



The Effect of Değirmendere on Hydrography and Nutrient Salt Distribution in the Southeastern Black Sea (Trabzon) Coastal Waters



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Abstract

In this study, the physical properties and nutrient salt composition of coastal waters affected by Değirmendere along the Trabzon coast of the Southeastern Black Sea were compared with stations representing open sea conditions relatively independent of river influence. Fieldwork was planned for March and August 2025 to capture two contrasting hydrographic conditions; sampling was carried out at depths of 0–200 m along the river-influenced TM (Trabzon-Center; TM1–TM4) line and the reference TY (Trabzon-Yomra; TY1–TY4) line. Temperature, salinity, and density profiles of the water column were obtained using CTD; dissolved inorganic nitrogen species (nitrate, nitrite, ammonium), orthophosphate, reactive silicate, and total nitrogen and total phosphorus concentrations were measured using an auto-analyzer and statistically evaluated using the Month×Line approach. In March, a cold and vertically well-mixed water column of 9 °C was observed in both channels, while in August, a warmer and less dense layer developed at the surface and a distinct thermocline/pycnocline formed between 20 and 40 m. While no significant difference was observed between TM and TY in terms of salinity and density, nutrient salts showed a significant change from the coast to the open sea and from the surface to the depths. Near the coast, TM showed a higher tendency for ammonium and total nitrogen, while total phosphorus and silicate were relatively higher in TY in most cases. The effects of month, line, and interaction were pronounced on total nitrogen, with enrichment being more prominent in TY in March and in TM in August. DIN:PO₄³⁻ ratios above the Redfield ratio generally indicate phosphorus limitation; although Değirmendere increases enrichment near the coast, this effect weakens within a few nautical miles, indicating that the trophic status of the region remains relatively balanced in terms of eutrophication. This study provides a local reference dataset that comparatively documents river effects during two distinct periods rather than representing an annual cycle.

Keywords Southeastern Black Sea, Değirmendere, Coastal waters, Nutrient dynamics, Phosphorus limitation, Eutrophication

INTRODUCTION

The Black Sea is considered a semi-enclosed basin with high sensitivity to external inputs due to its limited water exchange with the global ocean, distinct stratification, and relatively low salinity (Mee, 1992; Murray et al., 2007; Sadighrad, 2019; Lazar et al., 2021). Water circulation in the basin reveals a two-layer structure, with the oxygenated upper layer separated from the hy-

drogen sulfide-containing anoxic deep layer by a sharp pycnocline (Kondratiev and Masevich, 2024; Dubinin et al., 2024). This strong vertical stratification creates a favorable environment for limiting mixing, trapping riverine and anthropogenic materials, particularly in the upper layers; increasing nutrient salt stocks, and reshaping biogeochemical processes (Strokal and Kroeze, 2013; T.C. ÇSİDB and TÜBİTAK MAM, 2022; Varenik et al., 2023).



The southeastern coast of the Black Sea is a region where river-coastal interactions become pronounced over short distances due to its narrow continental shelf and steep coastal morphology. Numerous rivers that flow rapidly into the sea carry freshwater, suspended solids, and nutrients to the coastal zone; as a result, higher levels of dissolved inorganic nitrogen (DIN) and phosphorus compounds, increased chlorophyll-a levels, and strong spatial/seasonal variability can be observed compared to the open sea. (Erüz et al., 2000; İsmail and Erüz, 2023; Tan et al., 2023; Özşeker et al., 2024; Lazăr et al., 2024). Physical and biogeochemical findings in the region indicate that the stratification regime significantly governs vertical mixing and nutrient transport; nutrient concentrations generally decrease from the coast to the open sea, and maximums of nitrate (NO_3^-) in the upper oxygenated layers, phosphate (o-PO_4^{3-}) in deeper layers, ammonium (NH_4^+), and silicate (SiO_2) maximums can develop in deeper layers (Orekhova, 2021; Alkan et al., 2022; Kondratev et al., 2023; Chen et al., 2023; Ağırbaş and Fidan, 2024). These horizontal and vertical distribution differences contribute to the differentiation of food web relationships between coastal and open sea areas through primary productivity and community structure (Ağırbaş and Bakırcı, 2022; Gall et al., 2024).

Freshwater inputs play a key role in the process differentiation between coastal and open ocean systems by altering salinity zones and stratification (Gao et al., 2021). River-derived sediment transport can affect nutrient cycles, nutrient retention/transport dynamics, and the horizontal-vertical distribution of primary producers by transforming the physical-chemical properties of the water mass (Zilius et al., 2024). Understanding these mechanisms is critical for explaining ecosystem functioning and the sustainable management of marine resources (Mikaelyan, 2024; Ristea et al., 2025; Kache et al., 2025). Değirmendere near Trabzon stands out as a system that provides significant freshwater and nutrient input to the coastal ecosystem, as its basin is subject to combined urbanization, agricultural, and industrial pressures (Alkan et al., 2013; Yıldırım, 2021; Mete et al., 2022). Seasonal variations in flow/discharge conditions directly shape the nutrient load transported to the coast and the accompanying biological-chemical responses (Barroso et al., 2016; Gao et al., 2021).

Although there is extensive literature on Black Sea coastal ecosystems, studies that simultaneously address the impact of river inflows both along the coast–open sea axis and along the 0–200 m vertical axis, and that evaluate them comparatively with a “reference” line sharing the same regional regime, remain limited. Therefore, examining

the Değirmendere effect simultaneously through the river-influenced TM line and the TY line, which is distant from river influence, has the potential to fill an important information gap in terms of nutrient salt composition, N:P ratios, and eutrophication risk.

This study compares the TM line under the influence of Değirmendere and the TY reference line relatively distant from the river effect along the Trabzon coast during the March (mixing) and August (strong stratification) 2025 periods in the 0–200 m water column; it aims to quantitatively reveal the changes in temperature, salinity, and density, as well as the basic nutrient salt components ($\text{NO}_3^- + \text{NO}_2^-$ (NO_x), NH_4^+ , o-PO_4^{3-} , SiO_2 , total nitrogen (TN) and total phosphate (TP)) from the coast to the open sea and in the vertical direction. This comparison allows for the evaluation of the distribution and enrichment patterns of river-derived inputs in the water column under different hydrographic conditions.

MATERIALS AND METHODS

Study Area and Sampling

The study area encompasses the coastal section where the Değirmendere River flows into the sea in the center of Trabzon province in the Southeast Black Sea region, as well as reference areas representing open sea conditions where this riverine effect weakens/disappears. The study area was selected to determine the effects of freshwater inflows, nutrient loads, and suspended solids transported from the Değirmendere basin on regional water quality. Accordingly, the research area was designed to represent both the coastal zone, where river-derived inputs are dominant, and reference areas where open sea conditions prevail. The geographical locations of the study area and sampling stations are shown in Figure 1, and detailed information on the stations is presented in Table 1.

