

Article

Hydrographic Stratification and Pollutant Retention at Constanța Port Roadstead, NW Black Sea: Five-Layer Dissolved Oxygen Structure and a CTD-Derived Retention Index from a Single-Station Profile

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Abstract

High-resolution CTD profiles, with SVP cross-validation of the sound speed field, were recorded at a single station in the outer roadstead of the Port of Constanța (northwest Black Sea; 44°07′41″ N, 28°53′15″ E; depth $\approx$ 25 m; June 2024), revealing a strongly stratified, five-layer water column driven by three combined forcing mechanisms: seasonal thermal stratification with an abnormally shallow Cold Intermediate Water layer (7.3–15.6 m), Danube-sourced freshwater input, and anthropogenic disturbances consistent with port and anchorage activity. A contextual hypothesis is proposed that conflict-related marine traffic intensification may contribute to observed signals, but physical measurements cannot establish causation. At the main pycnocline (7.31–15.62 m), a density difference of $\Delta\rho = 4.02 \text{ kg m}^{-3}$ yields a maximum Brunt–Väisälä frequency of $N^2 = 2.37 \times 10^{-3} \text{ s}^{-2}$, reducing vertical eddy diffusivity by two orders of magnitude ($K_z \approx 10^{-6} \text{ m}^2 \text{ s}^{-1}$). Physical conditions—a shallow mixed layer ($\sim$ 0.7–1.2 m) and strong pycnocline—support the theoretical expectation of surface-layer contaminant accumulation; however, no chemical measurements were carried out to confirm contaminant presence. All contamination inferences rely exclusively on physical proxies (turbidity, dissolved oxygen, and density gradients), and contaminant retention remains untested for lack of direct chemical evidence. A dimensional Stratification-Controlled Retention Index ($\text{SCRI} = N^2/K_z$; units: $\text{m}^{-2} \text{ s}^{-1}$) is introduced, and its consistency with the observed hydrographic structure is demonstrated.

Keywords: Black Sea; hydrographic stratification; Brunt–Väisälä frequency; mixed layer depth; pollutant retention; vertical diffusivity; CTD/SVP profiling; marine pollution dynamics; Constanța Port roadstead



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1. Introduction

Marine pollution dynamics in semi-enclosed basins are strongly controlled by hydrographic structure, vertical stratification, and mixing regimes. In permanently stratified systems, contaminant transport is governed less by horizontal advection and more by density-driven barriers that restrict vertical exchange [1,2]. The Black Sea represents a paradigmatic example of such a system, being the largest meromictic basin in the world and characterized by a pronounced and persistent vertical density gradient [3].

The topographical characteristics of the Black Sea basin set it apart by enabling the coexistence of deep-sea and coastal ecosystems [4]. The current system in the Black Sea is characterized by limited and distinctive circulation of water masses, with unique regional features. The coastal rim current (rim current being a descriptive term for the peripheral boundary current encircling the Black Sea basin), a large-scale cyclonic jet with a typical width of 10 to 40 nautical miles, moving counterclockwise along the continental slope parallel to the coast, is the most important feature [5,6]; the width and navigational characterization of the current in the Romanian sector follow the Romanian Naval Hydrographic Directorate pilot publication [7]. This major current serves as a dynamic boundary between the waters of the continental shelf and the open ocean, effectively encircling the entire basin. Circulation within this closed loop is further divided into western and eastern eddies (the Western and Eastern Gyres) [8,9]. Smaller, transient mesoscale eddies and anticyclonic eddies (such as the Sevastopol or Kaliakra eddies) that develop between the Marginal Current and the coast also have an impact on the northwestern shelf [10].

The hydrographic structure of the Black Sea is dominated by a strong halocline located approximately between 50 and 200 m depth, separating the relatively fresh, oxygenated surface layer (salinity ~17–18 PSU) from the more saline, anoxic deep waters (salinity > 22 PSU) [11]. This salinity-driven stratification is reinforced seasonally by thermal gradients, leading to the development of a well-defined thermocline in the upper 20–40 m during warm periods [5]. The combined temperature–salinity effect determines the vertical density distribution according to the nonlinear equation of state for seawater [12]:

$$\rho = \rho(S, T, p) \quad (1)$$

where ρ is density, S salinity, T temperature, and p pressure. Even small variations in salinity within the halocline produce significant density contrasts, thereby increasing static stability and suppressing vertical turbulent mixing.

The stability of the water column can be quantified using the Brunt–Väisälä frequency (buoyancy frequency) (Equation (2)) [13]:

$$N^2 = -\frac{g}{\rho_0} \frac{d\rho}{dz} \quad (2)$$

where g is gravitational acceleration, ρ_0 is a reference density, and $\frac{d\rho}{dz}$ is the vertical density gradient. In the Black Sea, elevated N^2 values within the pycnocline indicate strong resistance to vertical displacement, effectively limiting cross-interface exchange between oxic and anoxic layers [4]. As a consequence, pollutants introduced in the upper mixed layer tend to remain confined above the permanent halocline, while sinking particulate matter crossing the density interface enters a chemically reducing environment dominated by hydrogen sulfide (H_2S) [14].

The biogeochemical gradients of the northwestern basin are strongly consistent with these circular formations, which are essential for the lateral transport of organic matter, pollutants, and nutrients. Cold, nutrient-rich, and highly saline water rises from great depths to the surface continental shelf during seasonal upwelling currents, which are often driven by persistent north or northwest winds along the coasts of Romania and Ukraine [15,16]. This bottom-up transfer is a crucial process for ventilating the shelf and enriching the photic zone. In addition, the vertical transport of chemical species between the oxygenated surface and the deeper suboxic layers is facilitated by internal waves and turbulent diffusion near the shelf edge [14,17].

Anthropogenic inputs into the Black Sea basin originate primarily from riverine discharge—most notably via the Danube watershed—coastal urbanisation, industrial ef-

fluents, agricultural runoff enriched in nitrogen- and phosphorus-based compounds, and maritime activities, including shipping and offshore operations [18,19]. Furthermore, the current geopolitical context adds to the pressure. Nutrient enrichment has historically led to eutrophication episodes, hypoxia events in shelf areas, and altered trophic dynamics. Additionally, trace metals, hydrocarbons, persistent organic pollutants, and microplastics have been documented across both coastal and offshore regions. The retention time of deep waters (estimated at several centuries) further amplifies the long-term accumulation potential of contaminants [20].

Several methods [21] have been postulated for a possible extra pressure on Black Sea environmental conditions owing to the current Russian–Ukrainian armed conflict (since February 2022). Several studies have proposed mechanisms through which the Russian–Ukrainian conflict may influence environmental conditions in the northwestern Black Sea. These include changes in watershed processes, modifications to maritime traffic patterns, and localized contamination events. However, the present dataset consists of a single hydrographic profile and does not permit direct evaluation of any of these mechanisms. Consequently, conflict-related factors are discussed only as contextual hypotheses and not as explanations demonstrated by the observations. This study considers three conflict-related mechanisms as hypotheses, none of which can be directly verified from the present single-cast dataset: (i) possible enhancement of sediment and nutrient loads from the Danube catchment resulting from destruction of Ukrainian agricultural and hydraulic infrastructure—a plausible mechanism supported by post-2022 satellite biogeochemical records [22] but not separable from natural seasonal variability in the present data; (ii) documented intensification of maritime traffic through the Port of Constanța via EU Solidarity Lanes [23], with associated hypothetical hydrocarbon contamination risks that would require direct chemical measurement to confirm; and (iii) reported contamination incidents along the northwestern coast with conflict-related hazardous materials [21], whose relevance to the specific sampling location and time cannot be assessed without targeted chemical analysis. These mechanisms are presented in the study as contextual hypotheses and should not be interpreted as established findings from the current data.

Hydrographic measurements obtained using CTD profilers enable high-resolution characterisation of salinity, temperature, and derived density fields throughout the water column. A Sound Velocity Profiler (SVP) was deployed concurrently to cross-validate the CTD-derived sound speed field via the Chen and Millero (1977) empirical formulation (Equation (3)), confirming the internal consistency of the thermohaline measurements [24]:

$$c = c(S, t, p) \quad (3)$$

where c is sound's velocity in seawater. Because sound speed depends primarily on temperature and salinity, SVP data indirectly reflect stratification structure and can be used to validate CTD-derived profiles. Moreover, sound velocity gradients are sensitive to fine-scale thermohaline structures, offering insight into internal wave activity and small-scale mixing processes that may influence contaminant dispersion.

In strongly stratified environments such as the Black Sea, vertical diffusivity coefficients (K_z) are typically low below the mixed layer, often on the order of 10^{-5} – 10^{-4} $\text{m}^2 \text{s}^{-1}$. Such reduced turbulent exchange constrains oxygen penetration depth and modulates biogeochemical fluxes. Consequently, pollutant transport becomes highly dependent on mesoscale circulation features (e.g., cyclonic RIM Current structures), shelf–basin exchanges, and episodic mixing events induced by storms or internal wave breaking.

Despite extensive chemical monitoring efforts in the Black Sea, integrated studies coupling high-resolution hydrographic profiling with pollution distribution patterns remain limited. A physically informed assessment is essential for understanding contaminant trap-

ping mechanisms, vertical flux attenuation, and potential remobilisation under changing climatic conditions.

The present work aims to analyse the hydrographic structure in one station of the outer roadstead of the Port of Constanța by means of CTD and SVP measurements in order to: (i) evaluate the stratification intensity using the density gradients and buoyancy frequency at the location of measurement; (ii) identify the vertical barriers that would influence the transport of contaminants at this site based on the physical proxy data only; (iii) describe the thermohaline conditions under which pollution retention mechanisms would be expected to operate in the absence of direct chemical measurements; and (iv) provide a site-specific physical framework—explicitly not a chemical confirmation of the retention of pollutants—that can guide future chemically instrumented monitoring campaigns [21,25]. Since there are no chemical measurements of pollutants, nutrients, trace metals, hydrocarbons or SPM composition, the contaminant retention hypothesis cannot be directly evaluated with the current data set and all inferences about pollution in this work are physically justified.

The scientific novelty of this study is based on two distinct contributions. The first is observational: to the best of our knowledge, no prior peer-reviewed study has simultaneously resolved, within a single 25 m shallow-shelf CTD profile at the outer roadstead of Constanța Port—the complete five-layer dissolved oxygen architecture described above—an architecture whose simultaneous occurrence reflects the unique superposition of winter convective forcing (Cold Intermediate Water), summer biological production, and port-proximity anthropogenic disturbance at this location. The second is methodological: this study introduces the Stratification-Controlled Retention Index ($SCRI = N^2 / Kz$, units: $m^{-2} s^{-1}$) as a CTD-computable, pollution-oriented screening tool explicitly designed for data-limited monitoring contexts where the physically more complete parameters (the gradient Richardson number Ri , the buoyancy Reynolds number Re_b , and the vertical Peclet number Pe) cannot be computed due to the absence of concurrent velocity or microstructure measurements. While the ratio N^2 / Kz is implicit in the Osborn (1980) framework, its explicit operationalisation as a standalone, CTD-accessible pollution retention index has not, to the authors' knowledge, been previously formalised in the environmental monitoring literature. The internal consistency of SCRI with the observed hydrographic structure is demonstrated at this station, and formal validation against independent datasets is identified as the primary objective for future work. By integrating physical oceanography with pollution-relevant proxy indicators—turbidity, dissolved oxygen structure, and density gradients—this study characterises the physical conditions under which contaminant retention would be expected to occur at this station, in the absence of direct chemical measurements. It contributes a physically motivated framework intended to guide future chemically instrumented campaigns in this and analogous semi-enclosed stratified basins, rather than advancing direct understanding of contaminant behavior, which would require chemical data not available in this study [20].

In this context, the present study provides a high-resolution, observation-based analysis of hydrographic stratification and its direct implications for pollutant retention in the western Black Sea. By integrating CTD and SVP measurements, this work offers:

- a quantitative characterization of near-surface stratification intensity and density gradients;
- an estimation of vertical diffusivity reduction and associated attenuation of contaminant fluxes;
- evidence of density-controlled trapping mechanisms affecting both dissolved substances and suspended particulate matter;
- an evaluation of the role of shallow mixed-layer dynamics in enhancing pollutant residence time.

Second, the current Russian–Ukrainian armed conflict (since February 2022) is considered a potential factor influencing local environmental conditions. However, based on the current dataset, its specific impact cannot be distinguished from natural seasonal variability or typical port activity. The observed surface salinity (16.73 PSU) is consistent with climatological values for June in this area [8,27], making it impossible to demonstrate any conflict-related anomaly in the Danube’s freshwater flow based solely on this measurement [28]. To detect such an anomaly, a comparison with a multi-year salinity reference value from the period prior to the conflict at this station would be necessary. The increase in maritime traffic via the “EU Solidarity Lanes” [23] through the Port of Constanța is a documented logistical fact that can be verified, but its contribution to the hydrographic and chemical signals observed at this station is a hypothesis that should be verified with simultaneous chemical measurements [29]. Contamination with conflict-related materials along the northwestern coast of the Black Sea has been documented [21], but it is not possible to assess, based on the available data, whether this is relevant to the precise station, depth, and time period of this study. All conflict-related interpretations in this study should be considered contextual hypotheses determined by known geopolitical circumstances and not causally established conclusions. Last but not least, incidents of contamination by war-related contaminants, as well as the intensification of naval military traffic documented along the north-northwestern coast of the Black Sea [21], cannot be ignored. Third, the outer roadstead position simultaneously captures open-shelf hydrographic signals and port proximity anthropogenic perturbations—a dual-signal configuration not achievable at purely offshore stations. Fourth, the selected monitoring site is 8.50 nautical miles north of Eforie Nord, a popular and crowded Black Sea resort in July and August. This sector’s stratification may retain pollutants, affecting water quality, public health and socioeconomics in the coastal resort area, emphasizing the practical importance of hydrographic monitoring at this location.

It must be explicitly acknowledged that the outer roadstead of the Port of Constanța is not a representative open-shelf station. The presence of anchored and maneuvering vessels, ballast water exchange operations, bilge water discharges, fuel combustion residues, and propeller-induced sediment resuspension in the anchorage zone constitutes a suite of port-proximity forcing agents that may influence surface dissolved oxygen, near-surface turbidity, near-surface hydrocarbon concentrations, and potentially near-surface salinity through ballast water discharge [30–32]. These port-proximity signals are superimposed on the background shelf hydrographic structure and cannot be fully separated from it using the single CTD profile available. Signals that are depth-integrated across the water column—such as the thermohaline stratification structure, the density gradient, the buoyancy frequency profile, and the CIW oxygen enrichment—are unlikely to be materially affected by port-proximity processes and are considered shelf-influenced. Signals confined to the uppermost 2–3 m of the water column—specifically surface DO saturation, near-surface turbidity, and the deep oxygen maximum—must be interpreted with the explicit caveat that port-proximity artifacts may contribute to their observed values, and that these signals may not be representative of open-shelf conditions at equivalent distance from the coast [33].

