nutrient levels between the two station types. These results emphasized the impact of flooding on nutrient dynamics and the distribution of certain species.

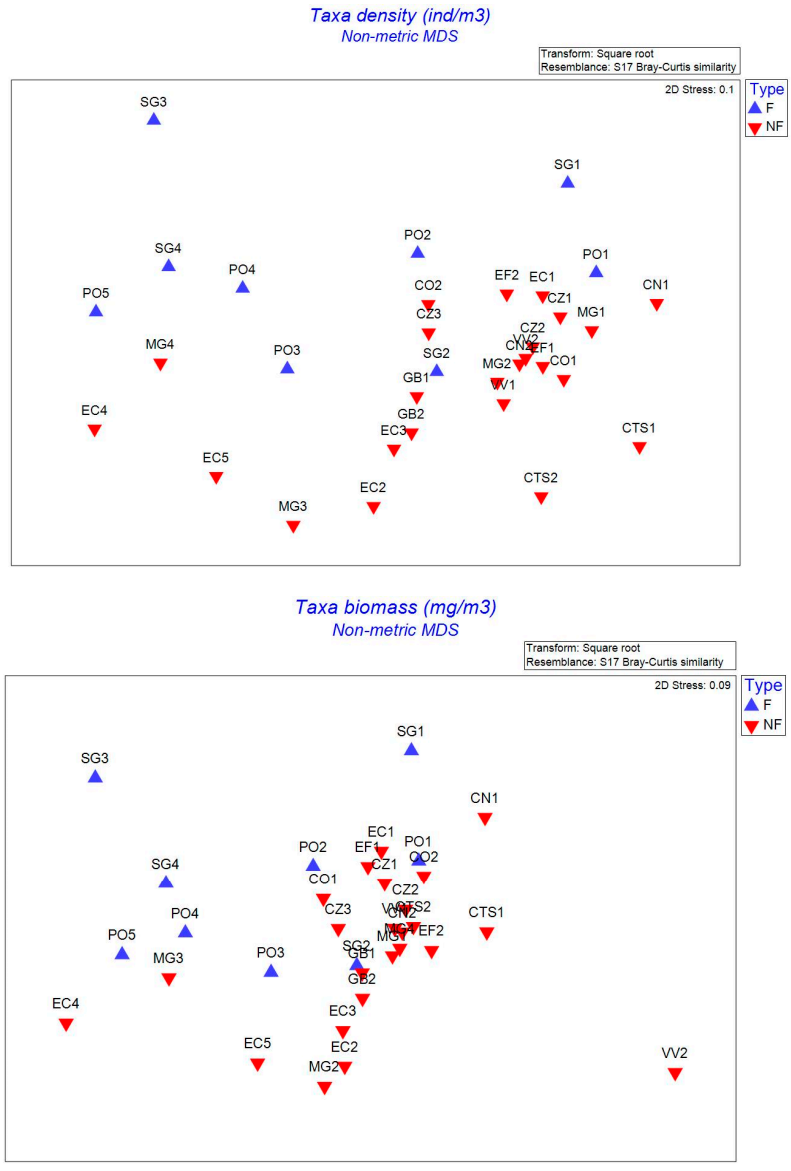

Figure 16. Non-metric multidimensional scaling (nMDS) plots illustrating the similarities in taxa density (ind/m^3) and taxa biomass (mg/m^3) between flooded (F) and non-flooded (NF) stations, June 2023.

Table 4. Descriptive statistics for mesozooplankton in June 2023, flooded stations (F).

Variable	Type = F Descriptive Statistics							
	Valid N	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.
Nonfodder ZPK (ind/m^3)	9	1064.628	482.804	0.0000	4951.80	176.3864	759.761	1587.451
Fodder Zpk (ind/m^3)	9	4428.995	2196.098	455.8800	12,429.96	706.0900	5130.833	4752.609
Copepoda (ind/m^3)	9	933.488	718.208	188.6400	2462.67	484.1387	1306.846	745.677
Cladocera (ind/m^3)	9	758.446	64.160	1.9650	4008.40	39.3000	951.933	1311.929
Meroplankton (ind/m^3)	9	2706.442	566.313	96.2850	9285.56	235.7880	4253.196	3264.641
Other groups (ind/m^3)	9	30.620	12.832	0.0000	87.77	4.3979	68.401	36.426
Nonfodder ZPK (mg/m^3)	9	93.687	42.487	0.0000	435.76	15.5220	66.859	139.696
Fodder Zpk (mg/m^3)	9	91.234	59.697	7.0087	282.86	17.0376	101.109	96.624
Copepoda (mg/m^3)	9	18.800	16.418	3.0206	42.04	8.2043	22.040	14.580
Cladocera (mg/m^3)	9	6.826	0.577	0.0177	36.08	0.3537	8.567	11.807
Meroplankton (mg/m^3)	9	63.190	14.077	0.5148	204.74	4.4122	89.382	79.067
Other groups (mg/m^3)	9	2.418	0.667	0.0000	9.66	0.4087	4.087	3.353

Table 5. Descriptive statistics for mesozooplankton in June 2023, non-flooded stations (NF).

Variable	Type = NF Descriptive Statistics							
	Valid N	Mean	Median	Minimum	Maximum	Lower Quartile	Upper Quartile	Std.Dev.
Nonfodder ZPK (ind/m^3)	24	4920.00	3438.75	0.0000	30,654.00	1137.490	5436.50	6440.606
Fodder Zpk (ind/m^3)	24	11,856.43	10,421.05	989.5740	41,105.71	4006.035	17,605.61	9845.823
Copepoda (ind/m^3)	23	1617.33	1458.47	499.1100	3183.14	1021.748	2230.27	675.297
Cladocera (ind/m^3)	24	1890.01	1231.37	9.8250	8331.18	375.806	2908.12	2052.697
Meroplankton (ind/m^3)	24	8249.89	7344.19	226.3680	39,140.81	1730.838	12,004.70	8682.248
Other groups (ind/m^3)	24	128.38	26.53	0.0000	1051.28	1.965	52.40	259.306
Nonfodder ZPK (mg/m^3)	24	432.96	302.61	0.0000	2697.55	100.099	478.41	566.773
Fodder Zpk (mg/m^3)	24	243.82	222.04	15.6367	1033.48	96.181	294.08	216.953
Copepoda (mg/m^3)	24	29.79	28.89	9.6796	55.80	17.343	39.96	13.509
Cladocera (mg/m^3)	24	17.01	11.08	0.0884	74.98	3.382	26.17	18.474
Meroplankton (mg/m^3)	24	187.38	172.97	1.1841	999.72	46.780	228.76	212.420
Other groups (mg/m^3)	24	9.63	1.70	0.0000	79.68	0.334	10.01	18.193

The canonical analysis revealed a robust relationship between environmental variables and biological assemblages in the dataset, with a canonical correlation of 0.99609 (Table 6). This high value demonstrated that the environmental factors, including silicates, strongly explained the variability observed in the biological communities. The statistical significance of the model, as indicated by $Chi^2(180) = 291.41$, $p = 0.0000$, underscored the importance of these environmental drivers in shaping biological responses.

Table 6. Canonical analysis summary.