The area where the river effect is most pronounced is considered to be the mouth of the Değirmendere River, and four fixed stations (TM1–TM4) have been established along the TM line from this point towards the open sea. The TM line represents a transition zone where the freshwater effect decreases, salinity increases, and the vertical structure of the water column changes as one moves away from the river. For comparison purposes, reference stations representing conditions distant from the river effect were selected off the coast of Yomra, east of Trabzon, and four fixed stations (TY1–TY4) were defined along the TY line. Thus, the study design was established based on a total of $n=8$ stations (TM1–TM4 and TY1–TY4).



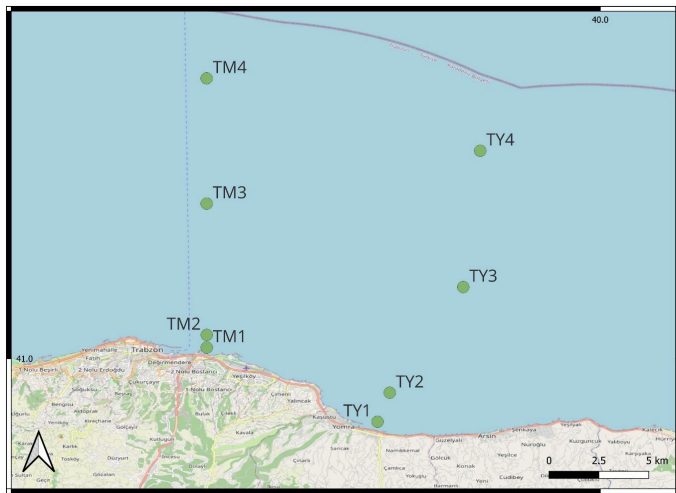


Figure 1. Measurement and sampling stations

Table 1. Information about sampling stations

City	County	Station code	Station No	Latitude	Longitude
Trabzon	Center	TM	1	41°00.400'N	39°45.930'E
		TM	2	41°00.850'N	39°45.930'E
		TM	3	41°05.562'N	39°45.926'E
		TM	4	41°10.058'N	39°45.926'E
	Yomra	TY	1	40°57.735'N	39°52.038'E
		TY	2	40°58.776'N	39°52.474'E
		TY	3	41°2.568'N	39°55.103'E
		TY	4	41°7.460'N	39°55.710'E

The stations are positioned in a gradual arrangement from the coast outwards:

Station 1: approximately 0.5 nautical miles (nmi) from the coast (total depth ~20 m),

Station 2: approximately 1 nmi from the coast (total depth ~50 m),

Station 3: approximately 5 nmi offshore (total depth ~200 m), and

Station 4: approximately 10 nmi offshore (total depth ~200 m).

Marine studies were conducted using the R/V Sürat Research Vessel belonging to the Fisheries Research Institute; sampling was carried out in two trips during the periods of March and August 2025. Each station was sampled once during each trip; multiple depth samples were taken per station to evaluate the vertical structure.

Hydrographic parameters (temperature, salinity, and density) were measured from the surface to 200 m using a Sea-Bird 19 Plus CTD. For nutrient salt and total nutrient element analyses, water samples were collected using a rosette sampler (SBE 32 Carousel, 12-position, 1.7 L) at 10 m intervals between the

surface and 50 m, and at 25 m intervals between 50 m and 200 m.

Nutrient Salt Analyses

Nutrient salt analyses were performed using the Seal Analytics auto-analyzer system (Seal X-Y-2 Sampler AA3). For dissolved inorganic nutrient salts, o-PO_4^{3-} (G-175-96, Rev. 13), NO_x (G-172-96, Rev. 11), NH_4^+ (G-171-96, Rev. 11), and SiO_2 (G-177-96, Rev. 9) protocols were applied. TP and TN analyses were performed after persulfate digestion, following the G-175-96 (Rev. 13) and G-172-96 (Rev. 11) methods, respectively. The method detection limits (MDL) were determined as $0.01 \mu\text{M}$ for NO_3^- , $0.003 \mu\text{M}$ for NO_2^- , $0.02 \mu\text{M}$ for o-PO_4^{3-} , $0.04 \mu\text{M}$ for NH_4^+ , and $0.1 \mu\text{M}$ for SiO_2 . All glassware was treated with 10% HCl and rinsed with distilled water prior to analysis; MOOS-3 reference material was used for quality assurance, and at least 10% of the samples in each analysis series were reanalyzed to monitor repeatability.

Statistical Analysis

All statistical evaluations in this study were performed using PAST 4.17 software (Hammer *et al.*, 2001). Minimum–maximum, mean, and standard error (SE) were calculated at the month (March, August) and line (TM, TY) levels for the physical (temperature, salinity, density) and nutrient salt variables (NO_x , NH_4^+ , o-PO_4^{3-} , SiO_2 , TP, TN) measured on the TM and TY lines. Prior to inferential tests, the normality of the residuals was assessed using the Shapiro–Wilk test and Q–Q plots, and the homogeneity of variance was assessed using the Levene test; appropriate transformations were applied when necessary.

When testing the temporal and horizontal differences between the TM and TY lines, the replication structure was defined as a station to reflect the sampling design; measurements taken along the depth at the same station were treated as intra-station repeated measurements. Therefore, analyses were conducted using a mixed/repeated measures approach that included fixed effects for Month (March, August) and Line (TM, TY) and the Month×Line interaction; stations were considered “subjects” (random effect) within the line, and the depth effect was included in the model as a repeated-measure component to represent intra-station dependency (univariate repeated-measures ANOVA framework in PAST).

When the interaction term was found to be significant, simple main effects were examined; multiple comparisons were made with appropriate adjustments (e.g., Tukey HSD), and the significance level was set at $p < 0.05$. In addition to F and p values, effect sizes were reported using partial eta-squared

(η^2_p); according to Cohen (1988), $\eta^2_p \approx 0.01$ was interpreted as a small effect, $\eta^2_p \approx 0.06$ as a medium effect, and $\eta^2_p \geq 0.14$ as a large effect.