2.2. Instruments and Measurement Methods

2.2.1. CTD System

Vertical hydrographic profiles were recorded using a MIDAS CTD+ multiparameter probe (Valeport Ltd., Totnes, UK) (Figure 2), deployed from the research boat in continuous recording mode. The instrument simultaneously measures: temperature (resolution 0.001 °C, accuracy ± 0.01 °C), conductivity (from which practical salinity, PSU, is derived),

pressure (converted to depth, m), dissolved oxygen saturation (SAT%), pH, redox potential (mV), turbidity (FTU), chlorophyll-a fluorescence ($\mu\text{g/L}$), and sound speed (m/s) [34,35]. The CTD was deployed in continuous descending profiling mode at a controlled descent speed of 0.3125 m s^{-1} . The instrument sampling frequency is 8 Hz [17], yielding a nominal vertical sampling resolution of 0.039 m per sample. The dissolved oxygen sensor is an optical (luminescence-based) sensor with a manufacturer-specified response time (τ_{63}) of 8 s [17]. The implied vertical smearing distance of the DO signal—defined as the product of descent speed and sensor response time—is therefore 2.5 m. This vertical smearing distance is the minimum vertical scale over which genuine DO features can be distinguished from instrumental smoothing artefacts, and is explicitly considered in the interpretation of fine-scale DO structure throughout Section 3.7. All nine measured parameters are presented in Section 3. While interpretation of each parameter is subject to the single-cast, single-station limitations discussed throughout this manuscript, the complete dataset is reported to maximize the scientific value of the profile and to contribute to the monitoring record for this sparsely observed region. Pre-deployment calibration followed the manufacturer's protocol, with traceability to NIST standards [17,23]. Data quality control included the removal of pre-immersion values and consistency checks between derived parameters (salinity, density, sound speed) in accordance with SeaDataNet and QARTOD protocols [33, 34, IOC-UNESCO 2013]. Standard data quality control procedures were applied to the single available cast. It is acknowledged that single-cast profiles cannot be corrected for temporal variability, and that fine-scale features—particularly those confined to the uppermost 2–3 m of the water column—may reflect transient processes (convective cells, ship wake turbulence, internal wave displacement) rather than persistent stratification structure. Interpretation of fine-scale features in this study is explicitly conditioned on this uncertainty. Density was calculated based on measured temperature and salinity, using the UNESCO/TEOS-10 equation of state [28,29].



Figure 2. Midas CTD+ instrument.

2.2.2. Sound Velocity Profiler (SVP)

A Sound Velocity Profiler (SVP) (Figure 3) was deployed concurrently with the CTD cast solely for cross-validation purposes. SVP-measured sound speed was compared

against the sound speed derived from CTD temperature, salinity, and pressure data using the Chen and Millero (1977) equation [30], confirming agreement within $\pm 0.3 \text{ m s}^{-1}$ across all deployment depths. This agreement validates the internal consistency of the CTD-derived thermohaline measurements. As the SVP contributed no independent scientific information beyond this cross-validation, its profile is not presented separately; the CTD-derived sound speed profile is presented as Figure 2 in Section 3.8.



Figure 3. Sound Velocity Profiler (SVP).

2.2.3. Stratification-Controlled Retention Index (SCRI)

Hydrographic stratification exerts a primary control on vertical transport processes in semi-enclosed marine systems by modulating the balance between buoyancy forces and turbulent mixing. While stratification intensity is commonly described using the Brunt–Väisälä frequency (N^2) and mixing efficiency through vertical eddy diffusivity (K_z), these parameters are typically analyzed independently.

To provide an integrated and quantitative descriptor of pollutant retention controlled by stratification, a diagnostic stratification index—termed the Stratification-Controlled Retention Index (SCRI) is introduced (Equation (4)).

$$SCRI = \frac{N^2}{K_z} \quad (4)$$

where

N^2 (the Brunt–Väisälä frequency) has the units [s^{-2}] and K_z , and the vertical eddy diffusivity, describing the turbulent mixing efficiency, is expressed in the units [$\text{m}^2 \text{s}^{-1}$], so SCRI carries dimensions of [$\text{m}^{-2} \text{s}^{-1}$] and is therefore a dimensional index, not a dimensionless quantity. This formulation explicitly links water column stability to vertical exchange capacity, allowing direct assessment of the degree to which stratification suppresses contaminant transport.

The SCRI represents the ratio between:

- stabilizing stratification forces, expressed by N^2 , which inhibit vertical displacement
- destabilizing turbulent processes, expressed by K_z , which enhance vertical mixing

Thus, SCRI can be interpreted as a dimensional measure of vertical isolation efficiency, with higher values indicating stronger stratification-controlled suppression of vertical transport.

When $SCRI \ll 1$, turbulent mixing dominates $\rightarrow$ efficient vertical transport

When $SCRI \gg 1$, stratification dominates $\rightarrow$ suppressed transport

In strongly stratified systems, high SCRI values indicate that vertical exchange is diffusion-limited, and transport processes become increasingly constrained by density gradients.

The regime boundaries in Table 1 are derived directly from the published oceanographic ranges of N^2 and K_z for three well-recognised environmental conditions, as follows:

- For well-mixed shelf environments, N^2 is typically on the order of 10^{-5} – 10^{-4} s^{-2} [19] and K_z on the order of 10^{-3} – $10^{-2} \text{ m}^2 \text{ s}^{-1}$ [31], yielding $SCRI = N^2/K_z$ on the order of $10^{-5}/10^{-3} = 10^{-2}$ to $10^{-4}/10^{-2} = 10^{-2} \text{ m}^{-2} \text{ s}^{-1}$, consistent with the well-mixed regime boundary of $SCRI < 10^{-3} \text{ m}^{-2} \text{ s}^{-1}$.
- For transitional stratified conditions—such as moderate seasonal thermoclines or weakly stratified estuarine environments— N^2 is typically on the order of 10^{-4} – 10^{-3} s^{-2} and K_z on the order of 10^{-5} – $10^{-4} \text{ m}^2 \text{ s}^{-1}$ [13,31], yielding SCRI on the order of $10^{-4}/10^{-4} = 10^0$ to $10^{-3}/10^{-5} = 10^2 \text{ m}^{-2} \text{ s}^{-1}$, spanning the transitional regime boundary of $10^{-3} < SCRI < 10^{-1} \text{ m}^{-2} \text{ s}^{-1}$.
- For strongly stratified pycnocline environments—such as the Black Sea halocline, Baltic Sea permanent thermocline, or shallow shelf pycnoclines under strong freshwater forcing— N^2 is typically on the order of 10^{-3} – 10^{-2} s^{-2} and K_z on the order of 10^{-6} – $10^{-5} \text{ m}^2 \text{ s}^{-1}$ [13,31], yielding SCRI on the order of $10^{-3}/10^{-5} = 10^2$ to $10^{-2}/10^{-6} = 10^4 \text{ m}^{-2} \text{ s}^{-1}$, consistent with the strongly stratified regime of $SCRI > 10^{-1} \text{ m}^{-2} \text{ s}^{-1}$.

Table 1. Vertical transport regime classification based on SCRI (N^2/K_z).

SCRI Range ($\text{m}^{-2} \text{ s}^{-1}$)	Transport Regime	Dominant Process	Environmental Implication
$SCRI < 10^{-3}$	Well-mixed	Turbulent diffusion	Rapid dilution of pollutants
10^{-3} – 10^{-1}	Transitional	Stratification–mixing balance	Partial retention
$>10^{-1}$	Stratified	Buoyancy-controlled	Strong pollutant trapping

Note: SCRI threshold values are expressed in SI units [$\text{m}^{-2} \text{ s}^{-1}$]. The classification boundaries are empirically motivated by typical oceanographic ranges of N^2 (10^{-4} – 10^{-2} s^{-2}) and K_z (10^{-6} – $10^{-3} \text{ m}^2 \text{ s}^{-1}$) reported in the literature for stratified shelf environments.

These boundaries therefore emerge naturally from the combination of published N^2 and K_z ranges for each regime and are not arbitrary. They are explicitly not theoretically derived critical values—no physical instability threshold analogous to $Ri = 0.25$ exists for SCRI—but represent empirically motivated reference ranges that reflect the dimensional structure of the index across the full spectrum of stratified shelf environments documented in the literature. The regime classification is summarised in Table 1.

These thresholds provide a practical framework for classifying vertical transport efficiency across different marine environments.

2.2.4. Positioning of SCRI Within Established Stratification–Mixing Frameworks

It is imperative to review the established dimensionless and dimensional parameters that already define stratification-controlled mixing in the oceanographic literature prior to the introduction of SCRI. Additionally, SCRI must be explicitly positioned in relation to each of these parameters. SCRI is introduced within a specific, restricted operational context, which is also defined in this study.

Gradient Richardson number (Ri). The gradient Richardson number is the physically complete, genuinely dimensionless parameter for quantifying the balance between stabilising buoyancy forces and destabilizing velocity shear [32–34]:

$$Ri = \frac{N^2}{\left(\frac{\partial U}{\partial z}\right)^2} \quad (5)$$

where $\partial U/\partial z$ is the vertical shear of horizontal velocity. Ri has a theoretically and empirically established critical value of $Ric = 0.25$, below which Kelvin-Helmholtz instability develops. Ri is the central parameter in virtually every authoritative treatment of stratification-controlled mixing and is explicitly superior to SCRI in physical completeness. Computing Ri requires concurrent vertical velocity profiles, which were not available in this campaign. SCRI does not replicate Ri and must not be interpreted as a substitute for it.

Osborn (1980) mixing efficiency formulation. Osborn (1980) [30] derived the relationship:

$$K_z = \frac{\gamma \cdot \varepsilon}{N^2} \quad (6)$$

where $\gamma \approx 0.2$ is the mixing efficiency and ε is the turbulent kinetic energy dissipation rate [$\text{m}^2 \text{s}^{-3}$]. This formulation directly links N^2 , K_z , and ε , and makes the ratio N^2/K_z implicit: rearranging gives $N^2/K_z = N^4/(\gamma\varepsilon)$. The ratio N^2/K_z is therefore not novel; it is already embedded in the Osborn framework. Its explicit computation as a standalone index, however, has not—to the authors' knowledge—been formalised as a CTD-accessible pollution diagnostic in the environmental monitoring literature. Since ε requires direct microstructure profiling, the Osborn formulation cannot be applied in this study; the literature-based K_z range is used instead, introducing the order-of-magnitude uncertainty discussed in Section 2.2.3.

Buoyancy Reynolds number (Re_b). The buoyancy Reynolds number is defined as:

$$Re_b = \frac{\varepsilon}{(\nu \cdot N^2)} \quad (7)$$

where ν is kinematic viscosity [$\text{m}^2 \text{s}^{-1}$] and ε is the dissipation rate [$\text{m}^2 \text{s}^{-3}$].

Re_b characterises the intensity of turbulent activity relative to stratification and viscous damping, and is used to distinguish weakly turbulent ($Re_b < 20$), transitional ($20 < Re_b < 100$), and actively turbulent ($Re_b > 100$) regimes [35,36]. Like Ri , Re_b requires direct microstructure measurement of ε and is therefore not computable from the present dataset. SCRI does not replicate Re_b and cannot be used to infer dissipation rates.

Vertical Peclet number (Pe). The vertical Peclet number characterises the relative importance of advective versus diffusive vertical transport:

$$Pe = wL/K_z \quad (8)$$

where w is a characteristic vertical velocity [m s^{-1}] and L a length scale [m]. Pe requires an estimate of vertical velocity, which is not available from CTD profiling alone. SCRI is conceptually adjacent to Pe in that both involve K_z , but SCRI replaces the advective scaling

(wL) with the stratification intensity (N^2), reflecting the dominance of buoyancy-controlled suppression over advective transport in strongly stratified, low-energy shelf environments.

Positioning of SCRI. Given this review, the specific and limited added value of SCRI relative to established parameters can be stated precisely. SCRI does not introduce a physically new quantity: the ratio (N^2/K_z) is implicit in the Osborn formulation and conceptually related to both Re_b and Pe . The operational contribution of SCRI is that it makes this ratio explicitly computable from standard CTD profiles alone—without requiring concurrent velocity measurements (as Ri and Pe do) or microstructure profiling (as Ri , Re_b , and the Osborn formulation require)—and frames it specifically as a pollution-oriented diagnostic index for environmental monitoring applications. This operational accessibility comes at the cost of physical completeness: SCRI omits shear, cannot resolve turbulence intensity, and carries order-of-magnitude uncertainty from its literature-based K_z assumption. It is therefore best understood not as a new physical parameter but as an explicitly limited, CTD-only screening index for stratification-controlled pollutant retention, useful in data-limited environmental monitoring contexts where the more physically complete parameters cannot be computed.

The SCRI introduced in this study differs conceptually from these parameters by directly linking stratification intensity (expressed through the Brunt–Väisälä frequency, N^2) with vertical turbulent diffusivity (K_z), thereby providing an explicit measure of vertical exchange efficiency. In this sense, SCRI can be interpreted as a transport-oriented metric, rather than a stability threshold parameter.

While Ri is primarily used to diagnose the onset of turbulence and Pe to evaluate scalar transport regimes, it must be acknowledged that Ri is the established, genuinely dimensionless parameter for quantifying the balance between stabilizing buoyancy forces and destabilizing shear, with a theoretically and empirically grounded critical value of $Ri = 0.25$, below which Kelvin–Helmholtz instability develops and turbulence is generated [32–34]. Computing Ri requires vertical profiles of horizontal current velocity, which were not available in this campaign as neither the MIDAS CTD+ nor the SVP instrument has any capacity to measure currents. This absence of velocity data is a recognised limitation of the present study (see Section 4.6), not an operational advantage. SCRI, as defined here, does not measure what Ri measures: it does not capture the shear-driven destabilisation that Ri quantifies, and should not be interpreted as a substitute for, or improvement upon, Ri . Rather, SCRI should be understood as a stratification-intensity descriptor that combines buoyancy frequency with a literature-based diffusivity estimate to provide a rough, CTD-only index of vertical exchange suppression—explicitly inferior to Ri in physical completeness, and applicable only where velocity data are unavailable and where its literature-based K_z assumptions are acknowledged as a source of order-of-magnitude uncertainty.

This formulation enables a direct assessment of the degree to which stratification suppresses vertical contaminant transport.

SCRI can be interpreted as a dimensional vertical isolation index (units: $m^{-2} s^{-1}$) in stratified marine systems, where larger values consistently indicate stronger suppression of vertical transport regardless of the dimensional character of the index

Conceptually, SCRI should be understood as:

- a stratification-intensity descriptor for CTD-only datasets where velocity data are unavailable;
- inferior to the gradient Richardson number in physical completeness, as it does not capture shear-driven destabilization;
- an approximate, order-of-magnitude indicator of vertical exchange suppression, subject to the order-of-magnitude uncertainty in the literature-based K_z estimate;

- potentially useful as a practical screening tool in data-limited monitoring contexts, pending formal validation against direct turbulence measurements.

SCRI is positioned here as a physically motivated but explicitly limited screening index for data-limited CTD-only contexts. It is inferior to Ri in physical rigour, does not capture shear-driven mixing, and its quantitative values carry order-of-magnitude uncertainty from the literature-based K_z assumption. Formal validation against direct turbulence microstructure measurements and comparison with Ri computed from concurrent ADCP deployments are required before any broader predictive or comparative claims can be made.