N = 33	Canonical Analysis Summary Canonical R: 0.99609 $Chi^2(180) = 291.41$ $p = 0.0000$	
	Left Set	**Right Set**
No. of variables	20	9
Variance extracted	63.7912%	100.000%
Total redundancy	51.8716%	79.2236%
Variables: 1	*Noctiluca scintillans*	T (°C)
2	*Acartia clausi*	S
3	*Eurytemora affinis*	O_2 (µM)
4	*Pseudocalanus elongatus*	O_2 (%)
5	*Paracalanus parvus*	PO_4 [µM]
6	*Centropages ponticus*	SiO_4 [µM]
7	*Calanus euxinus*	NO_2 [µM]
8	*Oithona similis*	NO_3 [µM]
9	*Oithona davisae*	NH_4 [µM]
10	*Harpacticoida*	
11	*Cyclops* sp.	
12	*Pleopis polyphemoides*	
13	Polychaeta larvae	
14	Bivalvia larvae	
15	Gastropoda larvae	
16	Balanus larvae	
17	Decapoda larvae	
18	*Oikopleura dioica*	
19	*Parasagitta setosa*	
20	*Mesopodopsis slabberi*	

A substantial portion of the variance in the biological dataset (63.79%) was explained by the canonical functions, while the environmental variables redundantly captured 51.87% of the biological variance. Similarly, 79.22% of the environmental variability was reflected in the biological responses, indicating that these two datasets were intricately linked. Among the environmental drivers, SiO_4 emerged as a key variable, closely associated with *Centropages ponticus*, a copepod reliant on diatom-dominated systems [38]. This linkage highlighted the role of silicates in sustaining diatom-based food webs, which support higher trophic levels. Additionally, PO_4 was linked to *Paracalanus parvus*, NO_2, NO_3, and NH_4, which were associated with species like *N. scintillans*, a dinoflagellate organism indicative of eutrophic conditions.

3.4. Semi-Quantitative Models of the Causal Relationships Between Mezozooplankton and Physicochemical Parameters

The correlation analysis revealed significant relationships between mesozooplankton, marine species, and various environmental factors, including temperature, salinity, oxygen, and nutrients (phosphate, silicate, nitrite, nitrate, and ammonium). Statistically significant correlations ($p < 0.05$) were found, highlighting the sensitivity of different species to specific environmental gradients (Table S4).

In transitional waters, *A. clausi* and *N. scintillans* were connected to environmental variables like phosphate (PO_4), nitrate (NO_2), and nitrite NO_3), indicating their reliance

on these nutrients for survival and growth. The positive interactions suggested beneficial relationships or dependencies, while the negative interactions were possibly due to competition for resources or nutrient depletion. Central to the system was salinity ("S"), which influenced the distribution and interactions of various species, including copepods and larvae of bivalves (Figure 17).

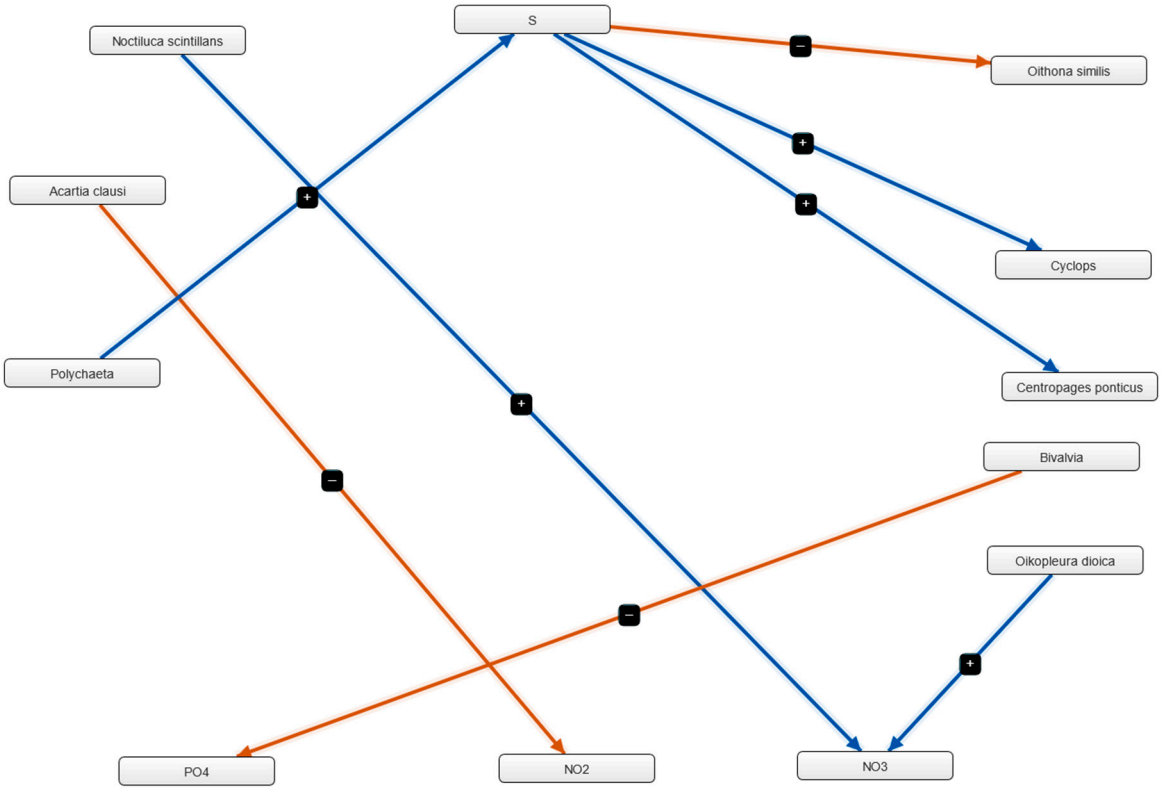

Figure 17. Fuzzy cognitive map—interactions between physicochemical parameters and mesozooplankton in Black Sea transitional waters.

In coastal waters, *N. scintillans*, *Pseudocalanus elongatus*, *Pleopis polyphemoides*, Cyclops, and Harpacticoida interacted with environmental factors, including essential nutrients like nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), phosphate (PO_4), and silicate (SiO_4), as well as oxygen (O_2), temperature (T), and salinity (S). Balanus, Decapoda, and Bivalvia larvae had numerous connections to both nutrients, suggesting their central role in the ecosystem as they influenced and were influenced by multiple factors. Salinity and temperature, represented by "S" and "T", played a pivotal role in shaping species distributions and interactions, as both are fundamental environmental factors affecting marine life (Figure 18).

In marine waters, species such as *A. clausi*, *E. affinis*, *Calanus euxinus*, and *P. polyphemoides* showed strong dependencies on key nutrients like phosphate (PO_4), nitrate (NO_3), and oxygen (O_2), while salinity (S) influenced the distribution of species like *E. affinis*. The positive interactions suggested that these species benefited from the availability of these nutrients and conditions, whereas the negative interactions indicated possible competition or limitations due to environmental factors, such as Bivalvia larvae's negative response to silicate (SiO_4). The central role of phosphate highlighted its importance in sustaining the food web, as it supported numerous organisms, including *Parasagitta setosa* and Gastropoda larvae (Figure 19).