RESULTS and DISCUSSION

Hydrographic Structure: Temperature, Salinity, and Density

The hydrographic structure was examined by jointly evaluating the temperature, salinity, and sigma-t distributions obtained on the TM and TY lines in March and August. The results of the two-way ANOVA with the factors Month (March–August) $\times$ Line (TM–TY) show that only the month effect is statistically significant ($p < 0.05$) for temperature and density (σ_t), while the line and interaction terms are not significant. For salinity, neither the month nor the line factor, nor the Month $\times$ Line interaction was found to be statistically significant ($p > 0.05$) (Table 2).

In March, surface–upper layer temperatures remained at approximately 9 °C on both tracks, with temperatures remaining nearly constant throughout the 0–200 m water column, indicating good vertical mixing and a single-layered structure. No significant thermocline/pycnocline developed during this period, and no meaningful horizontal differentiation was observed between TM and TY. In August, surface temperatures rose to approximately 27–28 °C, and the water column on both tracks transformed into a two-layered structure consisting of a warm, low-density surface layer and a thermocline/pycnocline zone developing between 20–40 m depths below it. Below the thermocline, the temperature dropped again to ≈ 9 –10 °C, and below 50 m, the TM and TY lines exhibited similar deep water conditions (Figure 2; Table 3).

Salinity distribution showed a similar seasonal pattern to temperature but with a narrower range of variation. In March, due to strong winter mixing, salinity was largely homogeneous throughout the TM and TY layers, both at the surface and at depths of 0–200 m. Low to moderate values characteristic of the upper layer of the Black Sea were observed, and no distinct halocline formed. Although Değirmendere's freshwater inflow is located on the TM line, it created only a limited dilution effect at the surface during this period because vertical mixing was dominant. In August, a distinct halocline developed on both lines, representing lower salinity at the surface and a transition to more saline intermediate layer waters below. On the TM line, the low salinity layer was thicker and extended slightly deeper due to the river effect, while on the TY line, this layer remained shallower; however, below 50 m, salinity on both lines converged to similar values,

and a common regional salinity regime was observed (Figure 2; Table 3).

The sigma-t (density) distribution also revealed a vertical structure consistent with temperature and salinity. In March, the TM and TY upper layer density averages were approximately 14.8 kg m⁻³, and the density field remained largely homogeneous throughout the 0–200 m range, with no pycnocline developing.

Table 2. Effects of Month, Line, and Month $\times$ Line on physical and nutrient salt parameters: two-way ANOVA.

Parameter	Impact	df (1,124)	F	p	η^2_p
Temperature	Month	1.124	35.23*	<0.001*	0.221*
Temperature	Line	1.124	0.99	0.322	0.008
Temperature	Month $\times$ Line	1.124	1.18	0.280	0.009
Salinity	Month	1.124	0.16	0.691	0.001
Salinity	Line	1.124	0.08	0.772	0.001
Salinity	Month $\times$ Line	1.124	0.16	0.690	0.001
Density	Month	1.124	14.29*	<0.001*	0.103*
Density	Line	1.124	0.78	0.379	0.006
Density	Month $\times$ Line	1.124	0.76	0.384	0.006
NO ₃ +NO ₂	Month	1.124	2.00	0.160	0.016
NO ₃ +NO ₂	Line	1.124	0.37	0.545	0.003
NO ₃ +NO ₂	Month $\times$ Line	1.124	0.04	0.850	0.000
NH ₄ ⁺	Month	1.124	0.59	0.445	0.005
NH ₄ ⁺	Line	1.124	2.84	0.094	0.022
NH ₄ ⁺	Month $\times$ Line	1.124	0.05	0.827	0.000
o-PO ₄	Month	1.124	0.34	0.562	0.003
o-PO ₄	Line	1.124	0.43	0.512	0.003
o-PO ₄	Month $\times$ Line	1.124	0.01	0.931	0.000
SiO ₂	Month	1.124	0.51	0.478	0.004
SiO ₂	Line	1.124	0.23	0.630	0.002
SiO ₂	Month $\times$ Line	1.124	0.23	0.634	0.002
TP	Month	1.124	1.35	0.248	0.011
TP	Line	1.124	1.79	0.183	0.014
TP	Month $\times$ Line	1.124	0.04	0.845	0.000
TN	Month	1.124	6.46*	0.012*	0.050*
TN	Line	1.124	7.66*	0.007*	0.058*
TN	Month $\times$ Line	1.124	35.96*	<0.001*	0.225*

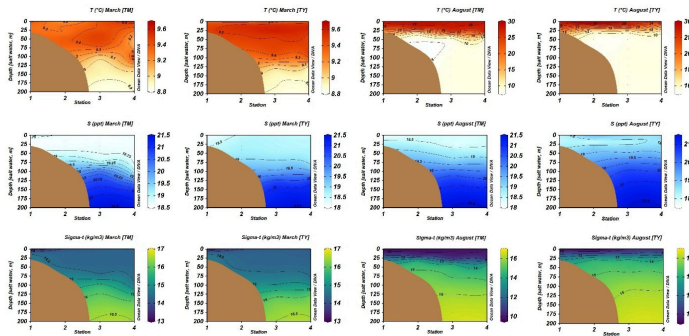


Figure 2. Measurement and sampling stations

table 3. Temperature, salinity, and sigma-t values at TM and TY stations in March and August according to depth (mean $\pm$ SD and min-max distributions)

Season	Station	Depth (m)	Temperature (°C)	Salinity (PSU)	Sigma-t (kg/m³)
March	TM	0	9.41 $\pm$ 0.09 (9.18–9.61)	18.71 $\pm$ 0.09 (18.55–18.96)	13.99 $\pm$ 0.29 (13.12–14.35)
March	TM	20	9.37 $\pm$ 0.03 (9.32–9.40)	18.64 $\pm$ 0.01 (18.63–18.65)	14.30 $\pm$ 0.01 (14.28–14.30)
March	TM	50	9.33 $\pm$ 0.10 (9.13–9.47)	18.76 $\pm$ 0.06 (18.66–18.86)	14.40 $\pm$ 0.04 (14.34–14.46)
March	TM	75	9.26 $\pm$ 0.16 (9.11–9.42)	18.83 $\pm$ 0.13 (18.70–18.96)	14.46 $\pm$ 0.08 (14.38–14.53)
March	TM	100	9.26 $\pm$ 0.26 (9.01–9.52)	19.72 $\pm$ 0.66 (19.06–20.38)	15.15 $\pm$ 0.54 (14.60–15.69)
March	TM	150	8.95 $\pm$ 0.00 (8.95–8.95)	21.00 $\pm$ 0.08 (20.92–21.08)	16.19 $\pm$ 0.06 (16.13–16.25)
March	TM	200	8.89 $\pm$ 0.02 (8.87–8.90)	21.41 $\pm$ 0.04 (21.37–21.45)	16.51 $\pm$ 0.03 (16.48–16.55)
March	TY	0	9.35 $\pm$ 0.02 (9.29–9.40)	18.40 $\pm$ 0.10 (18.10–18.57)	13.93 $\pm$ 0.26 (13.15–14.24)
March	TY	20	9.56 $\pm$ 0.01 (9.53–9.58)	18.65 $\pm$ 0.02 (18.62–18.69)	14.28 $\pm$ 0.02 (14.25–14.31)
March	TY	50	9.48 $\pm$ 0.00 (9.47–9.49)	18.77 $\pm$ 0.02 (18.73–18.81)	14.38 $\pm$ 0.02 (14.35–14.42)
March	TY	75	9.47 $\pm$ 0.01 (9.47–9.48)	18.99 $\pm$ 0.10 (18.89–19.09)	14.56 $\pm$ 0.08 (14.48–14.64)
March	TY	100	9.41 $\pm$ 0.02 (9.39–9.43)	19.51 $\pm$ 0.01 (19.49–19.52)	14.96 $\pm$ 0.01 (14.95–14.98)
March	TY	150	8.93 $\pm$ 0.01 (8.92–8.93)	21.11 $\pm$ 0.03 (21.09–21.14)	16.28 $\pm$ 0.02 (16.26–16.30)