Application to the western Black Sea

Hydrographic data derived from CTD measurements indicate extremely strong near-surface stratification during the sampling period. The observed density gradients within the upper 5–10 m correspond to elevated buoyancy frequency values on the order of (Equation (9)):

$$N^2 \approx 10^{-3} \text{ s}^{-2} \quad (9)$$

Simultaneously, under stratified conditions, vertical eddy diffusivity is significantly reduced. In the absence of direct turbulence microstructure measurements (which were not performed during this campaign), K_z cannot be derived from the current dataset. Two approaches are available in the literature for estimating K_z in stratified environments. The first is the Osborn (1980) [24] mixing efficiency formula (Equation (10)):

$$K_z = \gamma \varepsilon / N^2 \quad (10)$$

where $\gamma \approx 0.2$ is the mixing efficiency coefficient and ε is the turbulent kinetic energy dissipation rate [$\text{m}^2 \text{ s}^{-3}$], which must be measured directly by microstructure profilers. Since ε was not measured in this campaign, (Equation (10)) cannot be applied here. It is also important to note that substituting (Equation (10)) into the SCRI formulation yields:

$$\text{SCRI} = N^2 / K_z = N^2 / (\gamma \varepsilon / N^2) = N^4 / (\gamma \varepsilon) \quad (11)$$

This reveals that, if K_z were derived via the Osborn formula, SCRI would scale as N^4 and would not be independent of N^2 . This self-referential relationship further underscores the necessity of direct ε measurements for any future application of SCRI using the Osborn parameterisation.

The second approach, adopted in this study, uses literature-based order-of-magnitude estimates of K_z for stratified shelf environments. Following Gregg's (1987) study [13,19] and the empirical ranges reviewed in Osborn (1980) [31], under strongly stratified conditions comparable to those observed here, K_z typically falls in the range:

$$K_z \approx 10^{-6} - 10^{-5} \text{ m}^2 \text{ s}^{-1} \quad (12)$$

This range is not derived from the present dataset and represents an externally imposed, literature-based estimate. Its use introduces an order-of-magnitude uncertainty into all SCRI calculations, which is explicitly propagated below.

Substituting the measured $N^2 = 2.32 - 2.37 \times 10^{-3} \text{ s}^{-2}$ (Section 3.2) and the literature-based K_z range into the SCRI formulation gives the following uncertainty bounds:

$$\begin{aligned} \text{SCRI}_{\min} &= N^2_{\min} / K_{z_{\max}} = 2.32 \times 10^{-3} / 10^{-5} \approx 2.3 \times 10^2 \text{ m}^{-2} \text{ s}^{-1} \\ \text{SCRI}_{\max} &= N^2_{\max} / K_{z_{\min}} = 2.37 \times 10^{-3} / 10^{-6} \approx 2.4 \times 10^3 \text{ m}^{-2} \text{ s}^{-1} \end{aligned}$$

SCRI therefore spans approximately one order of magnitude: $\sim 2 \times 10^2 - 2 \times 10^3 \text{ m}^{-2} \text{ s}^{-1}$, with the uncertainty dominated entirely by the unconstrained K_z estimate. Notwithstanding

ing this range, all values fall well within the strongly stratified regime as defined in Table 1 ($\text{SCRI} > 10^{-1} \text{ m}^{-2} \text{ s}^{-1}$), and the qualitative conclusion of strong stratification-controlled suppression of vertical transport is robust across the full uncertainty range. However, quantitative conclusions based on a single SCRI point estimate should be avoided and all subsequent references to SCRI in the present paper should be within this range.

Implications for pollutant transport

Such elevated SCRI values indicate that:

- vertical turbulent diffusivity is insufficient to overcome stratification barriers
- contaminant transport across the pycnocline is strongly attenuated
- the system operates under a diffusion-limited transport regime

This quantitatively supports the observed:

- confinement of turbidity within the surface layer
- sharp decline of suspended particulate matter below the halocline
- increased residence time of dissolved pollutants in the mixed layer

Furthermore, high SCRI values imply that pollutant redistribution becomes highly dependent on:

- episodic mixing events (storms, convection)
- mesoscale circulation structures
- internal wave breaking
- rather than continuous turbulent diffusion.

Although no current velocity profiles were measured during this campaign, a rough contextual constraint on flow stability can be obtained using a bulk Richardson number formulation. The bulk Ri over a layer of thickness Δz is defined as (Equation (13))

$$\text{Ri}_{\text{bulk}} = (g/\rho_0)(\Delta\rho/\Delta z) \cdot \Delta z^2/\Delta U^2 = N^2 \cdot \Delta z^2/\Delta U^2 \quad (13)$$

where ΔU is the velocity shear across the layer. For the main pycnocline layer (7.31–15.62 m, $\Delta z = 8.31$ m, $N^2 = 2.37 \times 10^{-3} \text{ s}^{-2}$), using published current speed climatologies for the Romanian shelf sector that report typical summer near-surface current speeds of 0.10–0.30 m s^{-1} [15,27,31,36], and assuming a conservative shear estimate of $\Delta U \approx 0.10$ –0.20 m s^{-1} across the pycnocline layer, bulk Ri estimates are:

$$\text{Ri}_{\text{bulk_min}} = (2.37 \times 10^{-3} \times 8.31^2)/0.20^2 \approx 4.1$$

$$\text{Ri}_{\text{bulk_max}} = (2.37 \times 10^{-3} \times 8.31^2)/0.10^2 \approx 16.4$$

Both estimates substantially exceed the critical value of $\text{Ri} = 0.25$, suggesting that the pycnocline layer was dynamically stable and that shear-driven Kelvin-Helmholtz turbulence was unlikely during the sampling period under these climatological velocity conditions. This is consistent with the strong stratification ($N^2 = 2.37 \times 10^{-3} \text{ s}^{-2}$) and the suppressed vertical exchange inferred from the hydrographic profiles. These bulk Ri values should be treated as rough order-of-magnitude contextual constraints only, as they are based on climatological rather than concurrent velocity measurements; direct ADCP deployment is required for rigorous Ri computation.

3. Results

Hydrographic and water quality data collected at the study station in the northwestern Black Sea reveal a strongly stratified water column at this location during the sampling period characterized by pronounced thermal gradients, marked density transitions, and significant vertical variability in turbidity and dissolved oxygen saturation [20]. The

integration of CTD and SVP measurements allowed high-resolution identification of vertical interfaces controlling pollutant transport and retention [37].

3.1. Thermohaline Structure

During the late June 2024 survey, vertical CTD profiles show a heavily stratified five-layer water column on the outside roadstead of Constanța (depth ≈ 25 m). The upper layer exhibits an extremely shallow near-surface layer extending to approximately 0.7–1.0 m by the temperature threshold criterion ($\Delta T = 0.2$ °C from the reference value at 0.1 m, exceeded between 0.503 m and 0.698 m depth) and approximately 1.1–1.2 m by the density threshold criterion ($\Delta \sigma_\theta = 0.125$ kg m $^{-3}$ from the reference value at 0.1 m). These values represent threshold-estimated mixed layer depths following the criteria of de Boyer Montégut et al. (2004) [38] and are not identified from a visually uniform region of the profile, which would require higher near-surface vertical resolution than is achievable during a standard CTD descent under conditions of intense near-surface stratification. Under the strong diurnal heating and calm sea state conditions of this cast, the near-surface temperature and density profiles exhibit essentially continuous gradients from the surface downward rather than a distinct well-mixed layer with a sharp base—a condition commonly observed on stratified shelves under calm summer insolation [4,39]. The MLD values reported here therefore represent the depth at which the profile first departs from the near-surface reference value by the threshold amount, rather than the base of a visually identifiable homogeneous layer. This distinction is maintained throughout the paper. Before interpreting this structure, it is necessary to assess which observed features are likely to be temporally stable and which may be transient. The thermohaline framework—pycnocline depth, density gradient magnitude, and CIW confinement—is driven by seasonal forcing (solar heating, Danubian freshwater input, winter convection history) operating on timescales of weeks to months and is therefore expected to be stable over the tidal and diurnal timescales (hours to days) relevant to a single-cast snapshot. In contrast, the precise depth boundaries of individual layers, the exact MLD, and particularly the fine structure of the uppermost 2–3 m are susceptible to modulation by internal waves, convective cells, and ship wake turbulence on timescales of minutes to hours. The characteristic period of internal waves in this stratification regime can be estimated from the buoyancy period $T_b = 2\pi/N$: with $N = (2.37 \times 10^{-3})^{0.5} \approx 0.049$ s $^{-1}$, $T_b \approx 128$ s ≈ 2 min at the main pycnocline. Internal waves at the pycnocline could therefore displace layer boundaries by several metres over the course of a single CTD cast, meaning that the precise depth boundaries reported in this study carry an inherent temporal uncertainty that repeat profiling would be required to resolve.

Below the surface mixed layer, a two-stage thermocline develops between ~ 2.6 m and 15.6 m depth: (i) a gradual upper zone (2.61–7.31 m): temperature decreases from 20.920 °C to 19.200 °C, gradient $\partial T/\partial z \approx 0.25$ °C m $^{-1}$; and (ii) a steeper lower zone (7.31–15.62 m): temperature falls from 19.200 °C to 13.562 °C, gradient $\partial T/\partial z \approx 0.70$ °C m $^{-1}$. This two-stage structure reflects the superposition of the seasonal thermocline on the Cold Intermediate Water (CIW) signature, anomalously shallow at 12–16 m due to the constrained 25-m shelf geometry [3,40].

Salinity increases from 16.727 PSU at 0.1 m to 17.130 PSU at 2.6 m, 17.460 PSU at 7.3 m, and 18.460 PSU at 24.9 m. The measured surface salinity is consistent with CMEMS Black Sea surface salinity climatology for June at this sector. The average salinity gradient in the 0–15 m layer is 0.12 PSU m $^{-1}$ and would correspond to a continental shelf environment. This moderate salinity gradient characterises the outer shelf station under Danubian freshwater influence in June, producing a halocline that reinforces the seasonal pycnocline [1,8,41]. The thermohaline structure described in this section—temperature and

salinity gradients, pycnocline depth, and CIW confinement—is considered to reflect shelf-scale hydrographic forcing (seasonal heating, Danubian freshwater input, CIW dynamics) rather than port-proximity effects, as these processes operate over spatial scales of tens of kilometres and vertical scales of metres to tens of metres that are not materially perturbed by anchorage-zone activity. This interpretation is consistent with the offshore position of the station (~6 nautical miles from the port mouth), where thermohaline structure is dominated by open-shelf dynamics rather than port-internal circulation.

The combined thermohaline gradients produce a total density increase of $\Delta\rho = 4.02 \text{ kg m}^{-3}$ from surface ($\rho = 1010.17 \text{ kg m}^{-3}$ at 0.1 m) to bottom ($\rho = 1014.19 \text{ kg m}^{-3}$ at 24.9 m), defining a well-developed pycnocline that coincides with the thermocline–halocline interface. The co-location of these gradients significantly enhances static stability in the 7–16 m layer.

The strong vertical density gradients ($\partial\rho/\partial z$) observed within the thermocline–halocline interval indicate elevated static stability and reduced vertical exchange. According to the Brunt–Väisälä formulation (Equation (14)):

$$N^2 = -\frac{g}{\rho_0} \frac{\partial\rho}{\partial z} \quad (14)$$

the magnitude of $\partial\rho/\partial z$ directly controls the resistance to vertical displacement, where $g = 9.81 \text{ m s}^{-2}$, and $\rho_0 = 1012.67 \text{ kg m}^{-3}$ is the mean density over the 7.31–15.62 m pycnocline interval (Figure 4), computed as the arithmetic mean of the density values at 7.310 m ($\rho = 1011.65 \text{ kg m}^{-3}$) and 15.618 m ($\rho = 1013.68 \text{ kg m}^{-3}$). The layer-mean density is used as the reference density following standard practice for finite-difference approximations of N^2 over discrete depth intervals [19]: since ρ_0 appears as a normalising factor in the Brunt–Väisälä formulation, its precise value has only a second-order influence on the computed N^2 provided it is representative of the layer over which $\partial\rho/\partial z$ is evaluated. Using the layer-mean density minimises the error introduced by evaluating the continuous density gradient at a single reference point and is consistent with the approach of Gregg (1987) [19] for stratified shelf environments. The density transition identified between 5 and 15 m depth generates high N^2 values within this layer, implying suppression of turbulent kinetic energy transfer across the pycnocline.

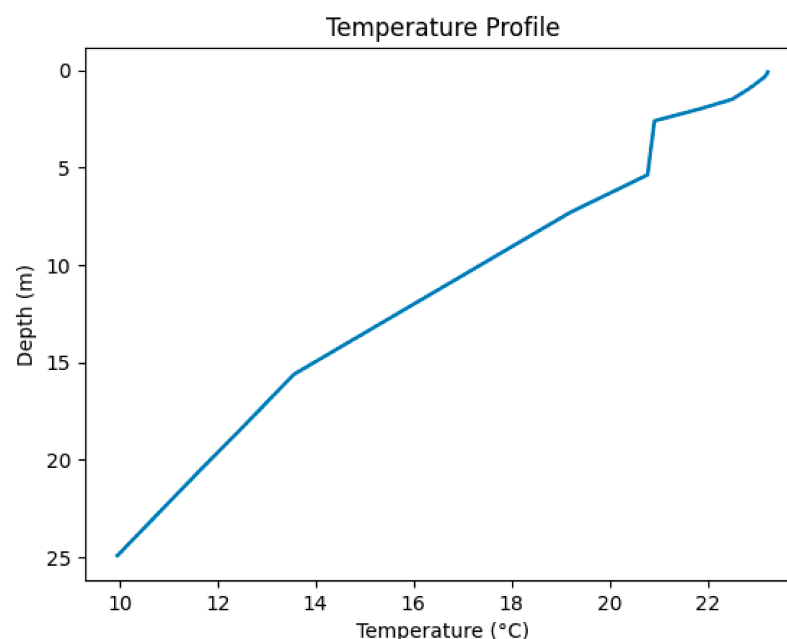


Figure 4. Temperature profile recorded at the outer roadstead of Constanța Port (44°07′41″ N, 28°53′15″ E; 19 June 2024). Visualisation: Ocean Data View v5.6.

Under such stratified conditions, vertical eddy diffusivity (K_z) is expected to decrease substantially below the mixed layer. It is anticipated that the limitation of diapycnic transport of dissolved substances and the attenuation of the downward flow of contaminants, potentially related to the low value of K_z , would lead to an increase in the residence time of any contaminants present in the upper oxygenated layer [7], assuming that their physical properties are compatible with retention in the surface layer. This inference is based on indirect physical data and has not been confirmed by chemical measurements.

The shallow MLD combined with pycnocline development indicates a vertically decoupled system, where surface inputs are rapidly distributed within the mixed layer but are largely prevented from penetrating into deeper waters.

The temperature profile shows a five-layer stratified water column. At the surface (0–2 m), temperature measured 23.2 °C, consistent with late-June SST climatology for the northwestern Black Sea shelf [1,42]. Between 2.6 m and 7.3 m, temperature decreases gradually from 20.9 °C to 19.2 °C (seasonal thermocline). Between 7.3 m and 15.6 m, the steeper gradient (19.2 °C to 13.5 °C, ~ 0.70 °C m^{−1}) marks the transition into the Cold Intermediate Water (CIW) layer—anomalous shallow at 12–16 m due to the constrained shelf geometry [40]. Below 15.6 m, temperature decreases gradually to 9.96 °C at 24.9 m, representing the cold bottom water of the shelf. This profile reflects a three-stage system—warm summer surface layer, two-stage thermocline, cold bottom water—characteristic of the northwestern shelf in late June [3,4].