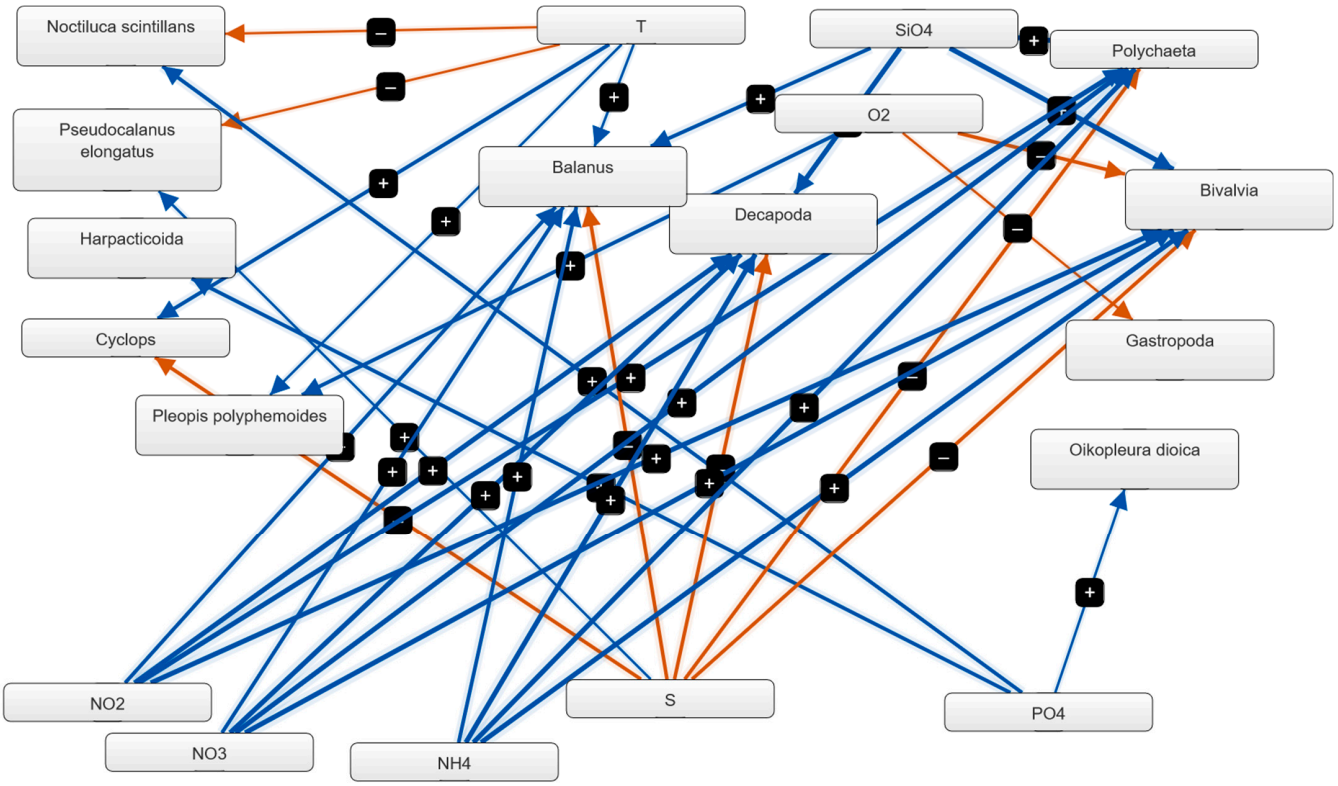

Figure 18. Fuzzy cognitive map—interactions between physicochemical parameters and mesozooplankton in Black Sea coastal waters.

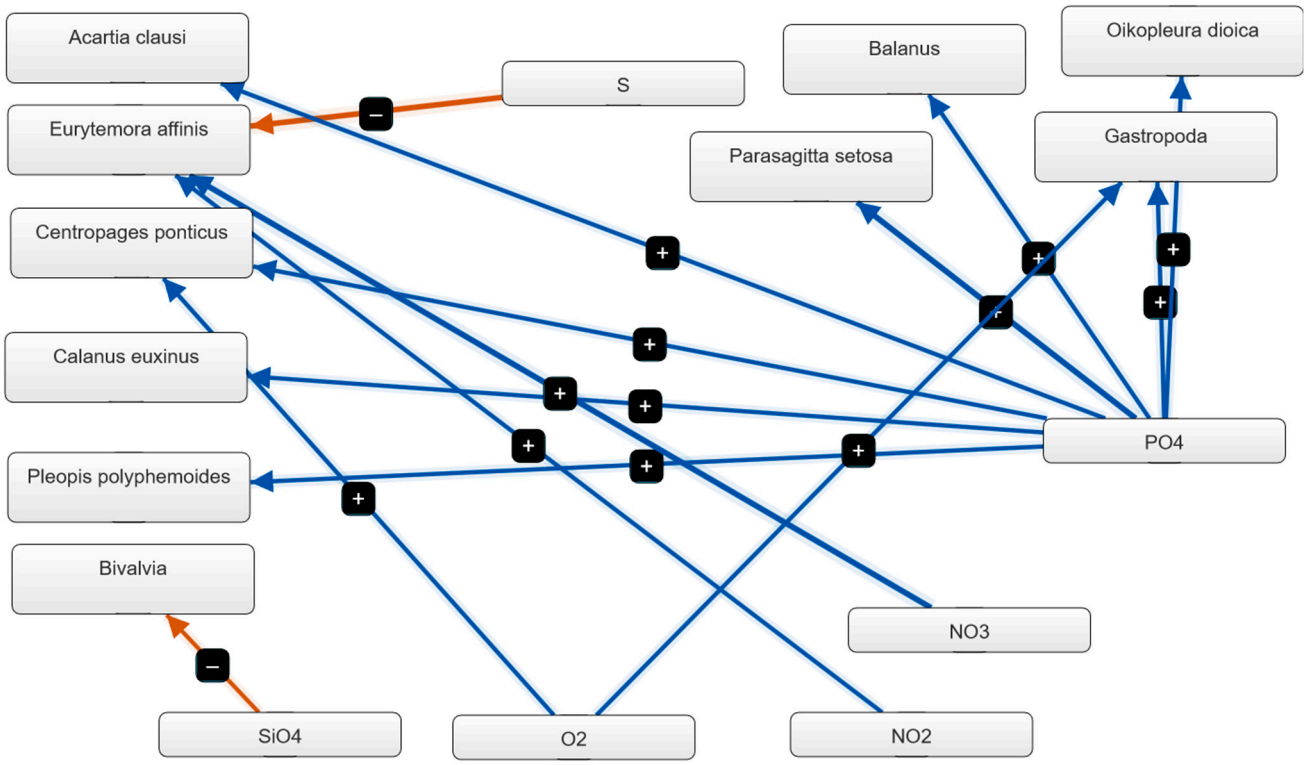

Figure 19. Fuzzy cognitive map—interactions between physicochemical parameters and mesozooplankton in Black Sea marine waters.

3.5. Assessment of Mesozooplankton Indicators and Environmental Status in the Black Sea

This analysis centers on key metrics, such as the biomass levels of copepods, mesozooplankton, and *N. scintillans*, in line with the Marine Strategy Framework Directive [39]. By assessing these indicators, we can obtain important insights into the health of pelagic habitats, the availability of food for higher trophic levels, and the overall resilience of the ecosystem. Understanding these dynamics is vital for developing effective management and conservation strategies that ensure the sustainability of the Black Sea environment.

The MSFD mandates reporting the percentage or square kilometers of surface area within each major habitat in a marine region that achieves GES [39]. Accordingly, the percentage for each marine reporting unit was determined based on the obtained biomass values for each indicator. Through expert judgment, a marine reporting unit is classified as having a good ecological status if more than 50% of its values fall within the established threshold (Table 1).

In marine waters, 15% of sampling stations attained GES for Copepoda biomass, while the remaining 85% were classified as Non-GES. Similarly, in transitional waters, only 15% of the biomass met GES criteria, with 85% failing to achieve this status. In coastal waters, the Copepoda biomass was entirely Non-GES, indicating the bad status of the marine environment (Figure 20).

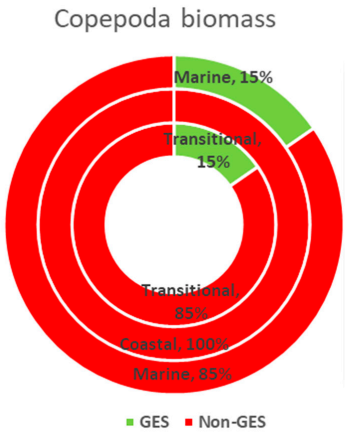

Figure 20. Ecological status of Copepoda biomass indicator in the Black Sea, June 2023.

Mesozooplankton biomass achieved GES exclusively within the coastal zone, comprising 82% of the total biomass, while the remaining 18% was classified as Non-GES. By contrast, both marine and transitional zones were entirely Non-GES, with 77% and 67% of their respective biomass not reaching threshold values (Figure 21).

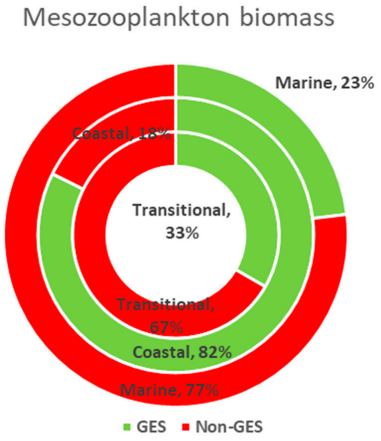

Figure 21. Ecological status of mesozooplankton biomass indicator in the Black Sea, June 2023.