Season	Station	Depth (m)	Temperature (°C)	Salinity (PSU)	Sigma-t (kg/m³)
March	TY	200	8.88 $\pm$ 0.00 (8.88–8.88)	21.43 $\pm$ 0.03 (21.40–21.46)	16.53 $\pm$ 0.02 (16.51–16.56)
August	TM	0	27.89 $\pm$ 0.10 (27.72–28.14)	18.30 $\pm$ 0.11 (17.97–18.47)	9.92 $\pm$ 0.07 (9.73–10.05)
August	TM	20	27.35 $\pm$ 0.11 (27.14–27.47)	18.47 $\pm$ 0.02 (18.44–18.52)	10.22 $\pm$ 0.05 (10.15–10.31)
August	TM	50	9.36 $\pm$ 0.27 (8.88–9.82)	18.87 $\pm$ 0.10 (18.75–19.06)	14.48 $\pm$ 0.11 (14.32–14.68)
August	TM	75	8.72 $\pm$ 0.09 (8.63–8.80)	19.10 $\pm$ 0.14 (18.96–19.24)	14.73 $\pm$ 0.10 (14.63–14.83)
August	TM	100	9.03 $\pm$ 0.01 (9.02–9.04)	20.13 $\pm$ 0.11 (20.02–20.24)	15.50 $\pm$ 0.09 (15.41–15.59)
August	TM	150	8.93 $\pm$ 0.00 (8.93–8.93)	21.13 $\pm$ 0.01 (21.12–21.15)	16.29 $\pm$ 0.01 (16.28–16.30)
August	TM	200	8.89 $\pm$ 0.01 (8.89–8.90)	21.50 $\pm$ 0.01 (21.49–21.50)	16.58 $\pm$ 0.01 (16.57–16.59)
August	TY	0	27.42 $\pm$ 0.08 (27.24–27.61)	18.48 $\pm$ 0.12 (18.15–18.72)	10.01 $\pm$ 0.28 (9.18–10.33)
August	TY	20	17.65 $\pm$ 0.05 (17.56–17.72)	18.15 $\pm$ 0.12 (17.94–18.38)	12.49 $\pm$ 0.10 (12.31–12.66)
August	TY	50	8.86 $\pm$ 0.05 (8.78–8.97)	18.98 $\pm$ 0.01 (18.96–18.99)	14.62 $\pm$ 0.01 (14.61–14.63)
August	TY	75	9.03 $\pm$ 0.00 (9.03–9.03)	19.86 $\pm$ 0.07 (19.80–19.93)	15.29 $\pm$ 0.05 (15.24–15.35)
August	TY	100	8.98 $\pm$ 0.00 (8.98–8.98)	20.60 $\pm$ 0.02 (20.58–20.62)	15.87 $\pm$ 0.01 (15.86–15.89)
August	TY	150	8.92 $\pm$ 0.00 (8.92–8.92)	21.20 $\pm$ 0.01 (21.19–21.20)	16.34 $\pm$ 0.00 (16.34–16.35)
August	TY	200	8.88 $\pm$ 0.00 (8.88–8.88)	21.49 $\pm$ 0.01 (21.48–21.51)	16.58 $\pm$ 0.01 (16.57–16.59)

During August, surface warming and the partial effect of freshwater caused a low-density upper layer to form at 0–10/20 m along the TM line, while a thicker pycnocline zone, defined by gradually increasing sigma-t values, formed between 20–40 m. On the TY line, the low-density layer was confined to a shallower depth range, with sigma-t rapidly reaching intermediate layer density values along a more abrupt pycnocline between 15–30 m. Below 50 m, sigma-t reached similar levels on both lines, and a common deep-water structure belonging to the same water mass prevailed.

In summary, the TM and TY lines are subject to essentially the same regional density and salinity regime from a hydrographic perspective. The vertical structure is primarily determined by seasonal stratification and thermocline/pycnocline development; the coastal effect associated with Değirmendere is limited to only the upper few tens of meters and manifests as weak horizontal variations. Detailed numerical values are presented in Table 3. These hydrographic contrasts provide the physical context for interpreting nutrient-salt variability, which is analyzed in Section 3.2.

Temporal and Spatial Distribution of Nutrient Salts

The joint evaluation of nutrient salts according to the Month×Line factors reveals that the TM (coastal line under river influence) and TY (open sea reference line) regions generally exhibit a similar trophic regime; however, the coastal–open sea differentiation is particularly pronounced in certain nitrogen and phosphorus compounds (Table 2). In the surface layer, both lines exhibit low to moderate levels of inorganic nitrogen and phosphorus, but relatively high TN loads. Detailed statistical values are presented in Table 4.

In the two-way ANOVA model established for NO_x, month, line, and Month×Line interaction were not found to be statistically significant, and average NO_x levels were quite similar in the TM and TY lines. This indicates that nitrification processes in the oxygenated upper layer operate similarly on a regional scale. For NH₄⁺, the season and interaction terms were insignificant, but the line effect showed a trend close to significance; higher NH₄⁺ concentrations were recorded in the TM line throughout the year compared to TY. This increase observed along the TM, especially during the summer period, indicates a richer accumulation of NH₄⁺ supported by organic matter decomposition, river inflows, and anthropogenic loads in the coastal strip under the Değirmendere effect (Table 2).