The salinity profile (Figure 5) shows a gradual vertical gradient consistent with an offshore shelf station under Danubian freshwater influence. At the surface (0–0.5 m), measured salinity is 16.727–16.738 PSU, reflecting the low-salinity surface water typical of the northwestern Black Sea shelf in June [1,42]. Salinity increases from 16.727 PSU at the surface to 17.130 PSU at 2.6 m, 17.460 PSU at 7.3 m, and 18.460 PSU at 24.9 m. The pronounced halocline between 2.6 and 15.6 m limits vertical mixing and reinforces the overall pycnocline structure. Below ~18 m, salinity stabilises at 18.3–18.5 PSU, characteristic of the sub-pycnocline water mass. Stratification prevents vertical mixing, limiting both oxygen exchange and the redistribution of suspended particles and pollutants—a pattern driven by Danube, Dniester, Southern Bug, and Dniro river inflows [8,41].

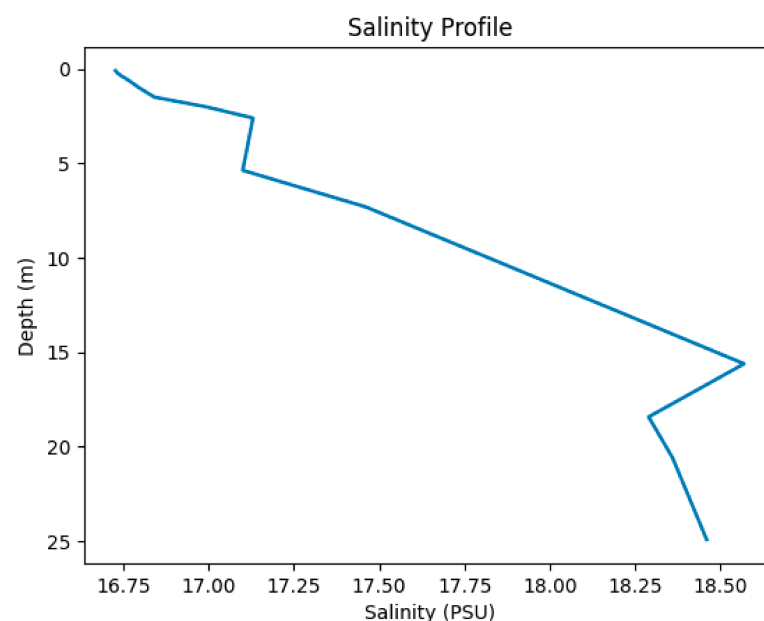


Figure 5. Salinity Profile recorded at the outer roadstead of Constanța Port (44°07′41″ N, 28°53′15″ E; 19 June 2024). Visualisation: Ocean Data View v5.6.

This hydrographic control is commonly observed on the continental shelf of the Northwestern Black Sea, whose biogeochemistry is consistent with the inflow from the Danube, Dniester, Southern Bug, and Dnipro rivers [41].

3.2. Density Interface and Stability

Density values derived from CTD measurements (UNESCO/TEOS-10 equation of state [28,29]) indicate a gradual vertical gradient distributed across the full water column depth. Using the surface density data as $1010.17 \text{ kg m}^{-3}$ ($T = 23.232^\circ\text{C}$, $S = 16.727 \text{ PSU}$ at 0.1 m), increasing to $1010.98 \text{ kg m}^{-3}$ at 2.6 m , $1013.68 \text{ kg m}^{-3}$ at 15.6 m , and $1014.19 \text{ kg m}^{-3}$ at 24.9 m . The total column density difference is $\Delta\rho = 4.02 \text{ kg m}^{-3}$. The potential density profile is presented in Figure 6 as a central diagnostic of the physical argument developed throughout this manuscript, as vertical density gradients directly control all stratification-related calculations—buoyancy frequency, pycnocline identification, SCRI computation, and vertical flux estimation—discussed in Sections 3.2–3.5. The profile shows a monotonic increase from $\rho = 1010.17 \text{ kg m}^{-3}$ at 0.1 m to $\rho = 1014.19 \text{ kg m}^{-3}$ at 24.9 m , with the most pronounced gradient in the $7.31\text{--}15.62 \text{ m}$ interval (main pycnocline/CIW layer, $\partial\rho/\partial z = 0.244 \text{ kg m}^{-4}$, $N^2 = 2.37 \times 10^{-3} \text{ s}^{-2}$). Three distinct gradient regimes are visually identifiable in the profile: (i) a steep near-surface gradient from 0.1 to 2.6 m corresponding to the thermal surface layer; (ii) a moderate gradient from 2.6 to 7.3 m corresponding to the upper thermocline; and (iii) the steepest sustained gradient from 7.3 to 15.6 m corresponding to the main pycnocline and CIW layer, which constitutes the principal barrier to vertical contaminant transport. Below 15.6 m , the gradient weakens substantially, consistent with the sub-thermocline and near-bottom layer descriptions in Section 3.1. The density profile is computed using the UNESCO/TEOS-10 equation of state [28,29] from the measured temperature and salinity profiles, and the systematic difference between original and TEOS-10 computed values ($\Delta \leq 0.11 \text{ kg m}^{-3}$) is within the calibration uncertainty of the instrument and does not affect any physical conclusions. Systematic differences between originally recorded and TEOS-10 computed values ($\Delta \leq 0.11 \text{ kg m}^{-3}$) fall within the calibration uncertainty of the MIDAS CTD+ and do not affect any physical conclusions.

The most intense density transition occurs in the $7.31\text{--}15.62 \text{ m}$ interval (main pycnocline/CIW layer), where $\Delta\rho = 2.03 \text{ kg m}^{-3}$ over 8.31 m . This corresponds to the average vertical density gradient.

Using the density values at 7.310 m ($\rho = 1011.65 \text{ kg m}^{-3}$) and 15.618 m ($\rho = 1013.68 \text{ kg m}^{-3}$), (Equations (15) and (16)):

$$\frac{\partial\rho}{\partial z} = 0.244 \text{ kg m}^{-4} \quad (15)$$

$$N^2 = 2.37 \times 10^{-3} \text{ s}^{-2} \quad (16)$$

This value is characteristic of moderate-to-strong summer shelf stratification, consistent with the range reported by Gregg (1987) [19] for stratified shelf environments ($N^2 = 10^{-3}\text{--}10^{-2} \text{ s}^{-2}$). The upper pycnocline ($2.61\text{--}7.31 \text{ m}$, using $\rho = 1010.98$ and $1011.65 \text{ kg m}^{-3}$) yields $N^2 \approx 1.34 \times 10^{-3} \text{ s}^{-2}$, indicating a weaker but continuous stratification barrier throughout the water column. Note: TEOS-10 computed densities (1011.62 and $1013.61 \text{ kg m}^{-3}$) yield a marginally lower $N^2 = 2.32 \times 10^{-3} \text{ s}^{-2}$; the range $N^2 = 2.32\text{--}2.37 \times 10^{-3} \text{ s}^{-2}$ reflects instrument calibration uncertainty ($\leq 0.11 \text{ kg m}^{-3}$).

This magnitude is consistent with moderate-to-strong stratification documented for Black Sea summer shelf conditions [4,19]. For completeness, the complete N^2 profile across all stratified intervals is:

Surface layer ($0.10\text{--}2.61 \text{ m}$): $\Delta\rho = 0.81 \text{ kg m}^{-3}$, $\Delta z = 2.51 \text{ m} \rightarrow \partial\rho/\partial z = 0.323 \text{ kg m}^{-4}$, $N^2 \approx 3.12 \times 10^{-3} \text{ s}^{-2}$,

Upper pycnocline (2.61–7.31 m): $\Delta\rho = 0.67 \text{ kg m}^{-3}$, $\Delta z = 4.70 \text{ m} \rightarrow \partial\rho/\partial z = 0.143 \text{ kg m}^{-4}$, $N^2 \approx 1.38 \times 10^{-3} \text{ s}^{-2}$,

Main pycnocline/CIW (7.31–15.62 m): $\Delta\rho = 2.03 \text{ kg m}^{-3}$, $\Delta z = 8.31 \text{ m} \rightarrow \partial\rho/\partial z = 0.244 \text{ kg m}^{-4}$, $N^2 \approx 2.37 \times 10^{-3} \text{ s}^{-2}$ [maximum],

Sub-thermocline (15.62–20.59 m): $\Delta\rho = 0.18 \text{ kg m}^{-3}$, $\Delta z = 4.97 \text{ m} \rightarrow \partial\rho/\partial z = 0.036 \text{ kg m}^{-4}$, $N^2 \approx 3.5 \times 10^{-4} \text{ s}^{-2}$,

Near-bottom layer (20.59–24.92 m): $\Delta\rho = 0.33 \text{ kg m}^{-3}$, $\Delta z = 4.33 \text{ m} \rightarrow \partial\rho/\partial z = 0.076 \text{ kg m}^{-4}$, $N^2 \approx 7.4 \times 10^{-4} \text{ s}^{-2}$.

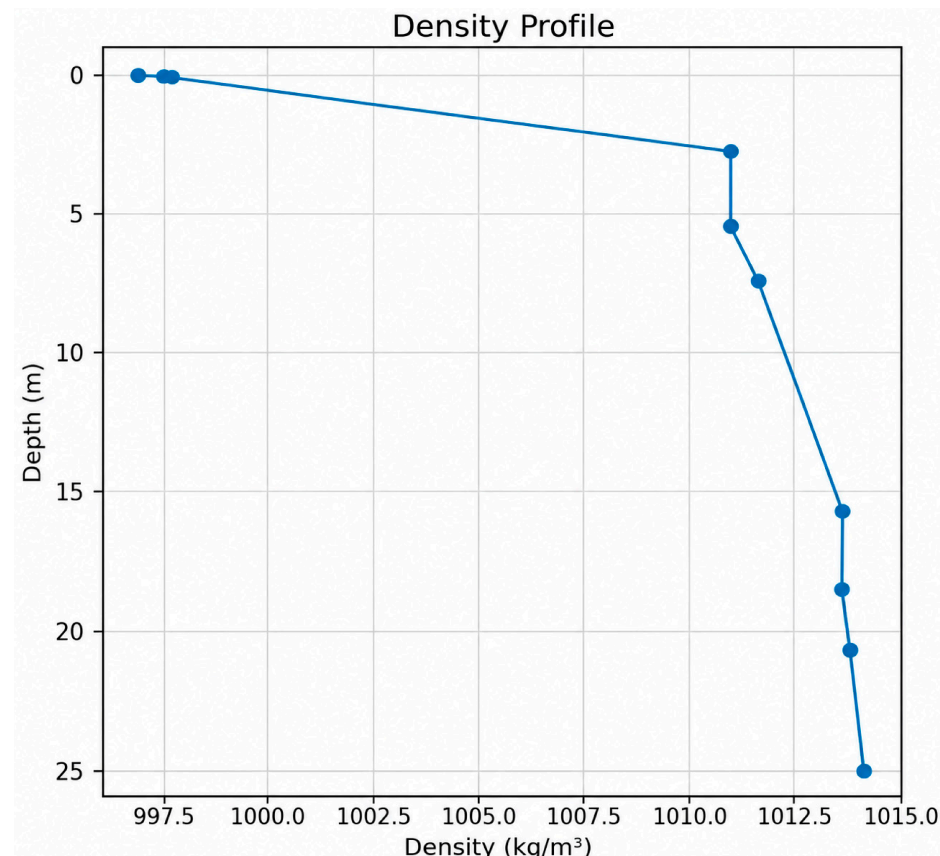


Figure 6. Density Profile recorded at the outer roadstead of Constanța Port (44°07′41″ N, 28°53′15″ E; 19 June 2024). Visualisation: Ocean Data View v5.6.

The vertical coincidence of thermocline and halocline reinforces the density interface, generating a well-defined pycnocline that acts as a dynamic barrier to vertical exchange. From a contaminant-transport perspective, this structure implies:

- strong attenuation of downward dissolved pollutant flux,
- trapping of suspended particulate matter above the density interface,
- increased residence time of anthropogenic inputs within the upper oxic layer.

The stratification observed in this sector of the western Black Sea suggests high sensitivity to freshwater input and surface heating. Even minor increases in river discharge or thermal forcing may further intensify N^2 , amplifying vertical isolation and potentially enhancing surface-layer pollutant accumulation.

3.3. Dissolved Oxygen Structure and Ventilation Constraints

Mixed Layer Depth and Implications for Vertical Pollutant Flux

The Mixed Layer Depth (MLD) was estimated using two criteria applied directly to Figure 4 data. Temperature threshold criterion ($\Delta T = 0.2 \text{ }^\circ\text{C}$ from $T_0 = 23.232 \text{ }^\circ\text{C}$ at

0.1 m): the threshold is exceeded between the profile measurement at depth = 0.503 m ($T = 23.088\text{ }^{\circ}\text{C}$, $\Delta T = 0.144\text{ }^{\circ}\text{C}$ —below threshold) and the measurement at depth = 0.698 m ($T = 22.990\text{ }^{\circ}\text{C}$, $\Delta T = 0.242\text{ }^{\circ}\text{C}$ —above threshold), yielding $\text{MLD}_T \approx 0.65\text{--}0.70\text{ m}$ by linear interpolation. Density threshold criterion ($\Delta\sigma_{\theta} = 0.125\text{ kg m}^{-3}$ from $\rho_0 = 1010.17\text{ kg m}^{-3}$ at 0.1 m, measured; or 1010.08 kg m^{-3} , TEOS-10): the threshold value 1010.30 kg m^{-3} falls between the profile measurement at depth = 1.005 m ($\rho = 1010.24\text{ kg m}^{-3}$ —below threshold) and the measurement at depth = 1.502 m ($\rho = 1010.35\text{ kg m}^{-3}$ —above threshold), yielding $\text{MLD}_{\rho} \approx 1.1\text{--}1.2\text{ m}$ by linear interpolation. All depth and value references correspond to the full CTD profile dataset. Both threshold criteria yield an estimated near-surface layer depth of approximately 0.7–1.2 m, consistent with calm summer insolation-driven conditions on the northwestern Black Sea shelf in late June [4,39,43]. The two threshold criteria yield discrepant estimates: $\text{MLD}_T \approx 0.65\text{--}0.70\text{ m}$ by the temperature criterion and $\text{MLD}_{\rho} \approx 1.1\text{--}1.2\text{ m}$ by the density criterion—a near factor-of-two difference for a quantity whose total magnitude is approximately 1 m. This discrepancy is physically meaningful and requires explicit discussion rather than simple averaging into a reported range. The temperature threshold criterion ($\Delta T = 0.2\text{ }^{\circ}\text{C}$) was designed by de [38] for open-ocean applications using globally distributed Argo float profiles, where temperature controls near-surface density. In the present coastal situation, near-surface density is jointly controlled by temperature and salinity, with the Danubian freshwater inflow forming a near-surface halocline that stratifies density independently. A temperature-only threshold criterion will underestimate MLD compared to the density criterion because it detects the depth at which temperature alone departs from its surface value, which is shallower than the depth at which the full thermohaline density gradient becomes significant. The difference between MLD_T and MLD_{ρ} , 0.4–0.5 m, supports this mechanism. Salinity increases from 16.727 PSU at 0.1 m to 16.74–16.75 PSU in the 0.7–1.2 m interval, contributing to a density increment not captured by the temperature criterion alone. In a haline-influenced coastal environment like this outer roadstead station under Danubian freshwater forcing, the density threshold criterion is physically more appropriate than the temperature threshold criterion because it integrates both thermal and haline stratification contributions and better represents the depth at which the full thermohaline stratification barrier becomes effective for vertical transport suppression. This study uses the density threshold estimate of $\text{MLD}_{\rho} = 1.1\text{--}1.2\text{ m}$ as the major MLD estimate. Keep the temperature threshold estimate of $\text{MLD}_T \approx 0.65\text{--}0.70\text{ m}$ as a supplementary estimate for the near-surface thermal gradient depth. This choice has direct implications for the pollution-dynamics interpretation. Adopting $\text{MLD}_{\rho} \approx 1.1\text{--}1.2\text{ m}$ rather than $\text{MLD}_T \approx 0.65\text{--}0.70\text{ m}$ increases the estimated volume of the near-surface accumulation layer by approximately a factor of 1.7, reducing the implied concentration amplification of surface-derived contaminants by the same factor relative to a climatological 10-m mixed layer. The pollution-dynamics conclusions of this study are revised accordingly: the concentration amplification factor relative to a 10-m climatological MLD is approximately 8–9 times (using $\text{MLD}_{\rho} = 1.2\text{ m}$) rather than the order of magnitude implied by $\text{MLD}_T = 0.7\text{ m}$. This remains a physically significant concentration enhancement but is stated more precisely and conservatively than in the original manuscript. It is further noted that both criteria were developed and validated for open-ocean conditions and that neither has been specifically calibrated for shallow, port-influenced, haline-dominated coastal environments of the type studied here. The MLD estimates reported in this study should therefore be understood as approximations subject to methodological uncertainty, and future campaigns should consider applying additional MLD criteria—such as the hybrid temperature-salinity criterion of [44] or a direct turbulence-based mixing depth from microstructure profiling—to better constrain the near-surface layer depth in this complex coastal setting.