In marine waters, 62% of the biomass attained GES, while 38% was categorized as Non-GES. A similar pattern was observed in the coastal zone, with 71% of the biomass meeting GES standards and the remaining 29% classified as Non-GES. In transitional waters, 75% of the biomass met GES criteria, whereas 25% did not reach the threshold value (Figure 22).

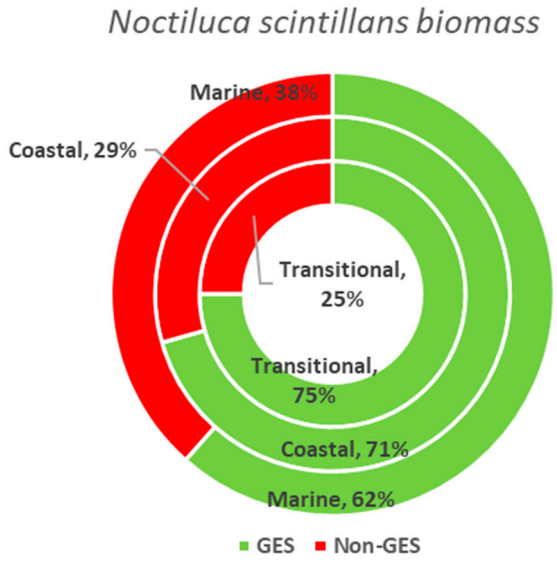

Figure 22. Ecological status of *Noctiluca scintillans* biomass indicator in the Black Sea, June 2023.

The negative IES (Indicator of Ecological Status) value (Figure 23) indicated degraded ecological conditions in the Black Sea. This status, marked by a predominance of Non-GES cases, raises serious concerns about the ecosystem's health and resilience. The imbalance suggests that critical ecological thresholds are not being met, potentially affecting biodiversity, species abundance, and overall ecosystem functionality.

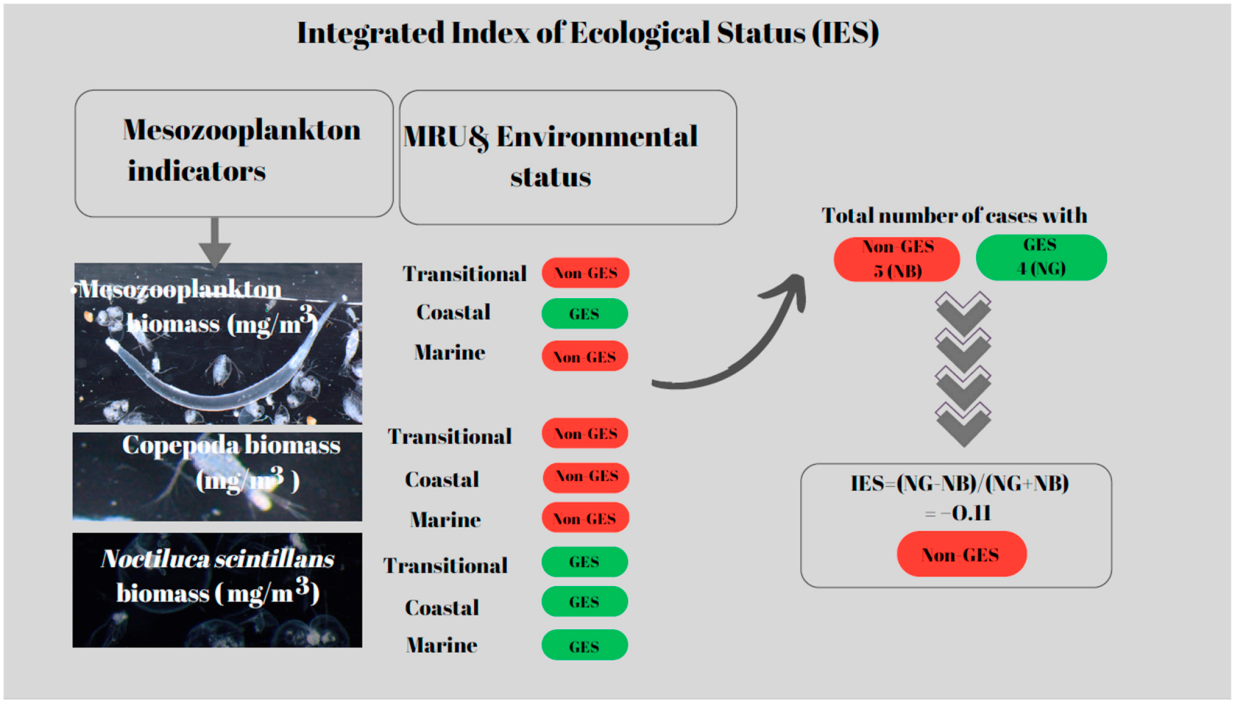

Figure 23. Integrated Index of Ecological Status of the Black Sea, June 2023, red—GES, green—Non-GES.

4. Discussion

4.1. Environmental Parameters

The analyses of water quality parameters revealed distinct patterns across the three studied regions—transitional, coastal, and marine—as in other studies [12,40–44]. Overall, water temperature remained consistent across all areas, exhibiting little variation. By contrast, salinity levels showed greater fluctuation, particularly in the marine region, where lower salinity was observed compared to both the coastal and transitional zones [45]. In the Black Sea, salinity distribution in the surface layer varied based on local circulation patterns and fluctuations in the Danube's flow [46]. Oxygen concentrations demonstrated relative stability, particularly notable in the transitional region, where temperature, salinity, and oxygen levels were consistently maintained [45,47]. Phosphate concentrations exhibited the least variability across regions, while silicate levels showed the greatest fluctuation due to the extreme values recorded after the dam breach, indicating differing nutrient behaviors and possibly reflecting biological activity and environmental conditions [48]. The addition of silicate to the ecosystem can facilitate prolonged exponential growth of algae, as increased silicate concentrations are directly linked to enhanced algal biomass. This boost in primary production has cascading effects throughout the food web, supporting higher trophic levels. Specifically, the increased algal biomass can lead to greater zooplankton populations, which feed on the abundant algae, ultimately increasing fish biomass as they prey on the zooplankton.

Temperature and salinity remained stable in the coastal region, although slight variations in oxygen levels and nutrient concentrations, especially ammonium, were evident. This suggests that while the coastal area maintains a relatively uniform environment, it may still be influenced by local factors such as runoff or biological processes that could lead to changes in nutrient availability [49]. The marine region was characterized by notably lower salinity due to the freshwater input after the dam breach and reduced oxygen levels, which further emphasizes the distinct environmental characteristics of this zone [42,49]. The darker water near the Black Sea coastline (Figure 24) following the Nova Kakhovka Dam breach likely indicates the presence of sediment plumes, pollutants, and potential algal blooms. The dam's destruction released floodwater carrying sediment, agricultural runoff, industrial chemicals, and other contaminants into the Black Sea, visibly altering water quality.