For o-PO₄³⁻, TP, and SiO₂, none of the terms month, line, and Month×Line are statistically significant; however, when all water column averages are considered, o-PO₄³⁻ and SiO₂ levels in the TY line are seen to be higher than in the TM line in some places. This structure indicates a more stable SiO₂ and o-PO₄³⁻ pool fed by processes such as diffusion from deep waters to the surface, particle sedimentation, and redissolution from bottom sediments on the open sea side. Surface o-PO₄³⁻ concentrations remain at trace levels throughout the year in both regions and are mainly noticeable during periods when bottom material is resuspended (Table 2).

TN has been the parameter that most clearly reflects trophic differences between lines. In the two-way ANOVA for TN, both the month and line effects, as well as the Month×Line interaction term, were found to be significant; it

was determined that TN enrichment was more pronounced in the open sea (TY) in March, while maximum TN values shifted to the coastal zone (TM) at the end of summer. These results indicate that at the end of winter/beginning of spring, nitrogen stocks transported from deep waters to the surface by winter mixing were dominant in the TY line; whereas in the summer period, a persistent nitrogen accumulation fed by river inflows, coastal organic matter load, benthic dissolution, and local anthropogenic sources was prominent in the TM line (Table 2).

Along the TM line, moving from the coast to the open sea, particularly in March, the relatively high levels of NO_x, NH₄⁺, and SiO₂ at the TM1 station closest to Değirmendere, which rapidly decrease a few miles offshore, indicate that river-derived enrichment is confined to a narrow coastal strip. In contrast, for NH₄⁺, TN, and TP, instead of a uniform decrease from the coast to the open sea, a more irregular horizontal-temporal structure was observed, characterized by local increases at some stations and periods. Which is consistent with short-term hydrodynamic conditions and/or biogeochemical transformation processes; however, since currents and meteorological conditions were not measured simultaneously in this study, the relevant mechanisms cannot be directly verified. Horizontal differences along the TY line are more limited, and the small-scale variations observed in NO_x, SiO₂, and TP may be related to the intensity of seasonal mixing and local variability. Overall, the findings indicate that the TM and TY lines are within the same regional productivity regime; but suggest that in the coastal section (TM), there is a more pronounced enrichment trend, particularly in reduced nitrogen forms and TN components, due to river inputs, while in the offshore section (TY), o-PO₄³⁻ and SiO₂ stocks may be relatively supported by processes associated with deeper layers (Figure 3a,b; Table 4).

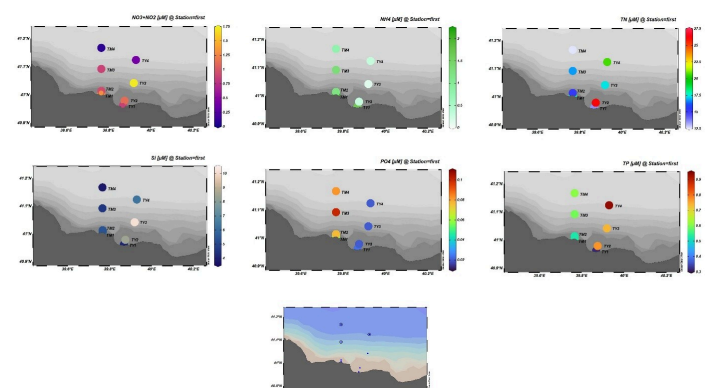


Figure 3a. Surface distribution of nutrients at TM and TY stations in March



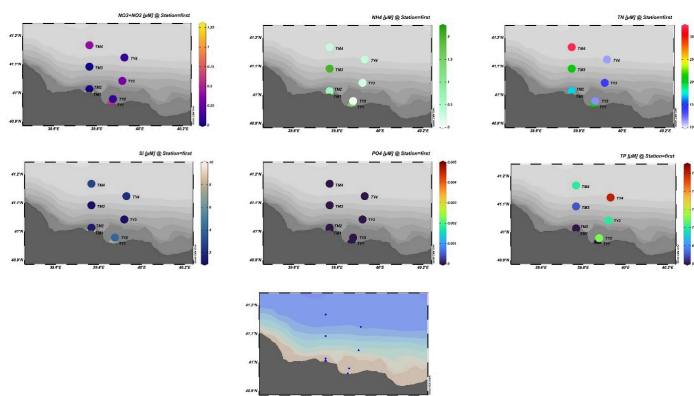


Figure 3b. Surface distribution of nutrient salts at TM and TY stations in August

Table 4. Surface nutrient salt concentrations at TM and TY stations for March, August, and the year as a whole (mean $\pm$ SD, min–max; μM)

Season	Station	NO_x (μM)	NH_4^+ (μM)	$[\text{PO}_4^{3-}]$ (μM)	$[\text{SiO}_2]$ (μM)	$[\text{TP}]$ (μM)	$[\text{TN}]$ (μM)
March	TM	0.80 ± 0.25 (0.10–1.31)	1.35 ± 0.27 (0.79–2.10)	0.08 ± 0.01 (0.06–0.10)	4.81 ± 0.42 (3.74–5.61)	0.57 ± 0.02 (0.52–0.61)	15.63 ± 1.18 (12.53–18.00)
March	TY	1.03 ± 0.27 (0.41–1.72)	0.59 ± 0.36 (0.13–1.65)	0.02 ± 0.00 (0.02–0.02)	7.27 ± 1.30 (4.17–10.14)	0.69 ± 0.13 (0.32–0.93)	19.42 ± 2.67 (13.54–26.16)
August	TM	0.44 ± 0.30 (0.01–1.30)	1.21 ± 0.46 (0.27–2.05)	0.02 ± 0.00 (0.02–0.02)	3.61 ± 1.91 (1.08–9.23)	0.73 ± 0.08 (0.59–0.97)	24.50 ± 3.43 (17.02–32.40)
August	TY	0.29 ± 0.12 (0.10–0.61)	0.52 ± 0.34 (0.04–1.53)	0.03 ± 0.01 (0.02–0.05)	3.71 ± 1.45 (1.10–7.68)	1.07 ± 0.21 (0.59–1.62)	14.55 ± 2.37 (11.29–21.43)
Year overall	TM	0.62 ± 0.19 (0.01–1.31)	1.28 ± 0.25 (0.27–2.10)	0.05 ± 0.02 (0.02–0.10)	4.21 ± 0.93 (1.08–9.23)	0.65 ± 0.05 (0.52–0.97)	20.07 ± 2.37 (12.53–32.40)
Year overall	TY	0.66 ± 0.20 (0.10–1.72)	0.55 ± 0.23 (0.04–1.65)	0.02 ± 0.01 (0.02–0.05)	5.49 ± 1.13 (1.10–10.14)	0.88 ± 0.14 (0.32–1.62)	16.98 ± 1.89 (11.29–26.16)

Surface layer (0 m) DIN:PO_4^{3-} ratios ranged from 10.84–109.39 in March and 6.95–167.30 in August; a more regular decrease was observed from the coast to the open sea along the TM line in March, while in August, a more fragmented pattern emerged, particularly with high ratios in TM1 and TY1. However, since o-PO_4^{3-} values were close to the detection limit in some samples, potentially inflating DIN:PO_4^{3-} ratios, these ratios were evaluated not as a definitive diagnostic criterion but as a qualitative indicator of potential nutrient balance (Table 5).