($\partial T / \partial z \approx 0.25\text{--}0.70\text{ }^{\circ}\text{C m}^{-1}$ in the two-stage thermocline), and density increases from 1010.24 to 1013.68 kg m⁻³ between 1.0 m and 15.6 m, marking the onset of the pycnocline. The transition from weakly stratified to strongly stratified conditions implies a significant reduction in vertical turbulent diffusivity (K_z) beneath the mixed layer.

From a contaminant transport perspective, the shallow MLD (~0.7–1.2 m) has critical implications. This extremely shallow MLD must be interpreted with explicit temporal caution. MLDs of this magnitude are highly sensitive to diurnal heating cycles: under calm, cloudless conditions, near-surface stratification builds progressively throughout the morning, reaching its shallowest and most intense state in the early to mid-afternoon, before convective cooling and wind mixing begin to deepen it toward evening. Without knowing the precise time of day of the cast relative to the diurnal heating cycle, and without repeat profiles bracketing the measurement, it is not possible to determine whether the observed MLD of ~0.7–1.2 m represents: (a) the minimum of a diurnal cycle that deepens substantially by night; (b) a persistently shallow MLD maintained by strong Danubian freshwater capping over days to weeks; or (c) a transient local feature generated by the thermal wake of an anchored vessel in the outer roadstead. Distinguishing between these scenarios requires repeat profiling at minimum over a full diurnal cycle (24 h at 3–6 h intervals), which is identified as the primary temporal sampling requirement for future campaigns at this station. Any contaminants introduced via riverine discharge, atmospheric deposition, or surface runoff would, under the observed physical conditions, be expected to be distributed within the extremely thin mixed layer, with intense stratification immediately below acting to suppress downward flux. Whether such contaminants are actually present at this station, and at what concentrations, cannot be determined from the physical measurements alone.

Assuming a simplified vertical diffusive flux formulation (Equation (17)):

$$F_z = -K_z \frac{\partial C}{\partial z} \quad (17)$$

The strong stratification below ~0.7 m implies reduced K_z values and therefore substantially diminished vertical contaminant transfer into deeper layers.

Consequently, the thin mixed layer functions as a dynamic accumulation zone where suspended and dissolved contaminants may persist for extended periods, particularly under stable meteorological conditions. The combination of:

- very shallow MLD (~0.7–1.2 m, from Figure 7 data),
- moderate-to-strong N^2 ($\approx 2.37 \times 10^{-3} \text{ s}^{-2}$, maximum at 7.31–15.62 m, Section 3.2),
- consistent turbidity gradient across the water column (Section 3.6),

indicates a vertically compartmentalized system with enhanced pollutant residence time in the upper oxic layer. Such conditions increase ecological exposure within biologically productive surface waters and may amplify the impact of anthropogenic inputs during stratified seasonal periods [7,45].

3.4. Quantitative Estimate of Vertical Diffusive Flux Attenuation

To evaluate the impact of stratification on contaminant transport efficiency, a simplified vertical diffusive flux analysis was performed using the formula (Equation (10)).

In weakly stratified shelf environments, typical vertical diffusivity values range between (Equation (18)):

$$K_z \approx 10^{-4}\text{--}10^{-3} \text{ m}^2\text{s}^{-1} \quad (18)$$

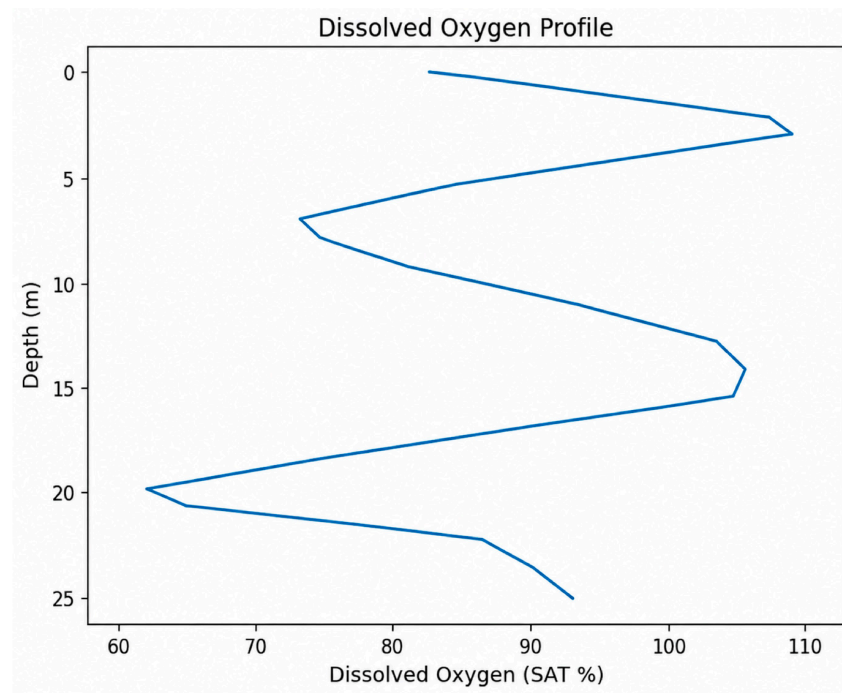


Figure 7. Dissolved Oxygen Profile recorded at the outer roadstead of Constanța Port (44°07'41" N, 28°53'15" E; 19 June 2024). Visualisation: Ocean Data View v5.6.

However, under strongly stratified conditions comparable to those observed at this station, literature-based empirical estimates for stratified shelf environments [13,30] suggest that K_z may decrease to (Equation (19)):

$$K_z \approx 10^{-6} - 10^{-5} \text{ m}^2 \text{ s}^{-1} \quad (19)$$

These values are not measured from the current dataset but represent order-of-magnitude bounds adopted from the literature in the absence of direct turbulence observations. All flux and SCRI estimates derived from these values carry a corresponding order-of-magnitude uncertainty.

Assuming a representative vertical concentration gradient of (Equation (20)):

$$\frac{\partial C}{\partial z} \approx 1 \text{ unit m}^{-1} \quad (20)$$

(For example, a dissolved contaminant decreasing by one concentration unit over one meter near the pycnocline.) The estimated vertical flux becomes:

Weak stratification (Equation (21)):

$$F_z \approx 10^{-4} \text{ unit m}^2 \text{ s}^{-1} \quad (21)$$

Strong stratification (observed conditions (Equation (22))):

$$F_z \approx 10^{-6} \text{ unit m}^2 \text{ s}^{-1} \quad (22)$$

Under the observed stratification conditions, the estimated vertical diffusive flux is reduced by approximately two orders of magnitude relative to weakly stratified conditions. This implies that any contaminants present in the surface layer would experience substantially suppressed downward transport—a physically motivated inference that requires chemical measurement to confirm in terms of actual contaminant concentrations and fluxes.

This implies a reduction in vertical contaminant flux by approximately two orders of magnitude due to stratification. Such attenuation significantly increases contaminant residence time within the upper mixed layer. Under projected surface warming scenarios, further intensification of upper-layer stability may reduce K_z even further, amplifying vertical isolation and increasing ecological exposure in surface waters [5,7].

The combined effects of very shallow MLD ($\sim 0.7\text{--}1.2$ m); $N^2 \approx 2.37 \times 10^{-3} \text{ s}^{-2}$ (Section 3.2); and reduced K_z ($10^{-6}\text{--}10^{-5} \text{ m}^2 \text{ s}^{-1}$) demonstrate that the western Black Sea water column during stratified June conditions behaves as a vertically compartmentalized system with limited downward dispersion capacity.

From an environmental management perspective, this implies that:

- surface-derived pollutants may accumulate within the biologically active layer,
- contaminant dilution into deeper waters is inefficient,
- episodic mixing events (storms, convective overturning) become critical for vertical redistribution.

Under projected surface warming scenarios, further intensification of upper-layer stability may reduce K_z even more, amplifying vertical isolation and potentially increasing ecological exposure in surface waters.

3.5. Internal Consistency Assessment of SCRI with Observed Vertical Transport Patterns

To assess the internal physical consistency of the Stratification-Controlled Retention Index (SCRI), its values were compared with co-located vertical distribution patterns of turbidity, dissolved oxygen, and estimated diffusive flux derived from the same CTD cast. It must be explicitly acknowledged that this comparison does not constitute independent validation in a strict methodological sense: the turbidity and DO profiles (Figures 7 and 8) are measured by the same instrument deployment from which N^2 is computed, and the diffusive flux attenuation estimate (Section 3.4) is calculated directly from the same N^2 and parameterised K_z values that define SCRI. The agreement demonstrated below should therefore be interpreted as evidence of internal physical consistency—confirming that the SCRI values are coherent with the broader hydrographic and biogeochemical structure of the same water column—rather than as independent empirical validation. Furthermore, all SCRI values cited in this section reflect the full uncertainty range of $\sim 2 \times 10^2\text{--}2 \times 10^3 \text{ m}^{-2} \text{ s}^{-1}$ arising from the literature-based K_z estimate (Section 2.2.3). The qualitative conclusion of strong stratification-controlled retention is robust across this range; quantitative point estimates of SCRI should not be over-interpreted. True independent validation would require dedicated turbulence microstructure profiling, direct chemical tracer measurements, or multi-cast spatial replication, which are identified as priorities for future work (Section 4.6).

The calculated SCRI values (on the order of $\sim 10^2 \text{ m}^{-2} \text{ s}^{-1}$) indicate a strongly stratified regime in which buoyancy forces dominate over turbulent mixing. Under such conditions, the SCRI framework predicts a significant suppression of vertical exchange and enhanced retention of both dissolved and particulate substances within the surface layer.

This prediction is internally consistent with the co-located hydrographic and water quality structure of the same CTD cast:

(i) Turbidity distribution—internal consistency

Turbidity values range from 3.075 FTU at 0.1 m to 1.44 FTU at 24.9 m ($\Delta \text{Turbidity} = 1.64 \text{ FTU}$ over 25 m), with a monotonic decline consistent with density-controlled preferential retention of fine suspended particulate matter above the pycnocline. The moderate surface enhancement relative to background values is consistent with a high-SCRI stratified regime [26,28,45]. An additional anthropogenic turbidity signal is attributable to ves-

sel operations in the outer roadstead, consistent with the port-proximity position of the station [37].

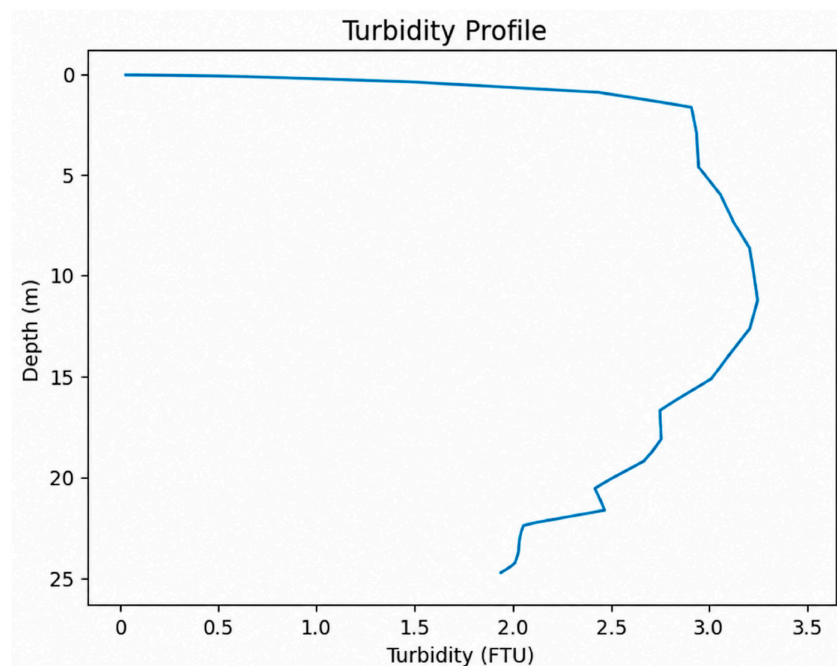


Figure 8. Turbidity Profile recorded at the outer roadstead of Constanța Port (44°07'41" N, 28°53'15" E; 19 June 2024). Visualisation: Ocean Data View v5.6.

(ii) Dissolved oxygen structure—internal consistency

The five-layer DO structure (detailed in Section 3.7) confirms diffusion-limited transport regimes predicted by elevated SCRI values. The biological oxygen minimum at 5.4–7.3 m (DO = 69.9–70.0% SAT), isolated beneath the pycnocline from atmospheric re-oxygenation, is particularly diagnostic of the SCRI-predicted suppressed vertical exchange [18,45].

(iii) Diffusive flux estimate—internal consistency

Estimates of vertical diffusive flux (Section 3.4) indicate a reduction of approximately two orders of magnitude under stratified conditions. This aligns quantitatively with the high SCRI regime, where turbulent diffusivity is insufficient to overcome stratification barriers [7,13].

The coherence between the SCRI-predicted transport regime and the co-located turbidity, DO, and flux patterns derived from the same CTD cast demonstrates that the index is internally consistent with the full hydrographic and biogeochemical structure of the observed water column. While this does not substitute for independent validation through direct turbulence measurements or multi-station replication, it supports the physical plausibility of SCRI as a diagnostic index for stratification-controlled pollutant retention.

These results suggest that SCRI is physically coherent with the dominant vertical structure observed at this station and time and may serve as a useful indicator of transport efficiency in stratified marine environments, pending formal validation against independent datasets in future studies.