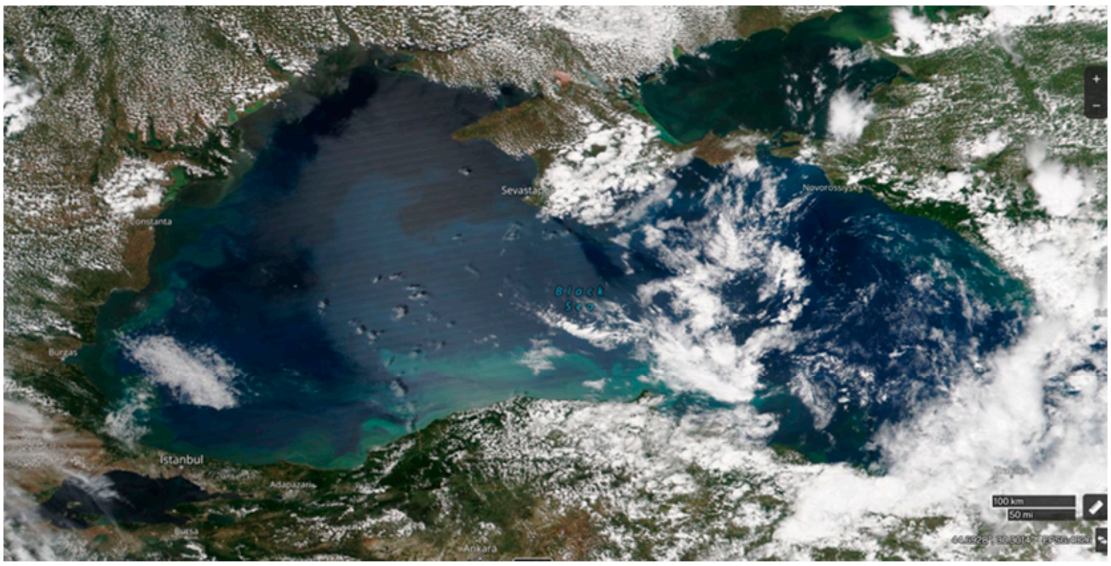

Figure 24. Satellite image of the Black Sea region following the Nova Kakhovka Dam breach, 21 June 2023.

4.2. Qualitative and Quantitative Structure of Mesozooplankton

The dominance of Copepoda as the most prevalent taxonomic group across various marine regions (MRUs) underscores its critical role in marine ecosystems, serving as a key food source for higher trophic levels [3,6,40,50]. Following copepods, meroplankton and Cladocera ranked as the second and third most abundant groups, respectively, although Cladocera appeared to be significantly less abundant. This distribution highlights the varying ecological roles that these groups play, with copepods often being integral to energy transfer in marine food webs [10,51]. It is well known that copepods do not solely rely on phytoplankton as a food source [52]; they also consume ciliates, which further diversify their role in the ecosystem [53,54]. This trophic interaction underscores the importance of copepods in linking different planktonic groups and facilitating energy transfer through the food web [55,56].

Additionally, it is essential to consider the role of bacteria, which serve as the baseline of the microbial food web [56]. Bacteria play a critical role in nutrient cycling by breaking down organic matter and releasing available nutrients for other organisms [56]. Nutrients are subsequently consumed by microzooplankton and higher trophic levels, including copepods [54,56]. This microbial food web forms a crucial foundation for the overall functioning of marine ecosystems, contributing to nutrient availability and the energy flow within the food chain [54].

The observed gradient in taxa richness across the different marine environments revealed biodiversity patterns. Transitional waters showed a slight reduction in species diversity, which may reflect the ecological stressors present in these environments as they serve as interfaces between freshwater and marine systems [13,49,57,58]. The coastal region also displayed low biodiversity, likely influenced by various factors such as habitat degradation, pollution, and increased human activities [49,59]. Marine waters exhibited the highest taxa richness, indicative of these areas' complex and diverse ecological interactions. This gradient highlights the increasing biodiversity and environmental quality from transitional to marine environments.

In transitional waters, Balanus larvae emerged as the most abundant species, contributing significantly to overall similarity (41.97%). This prevalence indicates that Balanus larvae are well-adapted to the fluctuating conditions characteristic of these environments. The presence of other species, such as *P. polyphemoides* and *A. clausi*, further illustrates the community's complexity and highlights the ecological interactions that occur in transitional zones.

In coastal waters, Balanus larvae continued to dominate but to a lesser extent (25.58%), suggesting their adaptability and resilience across different environments. Notably, the presence of *N. scintillans* and *A. clausi* signifies that these habitats still support a degree of biodiversity. In marine waters, *N. scintillans* became the leading species, representing 19.04% of the similarity. This shift from Balanus larvae dominance in transitional and coastal waters to *N. scintillans* in marine environments highlights the varying ecological preferences and adaptations of these species. *N. scintillans*, being a mixotrophic organism, can exploit high phytoplankton availability in nutrient-rich waters, reinforcing its prevalence in marine regions [60–62]. NASA worldview images highlight chlorophyll-a concentrations, a key indicator of phytoplankton levels in the water, with values represented by a color gradient. In June 2023, the northwestern region of the Black Sea showed notably high chlorophyll-*a* concentrations, indicated by red and orange color gradients (Figure 25). This area often experiences elevated nutrient levels due to river inflows, particularly from the Danube, which carries agricultural runoff rich in nitrogen and phosphorus, to which the impact of the dam breach was added. The dam breach also introduced significant quantities of silicates, essential for diatom growth. The observed chlorophyll-*a* concentrations serve

as a proxy for increased phytoplankton biomass, likely driven by the combined input of nutrients and silicates, highlighting the role of silicates in fueling diatom blooms and intensifying primary productivity in the region.

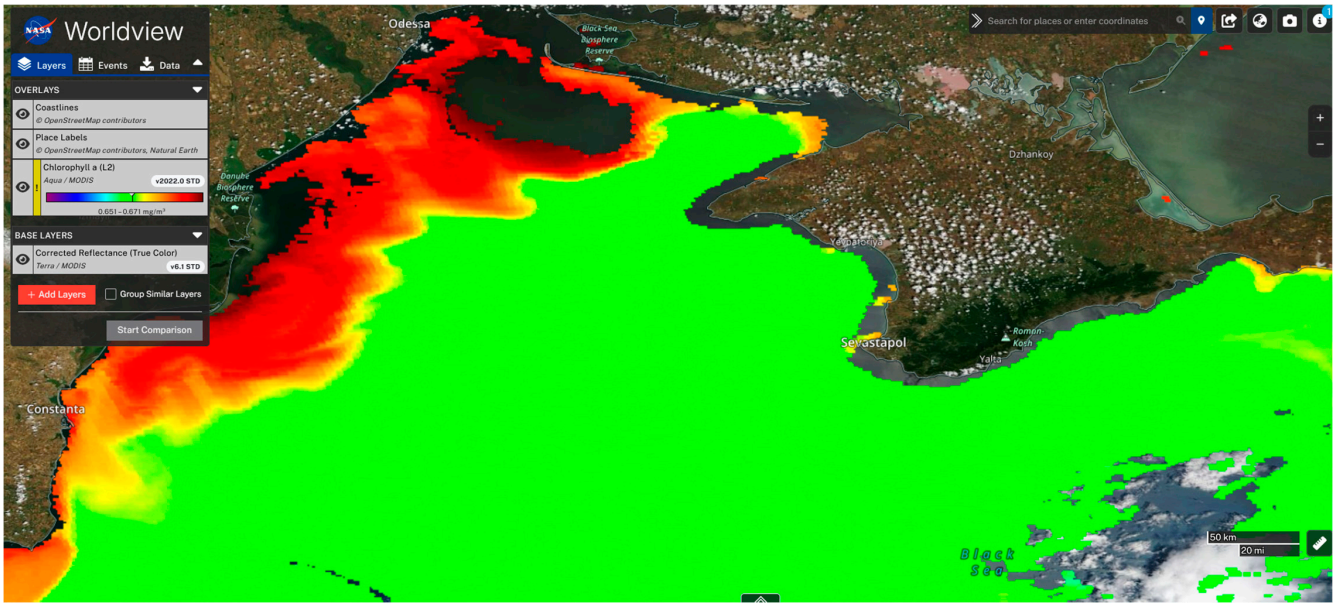

Figure 25. Satellite image of chlorophyll concentrations in the Black Sea, 15 June 2023.