Table 5. Surface DIN:PO_4^{3-} ratios at TM and TY stations for March and August

Station	DIN:PO_4^{3-} (March)	DIN:PO_4^{3-} (August)
TM1	59.87	167.30
TM2	28.02	28.50
TM3	22.00	100.75
TM4	10.84	34.15
TY1	109.39	107.45
TY2	70.40	6.95
TY3	92.25	22.38
TY4	35.65	8.04

The pattern from the coast to the open sea is particularly evident in March in TM1, where $\text{NO}_x\text{-NH}_4^+\text{-SiO}_2$ starts relatively high and rapidly decreases within a few miles; this indicates that river-derived enrichment may be confined to a narrow coastal strip. In contrast, NH_4^+ , TN, and TP exhibited a more irregular horizontal-temporal structure characterized by local increases rather than a uniform decrease at some periods/stations. Although this situation is consistent with short-term hydrodynamic conditions and/or biochemical transformations, the mechanism cannot be directly tested due to the lack of simultaneous current–meteorological measurements. The more limited horizontal differences in the TY line suggest that seasonal mixing intensity and local variability may be decisive factors.

Stoichiometric assessment has opened up an additional reading area for the limiting pattern. The fact that DIN:PO_4^{3-} ratios remain above the Redfield ratio in most cases indicates that phosphorus-based limitation may be dominant in the study area. Studies reporting relatively low o-PO_4^{3-} levels in Eastern Black Sea rivers, but wider ranges for TN and SiO_2 , support this framework (Alkan *et al.*, 2013). Considering that disruption in the N:P balance is a critical trigger for eutrophication (Strokal *et al.*, 2014; Yunev *et al.*, 2007) and that nutrient increases in coastal waters can transform ecosystem responses (Orehova, 2021; Alkan *et al.*, 2022), it can be said that the enrichment observed in TM due to the Değirmendere effect strengthens the “nitrogen-rich–phosphorus-limited” signature.

Temporal and Vertical Distribution of Nutrient Salts

Although the vertical nutrient salt profiles of the TM and TY stations generally have a similar structure, the concentration levels and the intensity of the maximum/minimum values differ significantly, especially between the March and August periods. Detailed numerical values are presented in Figure 4(a,b) and Table 6.

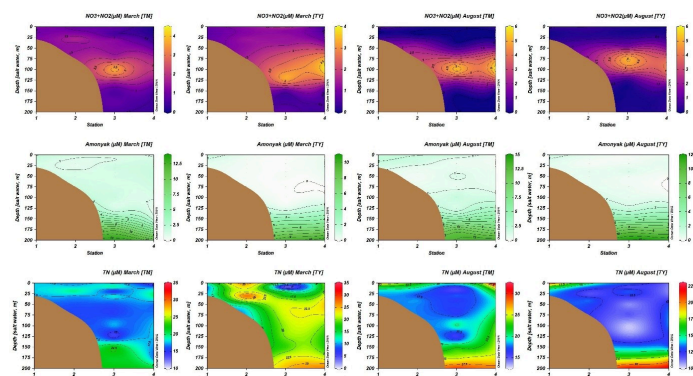


Figure 4a. Vertical profiles of nitrate+nitrite, ammonia, and total nitrogen at TM and TY stations for March and August

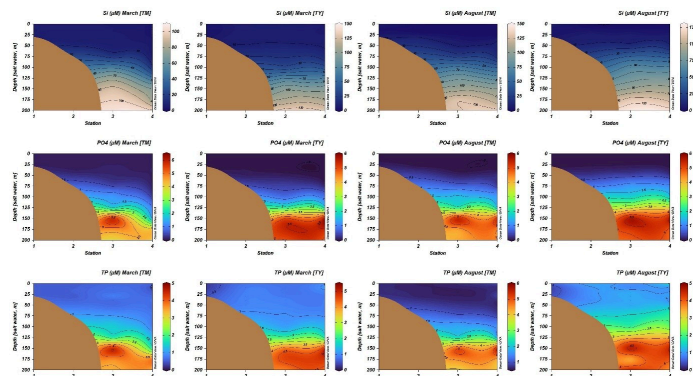


Figure 4b. Vertical profiles of silicate, phosphate, and total phosphate at TM and TY stations for March and August

Table 6. Vertical nutrient salt concentrations at TM and TY stations for March, August, and the year as a whole (mean $\pm$ SD, min-max; μM)

Parameter	Depth (m)	TM March	TM August	TM Year overall	TY March	TY August	TY Year overall
NO_x	0–	0.77 $\pm$	0.17 $\pm$	0.47 $\pm$	0.96	0.22 $\pm$	0.59
	20	0.12	0.12	0.11	± 0.11	0.05	± 0.10
		(0.10–1.36)	(0.01–1.30)	(0.01–1.36)	(0.41–1.72)	(0.08–0.61)	(0.08–1.72)
	20–	1.31 $\pm$	0.86 $\pm$	1.08 $\pm$	1.38	1.07 $\pm$	1.23
	50	0.12	0.25	0.14	± 0.07	0.17	± 0.09
		(0.75–1.92)	(0.01–2.10)	(0.01–2.10)	(1.18–1.74)	(0.40–1.69)	(0.40–1.74)
	50–	2.39 $\pm$	3.99 $\pm$	3.19 $\pm$	2.84	4.80 $\pm$	3.82
	100	0.60	1.14	0.67	± 0.39	0.44	± 0.46
		(1.53–4.14)	(1.36–5.93)	(1.36–5.93)	(2.33–3.98)	(3.88–5.72)	(2.33–5.72)
	100–	1.12 $\pm$	0.55 $\pm$	0.83 $\pm$	1.25	0.21 $\pm$	0.73
NH_4^+	200	0.42	0.32	0.27	± 0.48	0.03	± 0.27
		(0.36–3.80)	(0.01–2.06)	(0.01–3.80)	(0.42–3.57)	(0.09–0.36)	(0.09–3.57)
	0–	1.14 $\pm$	1.20 $\pm$	1.17 $\pm$	0.38	0.64 $\pm$	0.51
	20	0.12	0.22	0.12	± 0.15	0.26	± 0.15