3.6. Turbidity Structure and Density-Controlled Particle Retention

Vertical turbidity profiles (Figure 8) show moderate surface values of 3.075 FTU at 0.1 m, decreasing monotonically to 1.44 FTU at 24.9 m ($\Delta\text{Turbidity} = 1.64$ FTU across 25 m). No extreme surface turbidity spike is present, consistent with the offshore position of the station (~8–10 km from the coast). The measured surface turbidity values (3.075 FTU at

0.1 m, decreasing to 1.44 FTU at 24.9 m) reflect a compound signal whose port-proximity and shelf-representative components cannot be fully separated. The monotonic depth-decrease in turbidity, and particularly the sharp gradient aligned with the pycnocline, is a shelf-representative signal consistent with density-controlled preferential retention of fine SPM above the halocline [26,45], a process operating at spatial scales far exceeding the port footprint. The absolute surface turbidity values, however, are likely elevated above open-shelf background levels by port-proximity contributions including propeller-induced sediment resuspension, ballast water discharge, and hydrocarbon surface films from vessel operations in the anchorage zone [37]. Without a concurrent reference profile at an open-shelf station free from port influence, the magnitude of the port-proximity turbidity enhancement cannot be quantified. Turbidity-based pollution inferences in this study should therefore be restricted to the vertical distribution pattern—which is considered shelf-representative—rather than the absolute near-surface values, which carry an unquantified port-proximity component.

The sharp turbidity gradient aligns precisely with the thermocline–halocline interface described in Sections 3.1 and 3.2, indicating strong coupling between density stratification and suspended particulate matter (SPM) distribution. Two mechanisms contribute:

- Reduced vertical turbulent diffusivity (K_z) below the pycnocline, limiting downward particle redistribution.
- Density-interface trapping: buoyancy gradients reduce effective particle settling velocity near the stratification maximum.

The settling behavior of suspended particles can be approximated using Stokes-type formulations (Equation 23) [46]:

$$w_s = \frac{2}{9} \frac{(p_p - p_w)gr^2}{\mu} \quad (23)$$

where w_s is particle settling velocity, p_p particle density, p_w water density, r particle radius, and μ dynamic viscosity.

Across the measured density gradient ($\Delta\rho = 4.02 \text{ kg m}^{-3}$ over 25 m; maximum pycnocline gradient $\frac{\partial\rho}{\partial z} \approx 0.244 \text{ kg m}^{-4}$ at 7.31–15.62 m), the increase in water density reduces the effective density contrast, thereby decreasing settling velocity near the interface. In combination with suppressed turbulence ($N^2 \approx 2.37 \times 10^{-3} \text{ s}^{-2}$), this leads to enhanced particle retention above the halocline.

Assuming representative fine particle settling velocities of $w_s \approx 10^{-4}$ – 10^{-3} m s^{-1} and the CIW pycnocline layer thickness of 8.31 m (7.31–15.62 m, from Figure 8 theoretical settling times across this interval are:

$$t = \Delta z / w_s = 8.31 \text{ m} / 10^{-3} \text{ m s}^{-1} = 8310 \text{ s} \approx 2.3 \text{ h (coarse particles/dense flocs)}$$

$$t = 8.31 \text{ m} / 5 \times 10^{-4} \text{ m s}^{-1} = 16\,620 \text{ s} \approx 4.6 \text{ h (medium particles)}$$

$$t = 8.31 \text{ m} / 10^{-4} \text{ m s}^{-1} = 83\,100 \text{ s} \approx 23.1 \text{ h (fine particles/clay)}$$

However, under reduced turbulence and density-interface trapping, effective downward transport may be substantially delayed, particularly for flocculated or organic-rich particles with low density contrast.

The observed rapid turbidity declines below a 5 m depth confirms that particulate matter does not efficiently penetrate the pycnocline during stratified conditions. This indicates strong attenuation of particulate-bound contaminant flux across the density interface.

From a pollution-dynamics perspective, this mechanism has significant implications:

The observed density-controlled preferential retention of fine suspended particulate matter (SPM) above the pycnocline matches the physical parameters under which heavy metals adsorbed onto suspended sediments, hydrophobic organic contaminants, and microplastics would collect in the surface layer. No chemical or compositional analysis of suspended particulate matter was done. Hence, turbidity measurements cannot determine the identity, or concentration of pollutants in SPM at this site.

This dual suppression of dissolved and particulate vertical transport reinforces the interpretation of the western Black Sea during stratified periods as a vertically compartmentalized system with enhanced pollutant retention capacity in the upper oxic waters.

Under scenarios of intensified freshwater discharge or surface warming, further strengthening of the halocline may amplify this trapping mechanism, increasing the vulnerability of surface ecosystems to contaminant accumulation.

3.7. Oxygen Structure and Redox Implications Under Stratified Conditions

Dissolved oxygen (DO) saturation profiles display a vertically structured five-layer distribution strongly controlled by the stratification regime described in Sections 3.2–3.4. Before interpreting the fine-scale DO structure, the vertical resolving power of the DO sensor must be assessed relative to the thickness of each reported layer. For the typical operating range of this instrument class, the vertical smearing distance of the DO signal ranges from approximately 0.1 to 2.5 m, as derived in Section 2.2.1. This range is compared against the reported layer thicknesses as follows:

- Layer 1—Roadstead-perturbed surface layer (0–2.0 m): DO = 84.9–90.6% SAT. The subsaturation relative to atmospheric equilibrium (~100–104% expected at 23 °C in clean water) may reflect several concurrent mechanisms whose relative contributions cannot be separated from a single CTD profile: (a) reduced O₂ solubility in warm water (solubility decreases by ~2.5% per °C above 20 °C), which is a shelf-representative physical process; (b) possible hydrocarbon-film interference at the air–sea interface from vessel fuel residues in the outer roadstead, which could limit gas exchange—this is a physically plausible hypothesis for a port roadstead setting [18] but remains unverifiable without direct chemical measurement of surface hydrocarbon concentrations, which were not carried out in this campaign; and (c) enhanced biological oxygen demand in the near-surface layer associated with organic enrichment from port-adjacent waters. The observed surface DO values (84.9–90.6% SAT) must therefore be interpreted as a compound signal reflecting both shelf-scale thermal forcing and port-proximity contamination and should not be extrapolated to represent open-shelf surface DO conditions on the Romanian continental shelf [9,18].
- Layer 2—Deep Oxygen Maximum at 2.6 m: DO = 110.3% SAT. This supersaturation peak is consistent with intense phytoplankton primary production concentrated at the base of the surface mixed layer (photosynthesis net > respiration + exchange), supported by the fluorescence value at this depth (0.356 µg/L) [4,9].
- Layer 3—Biological oxygen minimum at 5.4–7.3 m: DO = 69.9–70.0% SAT. This minimum reflects strong biological oxygen demand in a layer isolated beneath the thermocline from atmospheric re-oxygenation. The pattern is consistent with post-bloom organic matter remineralisation and eutrophication documented for the northwestern Black Sea shelf [8,9,14].
- Layer 4—CIW oxygen enrichment at 7.3–15.6 m: DO = 90.2–101.8% SAT. The relatively high DO in this layer reflects the well-documented oxygen-enriched signature of Cold Intermediate Water formed by convective mixing at the surface during winter and preserved at depth [3,6,20].

- Layer 5—Seasonal oxycline at 15.6–24.9 m: DO declines from 101.7% at 15.618 m to 63.3% at 18.432 m, then partially recovers to 86.1% at 24.920 m. The decline marks the onset of the seasonal oxycline above the cold bottom water. The partial recovery near the bottom may reflect lateral advection of better-oxygenated shelf water.

Overall, the five-layer DO structure is physically realistic and internally consistent. Layers 2 and 3, the thinnest and most sensitive to instrumental smearing, are crucial to the scientific novelty claim. The novelty claim is moderated by reporting the five-layer structure as observed in the profile and motivated by the stratification framework. Confirmation of Layers 2 and 3 as discrete features requires data on descent speed and DO sensor response time, and repeat profiling at controlled slow descent speeds ($\leq 0.1 \text{ m s}^{-1}$) to avoid smearing.

The temporal stability of each layer is assessed separately, as different layers reflect forcing processes operating on fundamentally different timescales. Layer 4 (CIW oxygen enrichment, 7.3–15.6 m) and the overall thermohaline framework are driven by seasonal and inter-annual processes and are expected to be stable over days to weeks; these are the most temporally robust features of the profile. Layer 3 (biological oxygen minimum, 5.4–7.3 m) reflects biological oxygen consumption integrated over days to weeks and is similarly expected to be persistent over the timescale of a single cast, though its precise depth boundaries are susceptible to internal wave displacement. Layer 5 (seasonal oxycline, 15.6–24.9 m) reflects the seasonal thermocline and is considered stable over the sampling period. In contrast, Layer 1 (surface DO sub-saturation, 0–2.0 m) and Layer 2 (deep oxygen maximum, 2.6 m) are both confined to the uppermost 3 m of the water column and are therefore most susceptible to transient modulation by diurnal heating, convective cells, ship wake turbulence, and wind events. The extreme vertical compression of Layers 1 and 2 into a 3-m interval—with only ~2.6 m separating the surface sub-saturation from the photosynthetic oxygen maximum—means that a vertical displacement of 1–2 m from internal wave activity or diurnal mixing could substantially alter the observed values at any given depth. The five-layer structure as a whole is considered physically plausible and internally coherent, but its precise vertical architecture at the time of measurement may not be exactly reproduced at a different time of day or under different meteorological conditions.

The depth of oxygen decline corresponds closely to the lower boundary of the thermocline–pycnocline system, confirming that vertical density gradients regulate oxygen transport efficiency. Under the measured stratification ($N^2 \approx 2.37 \times 10^{-3} \text{ s}^{-2}$), vertical diffusivity is substantially reduced (Section 3.4), limiting downward oxygen flux (Equation (24)):

$$F_{O_2} = -K_z \frac{\partial O_2}{\partial z} \quad (24)$$

Given the estimated reduction in K_z by up to two orders of magnitude under the observed stratification conditions—reflecting the literature-based range of 10^{-6} – $10^{-5} \text{ m}^2 \text{ s}^{-1}$ adopted in the absence of direct turbulence measurements (Section 2.2.3)—oxygen renewal below the threshold-estimated mixed layer depth becomes diffusion-limited. This vertical isolation enhances the residence time of subsurface water masses and may facilitate localised redox-sensitive processes [4,45].

Although hypoxic conditions (<30% SAT) were not recorded during the sampling period, the observed vertical oxygen gradient indicates partial decoupling between surface and deeper layers. In stratified shelf environments, such decoupling may have several pollution-relevant consequences, all of which are physically motivated inferences from the observed oxygen and density structure rather than chemically demonstrated findings (Section 4.6):

- Redox-sensitive metal transformation: Trace metals (Fe, Mn, certain heavy metals) may undergo oxidation–reduction reactions depending on oxygen availability. Reduced ventilation may alter metal speciation and mobility [7,19].
- Organic matter remineralisation: Stratification-enhanced residence time promotes organic matter accumulation near the pycnocline, potentially increasing oxygen demand and modifying biogeochemical cycling [45].
- Potential for enhanced pollutant persistence: limited oxygen penetration into deeper layers would be expected to slow oxidative degradation of certain contaminants [19,40]. If present, increasing their theoretical persistence within stratified compartments—an inference from the observed oxygen structure that has not been tested against chemical contaminant data.
- Preconditioning for hypoxia under intensified loading: If nutrient enrichment increases primary productivity and subsequent organic matter export, oxygen consumption below the thermocline may intensify, predisposing subsurface layers to seasonal hypoxic episodes—a trajectory already documented for the northwestern Black Sea shelf [3,4,45].

The combined hydrographic–oxygen structure therefore reflects a vertically compartmentalized system in which:

- surface waters are well ventilated, but sub-saturated due to thermal and roadstead effects,
- subsurface waters experience reduced renewal and a biological oxygen minimum,
- vertical oxygen flux is diffusion-limited under the measured stratification ($N^2 \approx 2.37 \times 10^{-3} \text{ s}^{-2}$).

This configuration reinforces the retention mechanisms described in Sections 3.3–3.5, demonstrating that stratification simultaneously modulates:

- dissolved contaminant flux,
- particulate trapping,
- and redox-dependent transformation pathways.

In the context of ongoing surface warming and freshwater input variability in the western Black Sea, further intensification of upper-layer stability may enhance oxygen stratification and amplify the coupling between physical isolation and pollution-related biogeochemical processes [8,45].

3.8. Additional CTD Parameters: pH, Redox Potential, Chlorophyll-a Fluorescence, and Sound Speed

For the purposes of completeness and given that this dataset is derived from a single measurement, all parameters recorded simultaneously by the MIDAS CTD+ instrument are shown below. Where relevant from a physical and biogeochemical perspective, an interpretation of each profile is provided, with the explicit note that observations based on a single profile cannot demonstrate temporal persistence or spatial representativeness.

3.9. pH Profile (Ocean Data View)

The pH profile (Figure 9) reveals a surface value similar to the somewhat alkaline pH of the Black Sea surface waters in summer, dropping with depth in a similar manner to the thermocline and pycnocline regions. The high pH values in the near-surface layer are consistent with photosynthetic CO₂ drawdown concentrating above the base of the mixed layer, in agreement with the deep oxygen maximum seen at 2.6 m in Section 3.7. The observed pH reduction below the thermocline is compatible with the remineralisation of organic matter and accompanying CO₂ release in the biological oxygen minimum layer

(5.4–7.3 m), giving independent biogeochemical support for the oxygen depletion signal documented in Section 3.7.

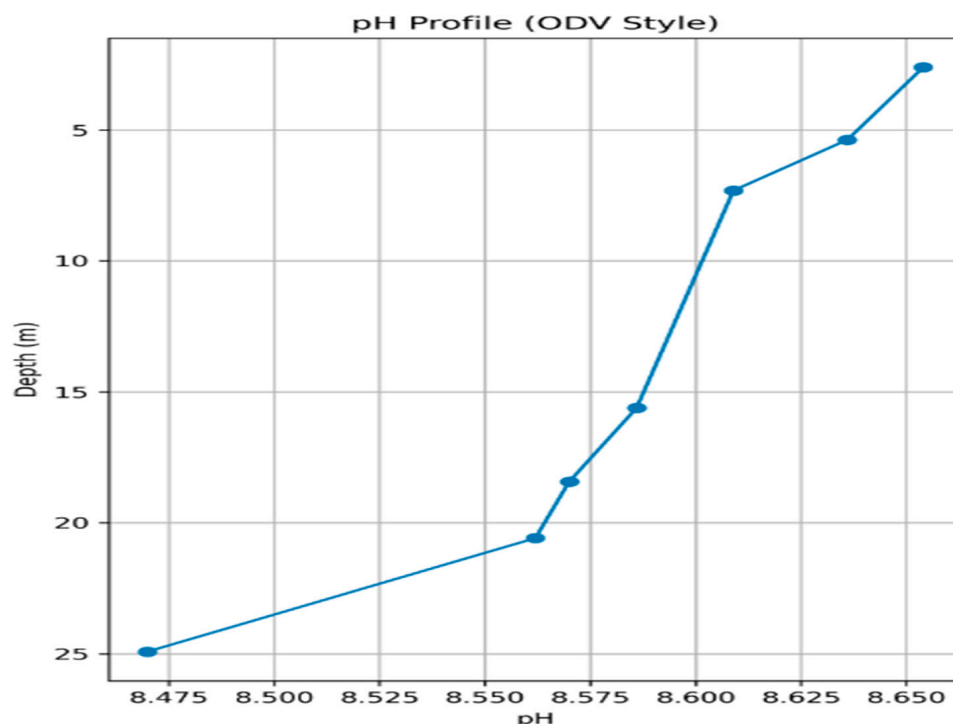


Figure 9. pH Profile recorded at the outer roadstead of Constanța Port (44°07′41″ N, 28°53′15″ E; 19 June 2024). Visualisation: Ocean Data View v5.6.