The coexistence of *A. clausi* alongside the dinoflagellate *N. scintillans* in marine waters underscores the intricate food web dynamics present in these ecosystems, revealing the importance of various species in maintaining ecological balance [2,62–64]. Copepods that selectively graze on diatoms may gain a competitive advantage over non-copepod zooplankton, especially when diatom production is high, as they are more efficient at feeding on these phytoplankton [65]. However, as the availability of diatoms declines, copepods that primarily rely on them for food could be outcompeted by other zooplankton species that favor non-diatom food sources, such as small flagellates or dinoflagellates [66]. Dinoflagellates can serve as an alternative food source for many zooplankton species, and their availability may influence the dynamics of the zooplankton community. When diatom populations decrease, species that prefer dinoflagellates may thrive, potentially displacing copepods from their dominant role in the food web. In recent decades, Romania's nearshore waters have undergone substantial changes due to major shifts in the nutrient dynamics of the Danube catchment area, significantly impacting the phytoplankton community structure in both quality and quantity [67]. Thus, the abundance and ecological impact of the copepod community may be closely linked to the relative availability of diatoms and dinoflagellates [68].

Overall, the distribution patterns of these taxa across different marine environments reflect the complex interplay of ecological factors, including nutrient availability, salinity, and habitat structure. Increased silicate levels can enhance mesozooplankton diversity in marine regions through mechanisms that promote diatom growth, enhance food availability, support complex trophic interactions, and create varied habitats. The Shannon–Wiener Index is a valuable metric for evaluating mesozooplankton biodiversity and, by extension, the ecological health of marine or freshwater systems [32,69]. Lower Shannon–Wiener Index values generally indicate a stressed environment, often due to pollution or other ecological disturbances. Under such conditions, the community composition shifts toward a few dominant, pollution-tolerant species, leading to a loss of biodiversity and a more homogenized ecosystem [29,60]. When pollution or environmental stress increases, sensitive

species tend to decline or disappear, while a few species capable of tolerating harsh conditions proliferate [70,71]. This lack of diversity can destabilize the ecosystem, as dominant species monopolize resources, leading to reduced ecological resilience. Furthermore, in aquatic systems, such dominance may favor species that thrive in nutrient-rich, low-oxygen conditions, setting the stage for algal blooms. Algal blooms, in turn, exacerbate environmental stress by altering water chemistry (e.g., depleting oxygen, increasing nutrient loads), further limiting the range of species that can survive [72,73]. This feedback loop continues to narrow biodiversity, favoring specific zooplankton species and reducing the overall diversity of the ecosystem [74–76]. Higher Shannon–Wiener Index values, conversely, indicate healthier and more balanced ecosystems where a variety of mesozooplankton species coexist, each with relatively stable population sizes. Such ecosystems are generally more resilient, capable of withstanding environmental fluctuations, and less prone to the issues caused by dominant, pollution-tolerant species [32,69]. Thus, the Shannon–Wiener Index serves not only as a biodiversity metric but also as a useful environmental quality indicator, where higher values signify a balanced, resilient ecosystem and lower values reflect a system under ecological stress [32,69].

The lower Shannon–Wiener Index obtained in this study suggests reduced zooplankton diversity, favoring a few dominant species. This shift can lead to algal blooms, further supporting specific mesozooplankton species and decreasing overall diversity.

The observed variations in zooplankton densities across transitional, coastal, and marine zones highlight important ecological dynamics and productivity within these habitats. Transitional waters, characterized by low densities and moderate variability in zooplankton biomass, may be less productive due to environmental stressors such as salinity and nutrient availability [2,40,77]. By contrast, coastal zones exhibit the highest zooplankton densities, reflecting optimal conditions for productivity from the nutrient input and favorable thermal conditions. These high abundances of fodder zooplankton and copepods support diverse food webs and indicate healthy ecosystems. At stations SG3 and SG4, there are lower biomass values, likely indicating environmental stressors that restrict productivity and biodiversity due to riverine input. The relatively stable biomass of meroplankton in coastal areas further underscores their role as nurseries for various marine species [63,64,74,78–82]. Conversely, marine zones present intermediate zooplankton densities with pronounced variability in biomass. The higher abundance observed in transitional and coastal areas compared to marine areas is likely influenced by the prevalence of meroplankton in these regions. Coastal and transitional zones often serve as critical spawning and nursery grounds for benthic invertebrates and some fish species, leading to increased concentrations of their planktonic larvae [40,41]. These areas are typically characterized by higher nutrient levels and more favorable conditions for meroplankton development, driven by freshwater inputs and dynamic environmental gradients. Additionally, the impact of climate change and human activities, such as pollution and coastal development, can exacerbate these differences, leading to potential shifts in community structures and overall ecosystem health [51,74].

The results also provide important insights into the ecological dynamics of *N. scintillans*, blooms of which can significantly impact water quality and marine life, especially in coastal zones where concentrations are highest [38]. Understanding these spatial patterns is essential for assessing the potential ecological impacts of *N. scintillans* blooms along the Romanian coastline of the Black Sea.

Understanding these dynamics is crucial for effective marine management and conservation efforts, particularly considering ongoing environmental changes. Future research should focus on the mechanisms driving these patterns and the implications of anthropogenic pressures on zooplankton communities.

These results highlight significant spatial variation in fodder biomass, with most stations displaying similar distributions, while a few exhibit distinct patterns, likely driven by local environmental conditions or ecological processes.

4.3. Semi-Quantitative Models of the Causal Relationships Between Mezozooplankton and Physicochemical Parameters

The analysis of zooplankton species abundance in relation to various environmental variables across MRUs reveals intricate relationships that underscore the complexity of marine ecosystems. The dataset highlights the significance of environmental factors such as temperature, salinity, oxygen, and nutrient availability (including phosphate, silicate, nitrite, nitrate, and ammonium) in shaping the distribution and abundance of zooplankton species.

In transitional waters, the positive correlations of species like *A. clausi*, *N. scintillans*, and Cyclops with nutrients like phosphate and nitrate indicate their reliance on these elements for growth and survival. These positive interactions suggest more nutrient availability form riverine sources which stimulates population growth. However, the presence of negative correlations, possibly due to resource competition or nutrient depletion, points to potential ecological stressors that could impact species abundance. Salinity plays a central role in influencing these interactions, as it affects species distribution and their competitive dynamics [83–86], particularly among bivalves and polychaetes.

Coastal waters demonstrated a similar pattern, with *N. scintillans*, *P. elongatus*, *P. polyphemoides*, Cyclops, and Harpacticoida exhibiting strong connections with essential nutrients such as nitrate, nitrite, ammonium, and phosphate. The numerous interactions between taxa like Balanus, Decapoda, and Bivalvia larvae with these nutrients emphasize their ecological importance and suggest they play a central role in the ecosystem's nutrient cycling. Salinity and temperature emerged as crucial environmental factors, significantly influencing species distributions and interactions [87]. Their roles in shaping community structure highlight the necessity for maintaining stable environmental conditions to support biodiversity in coastal zones.

The elevated silicate concentrations resulted from river discharge, as continental freshwaters typically contain high levels of silicates [88]. Furthermore, river plumes and the associated fronts can create physical barriers that hinder the dispersal of meroplankton, potentially concentrating or retaining them in nearby areas [88].

In marine waters, species such as *A. clausi*, *E. affinis*, *C. euxinus*, and *P. polyphemoides* exhibited strong dependencies on key nutrients, with phosphate emerging as particularly vital for sustaining the food web. The positive interactions with nutrients indicate that these species benefit from nutrient availability, reinforcing their roles in the ecosystem. However, the negative interactions, such as *E. affinis*'s negative response to salinity, underscore the potential limitations imposed by environmental conditions, which can delay species growth and distribution. With its opportunistic life strategy, *E. affinis* develops rapidly under favorable conditions [89]. This widespread species complex displays variability in development time, body size, and traits such as morphology and salinity tolerance [90,91]. Salinity significantly influences copepod development time, with lower salinity leading to shorter development periods [83,92]. This contrasts with findings that freshwater conditions generally prolong the development time for *E. affinis* [93]. Additionally, reduced salinity impacts metabolic and ingestion rates, and increased food availability enhances copepod tolerance to freshwater [93,94]. Consequently, the stress response induced by decreased salinity may elevate feeding rates, resulting in shorter development times in copepod populations. Some taxa have expanded beyond their native ranges due to different stressors, suggesting that invasive populations may adapt locally to new environments [89].