Parameter	Depth (m)	TM March	TM August	TM Year overall	TY March	TY August	TY Year overall
NO_2	0–	(0.79–2.10)	(0.27–2.22)	(0.27–2.22)	(0.04–1.65)	(0.04–2.83)	(0.04–2.83)
	20–	1.41 $\pm$	1.26 $\pm$	1.34 $\pm$	0.16	0.47 $\pm$	0.32
	50	0.15	0.40	0.21	± 0.03	0.12	± 0.07
		(0.68–2.21)	(0.30–3.83)	(0.30–3.83)	(0.07–0.36)	(0.09–1.21)	(0.07–1.21)
	50–	1.61 $\pm$	1.17 $\pm$	1.39 $\pm$	0.12	0.63 $\pm$	0.38
	100	0.26	0.45	0.25	± 0.03	0.18	± 0.13
		(1.18–2.20)	(0.32–2.37)	(0.32–2.37)	(0.05–0.17)	(0.34–1.12)	(0.05–0.12)
	100–	6.59 $\pm$	8.22 $\pm$	7.40 $\pm$	5.25	6.65 $\pm$	5.95
	200	1.70	1.58	1.14	± 1.42	1.51	± 1.02
		(0.77–13.40)	(0.88–13.83)	(0.77–13.83)	(0.19–10.86)	(1.13–11.96)	(0.19–11.96)
o-PO_4^{3-}	0–	0.08 $\pm$	0.02 $\pm$	0.05 $\pm$	0.02	0.02 $\pm$	0.02
	20	0.00	0.00	0.01	± 0.00	0.00	± 0.00
		(0.06–0.10)	(0.02–0.02)	(0.02–0.10)	(0.02–0.02)	(0.02–0.05)	(0.02–0.05)
	20–	0.15 $\pm$	0.13 $\pm$	0.14 $\pm$	0.04	0.16 $\pm$	0.10
	50	0.02	0.04	0.02	± 0.01	0.03	± 0.02
		(0.10–0.25)	(0.02–0.36)	(0.02–0.36)	(0.02–0.09)	(0.04–0.32)	(0.02–0.32)
	50–	0.60 $\pm$	1.02 $\pm$	0.81 $\pm$	0.56	1.43 $\pm$	0.99
	100	0.31	0.34	0.23	± 0.17	0.14	± 0.19
		(0.14–1.50)	(0.29–1.79)	(0.14–1.79)	(0.14–0.90)	(1.12–1.70)	(0.14–1.70)
	100–	3.41 $\pm$	3.98 $\pm$	3.70 $\pm$	4.41	4.74 $\pm$	4.57
SiO_2	200	0.66	0.58	0.43	± 0.58	0.33	± 0.32
		(1.11–6.28)	(1.37–5.93)	(1.11–6.28)	(1.65–5.89)	(3.21–5.92)	(1.65–5.92)
	0–	4.98 $\pm$	2.10 $\pm$	3.54 $\pm$	7.02	3.68 $\pm$	5.35
	20	0.23	0.74	0.49	± 0.60	0.69	± 0.57
		(3.74–6.17)	(0.74–9.23)	(0.74–9.23)	(3.42–10.14)	(1.10–7.68)	(1.10–10.14)
	20–	6.39 $\pm$	9.89 $\pm$	8.14 $\pm$	9.26	8.90 $\pm$	9.08
	50	0.47	1.71	0.96	± 0.38	0.55	± 0.33
		(4.68–9.19)	(1.97–18.54)	(1.97–18.54)	(8.02–11.71)	(6.97–11.34)	(6.97–11.71)
	50–	20.12	37.48	28.80	23.95	50.80	37.38
	100	± 9.62	± 11.59	± 7.70	± 4.35	± 7.47	± 6.46
TP		(6.20–48.58)	(13.31–64.16)	(6.20–64.16)	(13.71–32.71)	(35.67–64.51)	(13.71–64.51)
	100–	82.06	108.57	95.31	102.49 $\pm$	100.99	101.74
	200	± 8.29	± 7.47	± 6.39	8.44	± 7.01	± 5.31
		(33.98–105.47)	(73.89–132.51)	(33.98–132.51)	(69.35–134.52)	(74.77–126.16)	(69.35–134.52)
	0–	0.56 $\pm$	0.67 $\pm$	0.62 $\pm$	0.76	0.96 $\pm$	0.86
	20	0.02	0.03	0.02	± 0.07	0.10	± 0.06
		(0.47–0.67)	(0.53–0.97)	(0.47–0.97)	(0.29–1.11)	(0.35–1.62)	(0.29–1.62)



Parameter	Depth (m)	TM March	TM August	TM Year overall	TY March	TY August	TY Year overall
TN	20–50	0.64 ± 0.03 (0.52–0.87)	0.71 ± 0.04 (0.60–0.87)	0.68 ± 0.03 (0.52–0.87)	0.87 ± 0.01 (0.82–0.91)	1.05 ± 0.04 (0.85–1.26)	0.96 ± 0.03 (0.82–1.26)
	50–100	1.02 ± 0.19 (0.74–1.57)	1.34 ± 0.25 (0.83–1.92)	1.18 ± 0.16 (0.74–1.92)	1.13 ± 0.09 (0.95–1.40)	1.86 ± 0.11 (1.62–2.12)	1.50 ± 0.15 (0.95–2.12)
	100–200	2.93 ± 0.47 (1.25–4.86)	3.89 ± 0.53 (1.51–5.75)	3.41 ± 0.37 (1.25–5.75)	3.86 ± 0.45 (1.71–5.01)	3.98 ± 0.22 (3.31–4.88)	3.92 ± 0.24 (1.71–5.01)
	0–20	16.30 ± 0.82 (12.53–20.18)	20.36 ± 1.58 (15.44–32.40)	18.33 ± 0.98 (12.53–32.40)	18.77 ± 2.65 (15.9–34.67)	13.81 ± 0.87 (11.29–21.43)	16.29 ± 1.47 (15.9–34.67)
	20–50	19.17 ± 1.87 (16.05–33.63)	18.85 ± 0.77 (15.81–23.12)	19.01 ± 0.98 (15.81–33.63)	21.79 ± 1.61 (13.86–29.17)	12.08 ± 0.34 (10.68–13.87)	16.94 ± 1.42 (10.68–29.17)
	50–100	17.77 ± 0.93 (15.15–19.44)	19.77 ± 1.69 (16.12–23.52)	18.77 ± 0.97 (15.15–23.52)	20.82 ± 0.49 (19.67–22.04)	12.61 ± 0.98 (10.15–14.59)	16.72 ± 1.63 (10.15–22.04)
	100–200	19.09 ± 1.30 (12.46–23.53)	23.91 ± 1.66 (14.34–29.63)	21.50 ± 1.19 (12.46–29.63)	21.53 ± 1.22 (17.88–27.74)	16.08 ± 1.59 (10.92–22.21)	18.81 ± 1.20 (10.92–27.74)