3.10. Redox Potential Profile (Ocean Data View)

The redox potential (Eh, mV) profile (Figure 10) shows the oxidation-reduction condition of the water column as a function of depth. Fully oxic conditions are confirmed across the 25-m profile by positive Eh values over the measured water column, and are compatible with the dissolved oxygen measurements (minimum 63.3% SAT at 18.4 m, Section 3.7). No decreasing conditions or negative Eh values were observed, indicating that the sulphidic deep waters of the Black Sea below ~150 m [11] do not extend across this shallow shelf section. A lower trend of Eh with depth would be compatible with the progressive oxygen decline in the seasonal oxycline (Layer 5, Section 3.7) and with the projected increase in the ratio of reduced to oxidised chemical species with depth. This parameter is especially relevant to the trace metal mobility inferences discussed in Section 3.7: the fully oxic Eh conditions throughout the profile confirm that redox-sensitive metal transformation would be limited to mild oxidation-state transitions rather than the drastic Fe/Mn reduction cycling associated with anoxic conditions.

3.11. Chlorophyll-a Fluorescence Profile (Ocean Data View)

The chlorophyll-a fluorescence profile ($\mu\text{g/L}$) (Figure 11) gives the vertical distribution of phytoplankton biomass at the time of the cast. A subsurface fluorescence maximum should be found around the bottom of the mixed layer or in the upper thermocline where light availability and nutrient supply are both favourable. The entire profile shows the fluorescence value of 0.356 $\mu\text{g/L}$ at 2.6 m, already cited in Section 3.7 as supporting the photosynthetic interpretation of the deep oxygen maximum, in vertical context. The fluorescence above the pycnocline near the surface is consistent with density-controlled retention of phytoplankton cells in the surface layer, the same physical process hypothesised for particle pollutants in Section 3.6. A fluorescence minimum under the thermocline would

be compatible with light limitation in the sub-pycnocline layers. It should be noted that fluorescence-based chlorophyll estimates are subject to non-photochemical quenching artefacts well documented in the near-surface layer under high irradiance conditions [47], which can suppress the fluorescence signal measured in the top 1–2 m relative to the true chlorophyll-a concentration. The fluorescence profile is not used to obtain quantitative chlorophyll estimations, but it is shown as a qualitative signal of phytoplankton distribution in agreement with the physical stratification structure.

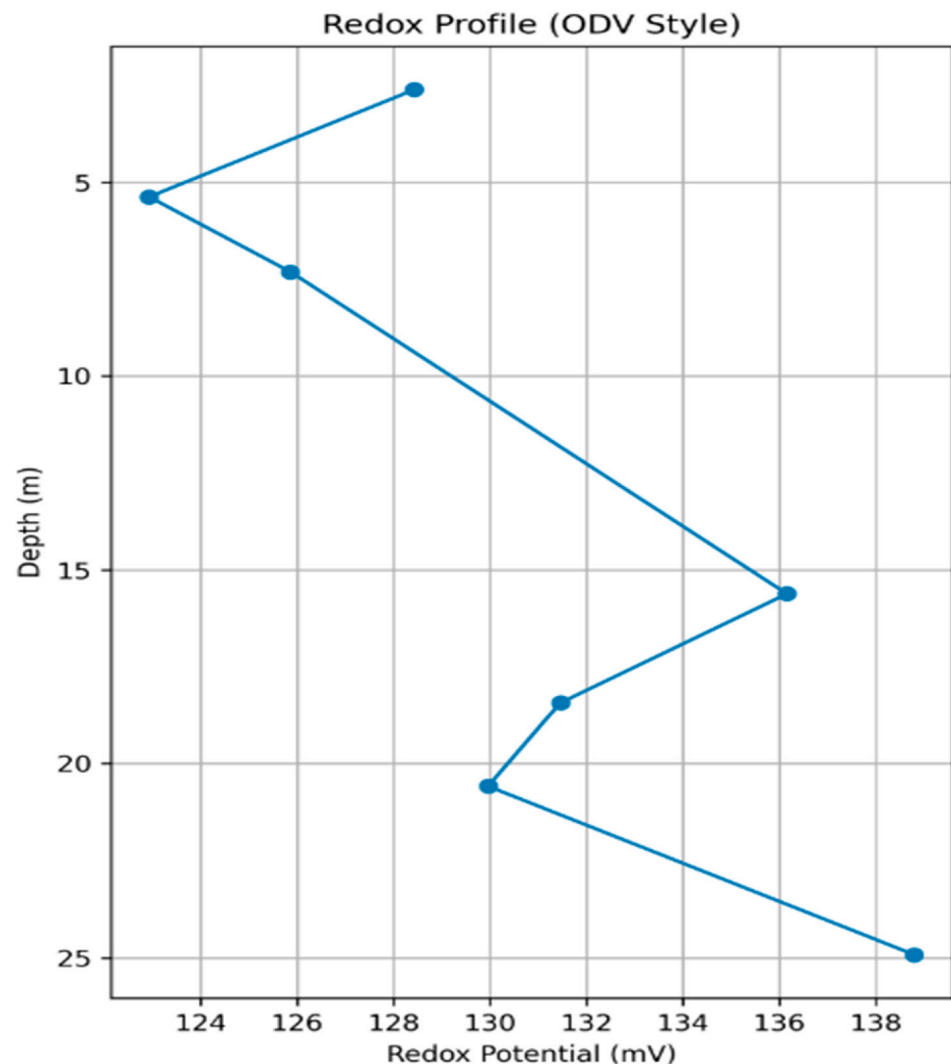


Figure 10. Redox Potential Profile recorded at the outer roadstead of Constanța Port (44°07'41" N, 28°53'15" E; 19 June 2024). Visualisation: Ocean Data View v5.6.

3.12. Sound Speed Profile (Ocean Data View)

The sound speed profile (Figure 12) is shown next to the SVP-measured profile for cross-validation as indicated in Section 2.2.2. The sound speed in seawater is primarily affected by temperature and secondarily by the effects of salinity and pressure [30]. The sound speed profile produced from the CTD data thus reflects the temperature structure indicated in Section 3.1, with maximum values on the warm surface layer and a strong decline across the thermocline corresponding to the temperature gradient of $0.70\text{ }^{\circ}\text{C m}^{-1}$ in the 7.31–15.62 m interval. The agreement between the SVP-measured and CTD-computed sound speed profiles within $\pm 0.3\text{ m s}^{-1}$ at all depths confirms the internal consistency of the thermohaline measurements and validates the CTD-derived density and stratification calculations used to underpin the physical analysis throughout this manuscript.

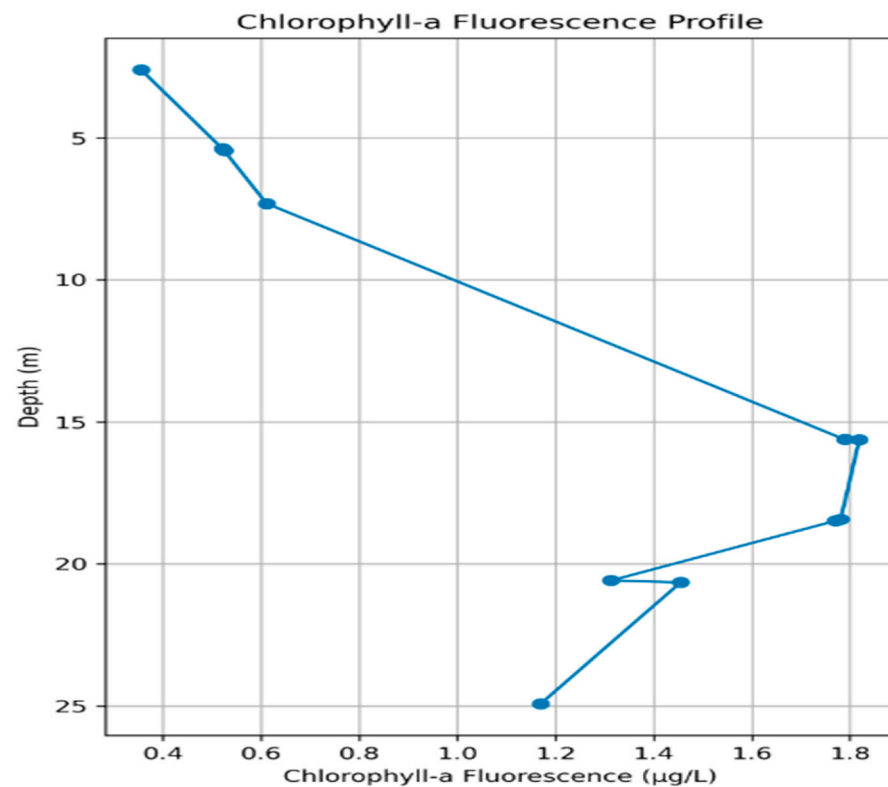


Figure 11. Chlorophyll-a Fluorescence Profile recorded at the outer roadstead of Constanța Port (44°07'41" N, 28°53'15" E; 19 June 2024). Visualisation: Ocean Data View v5.6.

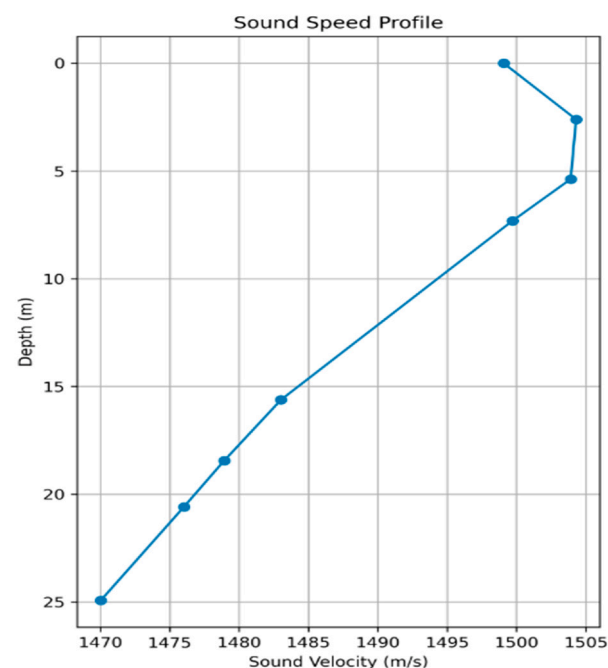


Figure 12. Sound Speed Profile recorded at the outer roadstead of Constanța Port (44°07'41" N, 28°53'15" E; 19 June 2024). Visualisation: Ocean Data View v5.6.

4. Discussion

The results obtained from high-resolution CTD profiling at the outer roadstead of the Port of Constanța reveal an exceptionally strong near-surface stratification regime during the second half of June 2024, driven by the combined effect of thermal and haline gradients under three compounding forcing mechanisms. The following discussion contextualises

these results within the broader Black Sea literature, assesses the internal consistency of the SCRI framework, and identifies the principal scientific novelty of this study.

4.1. Thermohaline Stratification and the Pollutant Transport Regime

The observed maximum $N^2 = 2.37 \times 10^{-3} \text{ s}^{-2}$ at the main pycnocline (7.31–15.62 m) falls within the upper range of summer stratification documented for the northwestern Black Sea shelf. In addition to the core thermohaline and oxygen parameters, the presentation of the full 9-parameter CTD dataset, including pH, redox potential, chlorophyll-a fluorescence and sound speed profiles, provides a more complete characterisation of the water column biogeochemical state than the partial datasets typically reported in single-station monitoring studies of this region. The mutual consistency of these parameters on the stratification boundaries derived from the density profile (Figure 6) supports the physical coherence of the five-layer interpretation, as pH, fluorescence and redox signals independently followed the same layer boundaries defined by the gradients of temperature, salinity and density. Comparison with published profiles from the same region—[12] report $N^2 \approx 10^{-3}$ – 10^{-2} s^{-2} for the open basin thermocline in summer, while [46] document N^2 values of 10^{-3} – $5 \times 10^{-3} \text{ s}^{-2}$ across the northwestern shelf—indicates that the observed stratification intensity at this station is consistent with but towards the lower end of reported summer maxima. The total column density contrast of $\Delta\rho = 4.02 \text{ kg m}^{-3}$ over 25 m compares well with shelf profiles reported by [41,45] for the northwestern shelf under strong Danubian influence, where comparable density contrasts are achieved over 20–30 m. These comparisons suggest that the observed stratification, while intense, is not anomalous for this region and season, and is broadly representative of stratified summer conditions on the Romanian shelf under Danubian freshwater forcing.