Overall, the observed patterns of zooplankton species interactions with environmental variables across the three regions highlight the intricate and interconnected nature of

marine ecosystems. These relationships underscore the importance of maintaining environmental integrity, as fluctuations in nutrient availability, salinity, and temperature can have cascading effects on species populations and ecosystem health [85,95–98].

4.4. Assessment of Mesozooplankton Indicators and Environmental Status in the Black Sea

As an EU Member State, Romania has implemented a set of indicators to monitor the pelagic habitat in the Black Sea, focusing on the mesozooplankton component. These indicators include general metrics, such as biomass, derived from specific sampling strategies and methodologies to evaluate changes in the status of pelagic habitats.

In alignment with the Marine Strategy Framework Directive (MSFD) [39], particularly Descriptor 1 (Biodiversity, criterion D1C6) and Descriptor 5 (Eutrophication, criterion D5C3), the assessment relies on indicators like Copepoda biomass, Mesozooplankton biomass, and *N. scintillans* biomass. These metrics provide essential insights into the health and diversity of pelagic habitats. Their biomass levels reflect the food availability for higher trophic levels, including fish and marine mammals, and serve as indicators of environmental conditions and ecosystem productivity [2,6].

As a result of not reaching the threshold values for copepod and mesozooplankton biomass, the marine ecosystem may be experiencing significant stress, signaling potential imbalances within the food web. These organisms are essential as they bridge energy from primary producers like phytoplankton to higher trophic levels, including fish. Low biomass indicates reduced food availability for fish larvae, which could cause a cascade to affect fish populations, biodiversity, and commercial fisheries [51,99,100]. This shortfall may emerge from various factors, such as nutrient limitations, pollution, temperature changes, or predation shifts, each potentially disrupting the ecological balance necessary for GES. Therefore, this result highlights the need for targeted research and intervention to understand and address these underlying stressors, ensuring the sustainability of the ecosystem and the goals set under the MSFD.

However, the biomass of *N. scintillans* did reach the threshold for GES, which can be a mixed signal in marine ecosystems. While this species reached expected levels, *Noctiluca scintillans* is often considered an indicator of nutrient-rich or even eutrophic conditions, which can be problematic if driven by excessive nutrients [14,49] (e.g., from agricultural runoff). High biomass of *Noctiluca* can contribute to red tides, which may disrupt local marine life by depleting oxygen levels or causing imbalances in food availability for higher trophic levels [60,101]. Therefore, while reaching GES may meet regulatory criteria, the presence of stations with high *N. scintillans* biomass necessitates a closer examination of the underlying factors contributing to these conditions, its thriving can sometimes highlight underlying issues like nutrient pollution or eco-system shifts toward opportunistic species. This imbalance between *N. scintillans* and the other two indicators could signal a restructuring of the food web, potentially driven by nutrient imbalances or environmental stressors, necessitating careful monitoring to ensure overall ecological balance.

If we integrate the assessments of copepod and mesozooplankton biomass along with the biomass of *N. scintillans*, the IES index is unfavorable. While *N. scintillans* has achieved GES, the low biomass of copepods and mesozooplankton suggests significant ecological imbalances that overshadow this isolated success. The low copepod biomass implies that primary consumers within the food web are experiencing significant challenges, which may result in diminished food availability for higher trophic levels. This could adversely affect commercially valuable fish species dependent on these organisms for sustenance. Additionally, *N. scintillans*, despite reaching GES, can be indicative of nutrient-rich conditions that may contribute to harmful algal blooms, further disrupting the ecological balance.

Consequently, when these three indicators are analyzed in conjunction, their integration indicates that the marine ecosystem is undergoing stress, which is associated with a decline in overall health and stability. This negative status suggests that key ecological thresholds, such as those ensuring adequate habitat quality, species diversity, and balanced food web dynamics, are not being met. The absence of GES in large portions of the ecosystem can result in lower biodiversity, with species either declining in abundance or disappearing altogether due to unsuitable conditions. Such biodiversity losses can reduce the ecosystem's capacity to withstand environmental stressors and adapt to changes, thus impairing its overall resilience.

In turn, this degradation can impact essential ecosystem services, such as nutrient cycling, water purification, and carbon sequestration, further stressing the ecosystem. Without targeted conservation and restoration efforts to bring these zones closer to GES, the negative IES trend may lead to long-term and potentially irreversible ecosystem shifts, harming not only marine and coastal biodiversity but also the human communities dependent on these ecosystems.

4.5. Impact of Silicate Dynamics on the Romanian Black Sea Ecosystem—Comparing 2013–2020 Trends with 2023

The studies on silicate dynamics along the Romanian Black Sea coastline provide valuable insights into the seasonal variability, spatial distribution, and ecological significance of silicates in supporting marine ecosystems. When comparing findings from 2013–2020 [40,41] with the extreme values observed in 2023, a clear distinction emerges between a relatively stable regime and the impact of a large-scale environmental disturbance.

Between 2013 and 2020, silicate concentrations ranged from 0.05 μM to 168.2 μM, with a peak observed in March 2017 at the East Constanța profile. The highest concentrations occurred in areas influenced by the Danube River, with seasonal enrichment during colder months, serving as a nutrient reserve for diatom blooms in the spring [40,41]. During warmer seasons, silicate levels decreased due to biological uptake, particularly in offshore regions where values often dropped below 5 μM [40,41].

By contrast, the 2023 observations revealed silicate concentrations reaching an unprecedented value of 615 μM, a deviation linked to the Nova Kakhovka Dam breach. This event released high quantities of sediment rich in silicates and other nutrients, fundamentally altering the nutrient composition of the Black Sea. Such extreme values likely disrupted the usual seasonal and spatial patterns observed in earlier studies.

While the 2013–2020 findings demonstrated a system where silicates facilitated diatom blooms and indirectly sustained mesozooplankton populations, the extreme nutrient inputs observed in 2023 pose risks of eutrophication and hypoxia. Such disruptions can cascade through the food web, affecting zooplankton, higher trophic levels, and overall ecosystem stability. This sharp contrast between earlier findings and recent observations underscores the vulnerability of the Black Sea to large-scale disturbances and highlights the importance of monitoring and management strategies.

From an ecological perspective, the analysis in June 2023 underscores the critical role of silicates in promoting healthy, diatom-driven ecosystems. High silicate levels favor species that depend on diatom-based food chains, while low silicate availability, coupled with elevated nitrogen levels, facilitates the dominance of opportunistic species like *N. scintillans*, often linked to eutrophic or degraded environments. Furthermore, temperature emerged as a secondary but significant driver, influencing specific biological variables and contributing to the overall variability in the dataset. The results provide a clear visualization of the distinct differences in zooplankton community composition between flooded (F) and non-flooded (NF) sites. The greater dispersion of flooded sites (blue triangles) suggests higher variability in zooplankton communities, which could be attributed to fluctuating

environmental conditions associated with flooding, such as changes in water levels, nutrient inputs, and increased turbidity. These dynamic factors likely created heterogeneous habitats, promoting diverse and less predictable community structures. By contrast, the tighter clustering of non-flooded sites (red triangles) indicates more homogeneous and stable zooplankton communities, likely resulting from consistent water levels and fewer disturbances. The separation between flooded and non-flooded sites highlights the significant influence of flooding on species distribution and abundance, suggesting that flooding altered community structure in response to specific ecological pressures.

These findings underscore the significant impact of flooding on ecosystem structure, particularly in terms of nutrient dynamics and species distribution. Flooding can introduce or redistribute nutrients, such as silicates and nitrates, into the ecosystem, leading to higher concentrations in flooded areas. This nutrient influx can stimulate primary productivity, supporting the growth of certain species, which may explain the higher densities of some organisms in flooded stations. At the same time, the variability in nutrient levels and species abundance observed in flooded stations suggests that flooding creates more dynamic, less predictable environments compared to non-flooded areas. Species that thrive under these fluctuating conditions may exhibit higher abundances, while others may be absent or less abundant due to different habitat preferences or tolerances.