In March, NO_x concentrations are low at the surface on both lines; they show a distinct maximum in the 75–100 m depth band; and they decrease again in deeper layers. During this period, corresponding to late winter/early spring, differences between TM and TY remain relatively limited due to vertical mixing conditions; however, NO_x levels are somewhat higher throughout the water column at TM stations near the coast compared to TY. NH_4^+ increases in both lines between 150–200 m depth; however, higher values are recorded in the TM line compared to TY at the surface and in the first 50 m, indicating stronger regeneration supported by river inflows and organic matter decomposition in the coastal zone. In terms of o-PO_4^{3-} , TM stations show a relatively richer structure in the surface–upper layer during March, while a more pronounced o-PO_4^{3-} stock emerges in TY stations below the pycnocline and in deep layers. SiO_2 and TP increase in deep waters in both regions in March; however, the surface and middle depths, especially the TY line, exhibit relatively richer values in terms of SiO_2 .

With increased stratification during August, TM–TY differences in the vertical distribution of nutrient salts become more

pronounced. NO_x reaches minimum levels at the surface on both lines, while maximums around 75–100 m become more pronounced; particularly at TY stations, a more distinct NO_x enrichment associated with open sea conditions is observed in this depth band. NH_4^+ reaches higher peak values at depths of 150–200 m on both tracks compared to March, but higher NH_4^+ levels are maintained on the TM track compared to TY both in the surface–50 m layer and at mid-depths. The vertical distribution of o-PO_4^{3-} becomes even more pronounced during the summer period; while TM stations again show relatively high o-PO_4^{3-} concentrations at the surface, the o-PO_4^{3-} stock below the pycnocline and in the deep layers becomes more dominant in the TY line. SiO_2 and TP show a marked accumulation in deep waters in both regions during the summer period, while the greater silica and o-PO_4^{3-} richness of TY stations at the surface and at mid-depths highlights the relative importance of deep water-derived nutrient recycling and upward nutrient transport towards the open sea.

Regional assessment frameworks (e.g., TRIX/BEAST/NEAT) indicate that coastal zones in the Black Sea may be under higher eutrophication pressure compared to the open sea, and that significant reductions in inorganic phosphorus loads may be necessary in some areas to achieve good environmental status (Lazăr, 2018; Lazăr, 2021; Tan et al., 2023; Lazăr et al., 2024; Tan et al., 2025). It is emphasized that land-based loads (urban wastewater, agriculture, industry, erosion) are among the main pressures on the Turkish Black Sea coast (Tuncer et al., 1998; Bakan et al., 2010; Bat et al., 2018). In this context, the nutrient levels and stock ratios measured in the Değirmendere line place the area in a “moderate but fragile” eutrophication risk class; while the relatively low level of o-PO_4^{3-} provides a buffering effect in the short term, it should not be overlooked that P increases originating from the basin could rapidly increase the risk level (Lazăr et al., 2019; Lazăr et al., 2024; Ristea et al., 2025).

In conclusion, this study provides a robust local-scale reference framework by examining the nutrient salt pattern formed by Değirmendere in the coastal waters of Trabzon, considering both the coastal–open sea direction and the 0–200 m vertical axis. However, the sampling being limited to two periods and a single measurement per station restricted the capture of event-based peaks and the entire annual cycle; therefore, the findings should be evaluated as a “snapshot.” Since river discharge/chemistry was not measured simultaneously, the load–response relationship could not be established directly; furthermore, the fact that o-PO_4^{3-} remained close to the MDL and the repeated measurement



structure increased the sensitivity of the ANOVA-based ratio (DIN:PO₄, TN:TP) constraint interpretations.

CONCLUSION

Hydrographic data obtained along the Değirmendere front TM line and the reference TY line show that both lines have a similar seasonal mixing and stratification regime: distinct mixing and homogeneity between 0 and 200 m in March; and a warm-low-density upper layer between 0 and 20/30 m and a thermocline/pycnocline developing between 20–40 m, confirming that winter mixing and summer stratification in the Black Sea upper layer are the key controllers (Mee, 1992; Murray et al., 2007; Orekhova, 2021; Varenik et al., 2023).

The increase in NO_x, NH₄⁺, SiO₂, and TN levels at the stations closest to Değirmendere (especially TM1) indicates that river-derived inputs cause nutrient enrichment in the coastal zone; however, the effect rapidly weakens within a few nmi. This pattern is consistent with regional studies reporting that land-derived inputs reach their maximum in areas close to the coast (Tuncer et al., 1998; Bat et al., 2009; Alkan et al., 2013; Tan et al., 2023).

The fact that DIN:PO₄³⁻ ratios exceed the Redfield ratio in most cases indicates that the dominant limitation is phosphorus-based and that the “nitrogen-rich-phosphorus-limited” trophic structure is also observed at the Değirmendere scale (Yuney et al., 2007; Alkan et al., 2013; Stokal et al., 2014; Orekhova, 2021; Alkan et al., 2022). Although this situation may limit the transition to excessive eutrophication in the short term, it should be considered an early warning signal highlighting the system's vulnerability to increases in phosphorus loads originating from the basin (Lazăr et al., 2019; Lazăr et al., 2024; Ristea et al., 2025).

From a management perspective, reducing N and especially P inputs from agricultural fertilizer applications, urban wastewater, and potential industrial discharges; treatment improvements that enhance phosphorus removal; and erosion control (vegetative buffer strips, sediment retention measures) can contribute to reducing nutrient and suspended solids loads along the coast. (Bakan et al., 2010; Bat et al., 2018; Mete et al., 2022; Yıldırım, 2021). Furthermore, multi-component monitoring covering all four seasons (river flow/ load + coastal water + biological indicators) will be critical for validating findings and capturing long-term trends (ÇŞİDB and TÜBİTAK MAM, 2022; ÇSB, 2023; Tan et al., 2023; Tan et al., 2025).



Peer Review Externally peer-reviewed.

Conflict of Interest The author have no conflict of interest to declare.

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