Enhancing silicate levels, potentially through riverine inputs or nutrient management, could help to promote diatom-dominated systems and mitigate harmful algal blooms. Additionally, controlling nitrogen inputs, particularly NO_3 and NH_4, is crucial to restore nutrient balance and prevent the dominance of eutrophic species like *N. scintillans*. Species such as *Centropages ponticus* and *N. scintillans* can serve as valuable bioindicators of silicate availability and eutrophication, respectively, aiding in the monitoring and management of coastal ecosystems.

Overall, flooding reshapes the habitat by altering nutrient availability and creating a more variable environment, which in turn drives changes in species composition and distribution.

4.6. Ecological Effects of Freshwater Inflows with Insights from Global Case Studies and Mitigation Strategies

Freshwater inflow events, such as dam breaches, riverine nutrient influxes, and major floods, provide critical insights into how semi-enclosed seas and coastal ecosystems respond to sudden, large-scale nutrient and sediment inputs [102–104]. By examining key examples of such events worldwide, we gain a better understanding of the challenges and necessary mitigation strategies for protecting these delicate ecosystems from nutrient overloads and ecological imbalances.

One significant case is the periodic flooding of the Mississippi River, which often results from natural flood events or controlled upstream dam releases. These floods carry high levels of nitrogen and phosphorus from agricultural runoff in the Mississippi River Basin into the Gulf of Mexico. Such nutrient influxes have created extensive hypoxic zones, also known as "dead zones", where low oxygen levels severely impact marine life, including fish and benthic organisms. Algal blooms frequently follow nutrient surges, leading to further oxygen depletion as the blooms decompose. The Gulf's dead zone can extend over thousands of square kilometers, disrupting fisheries and reducing biodiversity [105,106]. This case demonstrates the critical need to manage nutrient inputs to control hypoxia. Consequently, policies have focused on reducing nitrogen and phosphorus use, restoring riverbank wetlands, and implementing riparian buffers that filter out excess nutrients before they enter the Gulf.

The Three Gorges Dam on China's Yangtze River, one of the largest dams globally, offers another perspective on the impact of freshwater flow alterations. While the dam has

reshaped water flow and sedimentation along the Yangtze, it has also reduced sediment and nutrient transport to the East China Sea, contributing to coastal erosion and nutrient imbalance. This change has notably decreased silicate inputs, disrupting diatom populations and affecting local fishery yields, thereby altering the food web in the area [107–109]. The case of the Three Gorges Dam illustrates how large dams can disrupt the delicate balance of sediment and nutrient transport, highlighting the importance of environmental flow management. To mitigate these effects, strategies such as sediment supplementation, environmental flow releases, and seasonal flow adjustments have been proposed to restore balance and support estuary health.

The Danube River's impact on the Black Sea is a prime example of the complex dynamics of transboundary rivers. Flowing through multiple European countries before reaching the Black Sea, the Danube contributes significant nutrient pollution to the sea due to agricultural and industrial runoff [49,57,110–112]. This excess nutrient load has led to eutrophication, algal blooms, and hypoxic zones, causing a decline in fish stocks and benthic organism populations. The Danube's impact underscores the need for coordinated international management of transboundary rivers. Through the efforts of the International Commission for the Protection of the Danube River (ICPDR), countries within the Danube Basin have developed joint policies to reduce nutrient pollution, improve wastewater treatment, and restore wetlands to function as natural nutrient filters [113,114].

Lake Okeechobee in Florida, which supplies water to the Everglades, faces similar nutrient challenges, often from agricultural runoff. When excess water is released from the lake, it transports high nutrient loads into surrounding wetlands and coastal ecosystems, resulting in algal blooms that disrupt natural balance and harm local fish populations and tourism [115–117]. This case highlights the importance of carefully controlling release timing and nutrient levels to prevent harmful algal blooms. Mitigation strategies here have included the construction of stormwater treatment areas, efforts to restore flow patterns to the Everglades, and nutrient management practices to reduce agricultural runoff.

These case studies collectively emphasize key strategies for managing nutrient influxes and protecting coastal ecosystems. Nutrient control stands out as a primary solution, with practices such as precision farming, fertilizer reduction, and buffer strip usage proving effective in minimizing eutrophication risks. Wetland restoration is another essential approach, as wetlands serve as natural filters for nutrients and sediments, helping to maintain biodiversity and water quality in coastal regions.

Collaborative management is also vital, particularly for rivers that cross political borders. ICPDR's work on the Danube showcases the effectiveness of international cooperation in reducing pollution and protecting downstream ecosystems. Similarly, environmental flow management has emerged as a key strategy, especially in regions with extensive dam infrastructure. Controlled dam releases that mimic natural flow patterns help maintain downstream ecosystems by supporting seasonal nutrient cycles and biodiversity.

Finally, adaptive monitoring and management are crucial for responding to the dynamic nature of aquatic ecosystems. Continuous monitoring of nutrient levels, algal blooms, and water quality enables timely interventions and the ability to adapt management strategies based on real-time data. These adaptive measures provide a responsive approach that can effectively safeguard coastal ecosystems against the impacts of freshwater inflows and nutrient pollution. Together, these insights form a comprehensive framework for sustainable ecosystem management, guiding future policies and practices to mitigate the impacts of freshwater inflow events on semi-enclosed seas and coastal environments.

5. Conclusions

The breach of the Nova Kakhovka Dam has brought significant, immediate disruption to marine ecosystems downstream, highlighting both the fragility of these environments and the urgent need for effective, sustainable management. This unexpected influx of freshwater, sediments, and pollutants into the northwestern shelf has drastically altered salinity levels, increased turbidity, and introduced an array of nutrients and contaminants. These sudden shifts can disrupt the carefully balanced ecosystem dynamics that support mesozooplankton, phytoplankton, and fish populations, triggering changes throughout the food web.

While this study provides valuable insights, its short-term focus limits the ability to assess long-term ecological impacts and recovery. The absence of baseline data restricts comparisons with pre-breach conditions, highlighting the need for future studies to address this gap. Although the research primarily examines specific environmental factors, it offers a solid foundation for understanding the effects of the breach. Potential confounding factors, such as climate variability and other anthropogenic influences, were not fully explored, suggesting opportunities for future research. The study's spatial scope, while informative, could be expanded to capture more localized effects. A multi-disciplinary approach, including long-term monitoring and modeling, would further enhance our understanding of the breach's broader impacts.

One critical consequence of these altered conditions is the heightened risk of eutrophication, where nutrient overloads spur excessive algae growth. This can lead to oxygen depletion, harming fish and other marine life that depend on stable oxygen levels for survival. The increased nutrient loads also impact mesozooplankton populations, especially copepods, which play a vital role as both grazers of phytoplankton and prey for larger species. Changes in salinity, nutrient concentrations, and oxygen levels may allow opportunistic species to thrive, potentially outcompeting native species and disrupting energy transfer within the ecosystem. This dominance leads to reduced biodiversity, impacts nutrient cycling, and affects primary production, leading to decreased overall ecosystem productivity and resilience.

As recovery initiatives unfold, it is essential to implement comprehensive monitoring and mitigation strategies to address these cascading ecological impacts. Close observation of nutrient levels, salinity changes, and mesozooplankton dynamics will provide insights into the health of the marine environment and help to identify early signs of distress. Long-term research on these dynamics is crucial to developing informed conservation and management strategies that support ecosystem stability and resilience. By gaining a deeper understanding of these interactions, particularly in the face of environmental stressors, conservation efforts can be adapted to safeguard these ecosystems against future disturbances.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse13010067/s1, Table S1. Descriptive statistics of environmental parameters in June 2023, Table S2. Descriptive statistics for mesozooplankton in June 2023, Table S3. T-test results of comparison between flooded stations (Group 1) and non-flooded stations (Group 2) for various variables, Table S4. Correlations between mesozooplankton taxa and environmental parameters.

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