The most distinctive feature of this dataset relative to the published literature is the extremely shallow MLD of ~0.7–1.2 m. Standard summer climatologies for the western Black Sea shelf consistently report MLD values of 10–25 m [4,8] and even under calm conditions, MLDs shallower than 5 m are rarely reported in the open-shelf literature for this region. It is further noted that the MLD values reported here are threshold estimates rather than visually identified well-mixed layer depths, as the near-surface profiles exhibit continuous stratification rather than a distinct homogeneous layer with a sharp base. This is consistent with intense diurnal heating under calm conditions, which is known to produce a continuously stratified near-surface layer rather than a well-defined mixed layer [38]. The comparison with climatological MLD values of 10–25 m—which are also typically estimated by threshold criteria in the literature—remains valid, as both values use equivalent estimation methods. However, the physical interpretation differs: whereas a climatological summer MLD of 10–25 m may reflect a genuine well-mixed layer maintained by wind-driven turbulence over days to weeks, the threshold-estimated MLD of 0.7–1.2 m in this cast more likely reflects the depth at which the intense diurnal near-surface stratification first satisfies the threshold criterion, and may not correspond to a persistent well-mixed layer in the classical sense. Three non-exclusive mechanisms could explain this anomalously shallow MLD. First, the calm sea state (Beaufort ≤ 4) suppressed wind-driven mechanical mixing, which is the primary deepening mechanism for the summer mixed layer. Second, strong late-June solar insolation created intense near-surface buoyancy flux, generating a diurnal thermocline compressed into the uppermost metre—a phenomenon well-documented in tropical and subtropical shelves during calm periods [19,38] but less frequently reported for the Black Sea shelf specifically. Third, the very low surface salinity (16.73 PSU)—consistent with strong Danubian freshwater capping during the high-discharge June period—imposed a haline density gradient that further compressed the mixed layer by resisting wind-driven entrainment. An important alternative explanation

that cannot be excluded is that the shallow MLD reflects a transient diurnal heating signal rather than a persistent seasonal feature: a profile collected in the early afternoon under calm, cloudless conditions would capture the shallowest diurnal mixed layer, which may deepen substantially by night or under any wind event. Without repeat profiles spanning at minimum a full diurnal cycle, distinguishing between a persistent shallow MLD driven by Danubian freshwater capping and a transient diurnal heating signal is not possible from this single cast. The practical consequence for the pollution-dynamics interpretation is significant: the ~ 1 -order-of-magnitude concentration amplification implied by an MLD of <1.2 m relative to a climatological 10-m MLD is only ecologically meaningful if the shallow MLD persists over timescales comparable to the residence time of the pollutant of interest. For volatile hydrocarbons, residence hours may be sufficient; for heavy metals or microplastics, ecologically relevant residence times extend to days or weeks. If the shallow MLD is a transient diurnal feature that deepens to several metres by night, the time-averaged concentration amplification would be substantially reduced. This distinction cannot be resolved without repeat profiling and is identified as the most consequential temporal uncertainty in the dataset for pollution-dynamics applications. This ambiguity directly affects the pollution-dynamics interpretation: the ~ 1 -order-of-magnitude concentration amplification implied by an MLD of <1.2 m relative to a climatological 10-m MLD would only persist if the shallow MLD is sustained over ecologically relevant timescales, which remains unconfirmed. The implication for pollutant dynamics depends on which MLD criterion is adopted. Using the density threshold estimate $MLD_{\rho} \approx 1.1\text{--}1.2$ m—which is more physically appropriate for this haline-influenced coastal environment—the implied concentration amplification of surface-derived contaminants relative to a climatological 10-m mixed layer is approximately 8–9 times. Using the temperature threshold estimate $MLD_T \approx 0.65\text{--}0.70$ m, the amplification approaches an order of magnitude. Both estimates represent substantial concentration enhancement within the near-surface layer, but the more conservative density-threshold value is adopted as the primary estimate. This concentration amplification is a physically motivated inference from the threshold-estimated MLD and has not been confirmed by direct chemical measurement, as discussed in Section 4.6. The near factor-of-two discrepancy between MLD_T and MLD_{ρ} reflects the haline contribution to near-surface stratification from Danubian freshwater input, which causes density to depart from its surface reference value at a greater depth than temperature alone. This discrepancy illustrates the inadequacy of temperature-only MLD criteria in river-influenced coastal environments and underscores the need for density-based or hybrid criteria in future monitoring studies at this station. It also introduces an irreducible methodological uncertainty into the MLD estimate that cannot be resolved without direct turbulence measurements defining the base of the actively mixing layer.

A fourth mechanism that must be considered is direct port-proximity influence: warm water discharge from vessel cooling systems, ballast water exchange at the surface, and hydrocarbon surface films from fuel residues could all locally suppress evaporative cooling and wind-driven mixing in the immediate vicinity of anchored vessels, producing a shallower and more stable near-surface layer than would be observed at an equivalent open-shelf station. Given the station's position within the outer roadstead anchorage zone, this port-proximity thermal and chemical forcing cannot be excluded as a partial contributor to the anomalously shallow MLD and represents an additional source of uncertainty in extrapolating the MLD observation to open-shelf conditions.

The two-stage thermocline structure and the anomalously shallow CIW confinement at 12–16 m are consistent with the shelf-specific dynamics described by [11,18], who document CIW shoaling on the constrained Romanian shelf relative to the open basin (where CIW resides at 50–150 m). However, ref. [20] project that warming-driven weakening of

winter convection may reduce CIW formation rates and ultimately erode the CIW oxygen signature at intermediate depths. If this trajectory continues, the secondary stratification barrier provided by the CIW layer—clearly evident at this station—may weaken over decadal timescales, with consequences for the vertical oxygen architecture documented in Section 3.7. This represents a literature-grounded mechanistic hypothesis that the single profile cannot test but that future repeat surveys at this station could address.

4.2. The SCRI: Validation and Predictive Capability

The consistency of SCRI ($N^2/Kz \approx 2 \times 10^2$ – $2 \times 10^3 \text{ m}^{-2} \text{ s}^{-1}$, reflecting the order-of-magnitude uncertainty in the literature-based Kz estimate) with the observed hydrographic structure is assessed using three co-located indicators derived from the same CTD cast: a two-order-of-magnitude reduction in estimated diffusive flux, a five-layer DO structure, and a monotonically decreasing turbidity profile (1.64 FTU per 25 m). As these indicators are not independent of the N^2 and Kz values used to compute SCRI, this assessment reflects internal physical consistency only, and the term “validation” is explicitly withdrawn. Genuine validation of SCRI would require its application to an independent dataset from a different location or time period, with SCRI predictions compared against direct turbulence microstructure measurements or tracer-based diffusivity estimates. This is identified as a primary objective for future work. Notwithstanding this limitation, the coherence of optical, chemical, and physical structure across the same water column supports the physical plausibility of SCRI as a site-specific diagnostic index for stratification-controlled pollutant retention.

The relationship between SCRI and established oceanographic mixing parameters requires explicit clarification in light of the existing literature. The gradient Richardson number ($Ri = N^2/(\partial U/\partial z)^2$) is the physically complete, genuinely dimensionless standard for stratification-controlled mixing [32–34]. It could not be computed here due to the absence of velocity data, a recognised instrumentation limitation. The buoyancy Reynolds number ($Re_b = \varepsilon/(\nu N^2)$) and the [31] formulation ($Kz = \gamma\varepsilon/N^2$) both demonstrate that the ratio N^2/Kz is already implicit in established frameworks and is not physically novel. The vertical Peclet number ($Pe = wL/Kz$) is conceptually adjacent to SCRI but requires vertical velocity estimates unavailable from CTD data alone. SCRI does not replicate any of these parameters, nor does it introduce a new physical quantity. Its specific and limited contribution is operational: it makes the N^2/Kz ratio explicitly computable from CTD profiles alone and frames it as a pollution-oriented screening index for data-limited environmental monitoring contexts. This operational accessibility comes at the cost of physical completeness—SCRI omits shear, cannot resolve turbulence intensity, and carries order-of-magnitude uncertainty from its literature-based Kz assumption—and must be interpreted accordingly. A rough contextual check using bulk Ri estimates based on published current climatologies for this shelf sector yields $Ri_{\text{bulk}} \approx 4$ –16 (Section 2.2.3), well above the critical value of 0.25, suggesting dynamic stability of the pycnocline during the sampling period and lending qualitative support to the suppressed vertical exchange inferred from the hydrographic profiles.

The predictive scaling relationships derived from SCRI (Equations (25) and (26)) are physically motivated but should be interpreted with caution.

$$F \sim \frac{\frac{\partial C}{\partial z}}{SCRI} \quad (25)$$

$$T \sim SCRI \cdot \left(\frac{L^2}{N^2} \right) \quad (26)$$

Their derivation assumes that K_z is the sole control on vertical transport, which is an oversimplification: in shelf environments, episodic mixing events driven by storms, internal wave breaking, and near-inertial oscillations can generate K_z values orders of magnitude above the background stratified value on timescales of hours [19,33]. If such events occurred in the days surrounding the sampling period—which cannot be assessed from a single profile—the effective time-averaged K_z would be substantially higher than the background estimate, and the implied pollutant residence times would be correspondingly shorter. The relevant timescale for pollutant retention is therefore not the instantaneous stratification state captured by a single profile, but the time-averaged mixing environment integrated over the residence time of the pollutant of interest, which may range from hours (for petroleum hydrocarbons subject to volatilisation) to weeks (for heavy metals adsorbed onto fine particulate matter). This distinction is not currently made in the manuscript and represents a conceptual refinement necessary for any future application of the SCRI-based residence time estimate.

Comparison with analogous stratified shelf systems further contextualises the SCRI range obtained here. On the Baltic Sea shelf—a system with similarly strong haline stratification under riverine freshwater forcing—background K_z values of 10^{-6} – 10^{-5} $\text{m}^2 \text{s}^{-1}$ in the halocline have been directly measured by microstructure profiling [6], consistent with the literature range adopted here. On the Po-influenced Adriatic shelf, comparable N^2 values and similarly suppressed vertical diffusivities have been documented under summer. These analogues lend support to the order-of-magnitude plausibility of the K_z range used, without substituting for direct measurement.

A final consideration concerns the temporal robustness of the five-layer DO structure as a whole. Internal waves at the main pycnocline (buoyancy period $T_b \approx 2$ min) could vertically displace the layer boundaries by 1–3 m over the duration of a single CTD cast, meaning the precise layer boundaries reported here carry an inherent uncertainty of this order. Ship wakes from vessels manoeuvring in the outer roadstead could generate localised turbulent patches in the uppermost 5 m that would transiently erode Layers 1 and 2. The most temporally robust interpretation of the five-layer structure is therefore not the precise depth boundaries of individual layers, but the existence and ordering of the five distinct biogeochemical regimes—subsaturated, supersaturated, minimum, enrichment, and oxycline—which reflect forcing processes operating on timescales of weeks to months and are unlikely to be entirely artefactual. Even two or three repeat casts separated by 3–6 h would allow assessment of the stability of these boundaries and substantially strengthen the physical interpretation of this structure.

4.3. The Five-Layer Dissolved Oxygen Structure: Scientific Novelty

The five-layer DO structure documented at this station—subsaturated surface layer, deep oxygen maximum, biological oxygen minimum, CIW enrichment, and seasonal oxycline—is contextualised here against published oxygen profiles from the northwestern Black Sea shelf and alternative mechanistic explanations are evaluated.

The deep oxygen maximum at 2.6 m (110.3% SAT) is interpreted as a photosynthetic signal concentrated at the base of the extremely shallow mixed layer. This interpretation is consistent with published fluorescence-DO co-variations on the Black Sea [29,41] where subsurface chlorophyll maxima and associated oxygen supersaturation are commonly observed at the pycnocline base during stratified summer conditions. An alternative explanation—bubble injection from vessel propellers in the outer roadstead anchorage—cannot be entirely excluded, as mechanical aeration from ship traffic can produce localised oxygen anomalies [37]. However, the co-location of the DO maximum with the fluorescence peak at 2.6 m ($0.356 \mu\text{g/L}$) strongly favours the biological interpretation. It

is additionally noted that the deep oxygen maximum and the surface DO sub-saturation are both confined to the uppermost 3 m of the water column, precisely the depth range most susceptible to port-proximity artifacts. The possibility that vessel-induced mixing, aeration, or chemical interference partially modifies these signals at this specific station means that the full five-layer DO structure—while internally coherent and physically plausible—may not be fully reproducible at an equivalent open-shelf station free from port influence. Future campaigns should include a paired open-shelf reference station to assess the port-proximity contribution to near-surface DO structure. In the absence of simultaneous measurements of the primary production rate, the relative contributions of photosynthesis and mechanical aeration cannot be determined with precision.

The scientific novelty claims for the five-layer DO structure must be explicitly conditioned on the instrumental resolution assessment presented in Section 3.7. The two features that define the novelty of this structure—the deep oxygen maximum at 2.6 m (Layer 2) and the biological oxygen minimum at 5.4–7.3 m (Layer 3, thickness 1.9 m)—are the thinnest features in the profile and fall within the range of possible vertical smearing artefacts for this instrument class at typical descent speeds and DO sensor response times. The novelty claim is therefore contingent on confirmation that the actual descent speed and response time during this cast were sufficient to resolve features at the 1–2 m scale. This confirmation requires values from the deployment logbook and instrument specifications that must be reported in the final manuscript. Until confirmed, the five-layer structure should be presented as physically motivated and observationally consistent, rather than as an unambiguously resolved novel finding.

The biological oxygen minimum at 5.4–7.3 m (69.9–70.0% SAT) is interpreted as a consequence of organic matter remineralisation in a layer isolated beneath the thermocline from atmospheric re-oxygenation. This pattern is well-documented for the northwestern Black Sea shelf under eutrophic conditions following spring bloom sedimentation [41,46]. However, two alternative explanations merit consideration. First, the minimum could reflect horizontal advection of a low-oxygen water mass from a different upstream location rather than in-situ consumption—a possibility that cannot be excluded without concurrent current measurements or water mass tracer data. Second, the minimum is separated from the deep oxygen maximum above it by only ~3 m of water column, an unusually compressed vertical separation that may reflect the extremely shallow MLD at this station compressing all biogeochemical gradients into the uppermost few metres. If the MLD is a transient diurnal feature (as discussed in Section 4.1), the vertical compression of these oxygen layers may also be transient, which would affect the permanence of the pollutant retention mechanisms inferred from this structure.

The CIW oxygen enrichment at 7.3–15.6 m (90.2–101.8% SAT) is the most robust feature of the five-layer structure from a mechanistic standpoint, as it reflects the well-documented winter ventilation history of Black Sea CIW [11,12,42], and is independently supported by the concurrent temperature minimum (13.5 °C) at the same depth interval. This feature is unlikely to reflect a measurement artefact or alternative local process and represents the strongest evidence for a physically coherent five-layer structure rather than measurement noise.

The claim that this constitutes the first in situ documentation of the complete five-layer DO architecture on the northwestern Black Sea shelf within a 25-m water column is qualified by the inherent difficulty of proving a negative from the literature. While this specific combination of layers within a 25-m shallow shelf profile has not been identified in the reviewed literature, the possibility that equivalent profiles exist in unpublished monitoring datasets of the Romanian or Ukrainian Hydrometeorological Services cannot

be excluded. The observational novelty claim is therefore maintained as a claim about the peer-reviewed literature specifically and is moderated accordingly.

4.4. Conflict-Modulated Environmental Forcing

In this section, the Russian–Ukrainian conflict is considered as a contextual factor that can affect the environmental circumstances at the study site. It is important to note at the outset that none of the three mechanisms discussed below can be causally demonstrated from the current dataset. All are presented here as explicitly labelled hypotheses, motivated by the known geopolitical context and supported where possible by independent post-2022 sources, but impossible to verify from a single CTD cast without chemical measurements or pre-conflict baseline data.

- *Hypothesis 1—Enhanced Danubian freshwater and nutrient input.* The destruction of agricultural and hydraulic infrastructure in Ukraine since February 2022 has been identified as one of the causes of the increase in diffuse nutrient and sediment inputs into the Danube–Black Sea system [48]. This hypothesis is consistent with biogeochemical data obtained via satellite; thus, post-2022 satellite biogeochemical records consistent with increased nutrient and sediment inputs to the Danube–Black Sea system are documented in Copernicus Marine Service reanalysis products [24,43] and discussed in the context of conflict-related infrastructure destruction by [48]. However, the surface salinity at this site (16.73 PSU) is consistent with the climatological values for June at this location, as specifically noted in Section 3.1. Therefore, this single measurement cannot prove any salinity anomaly compared to pre-conflict conditions. The theory of increased Danube inflow is still possible, but it must be tested by systematically comparing post-2022 salinity and nutrient data with a multi-year baseline from the pre-conflict period at this location.
- *Hypothesis 2—Port disturbance from conflict-related traffic intensification.* The rerouting of grain exports from Ukraine via the EU’s “Solidarity Corridors” has led to a documented increase of approximately 30% in maritime traffic through the Port of Constanța [23]. This increase in traffic is physically realistic and consistent with the port-roadstead context, and has heightened the risks of oil contamination (bilge water discharges, ballast water exchanges, fuel combustion residues). However, the sub-saturation of dissolved oxygen at the surface (84.9–90.6% SAT) and high surface turbidity (3.075 FTU) observed at this station could be attributed to increased maritime traffic within the Solidarity Lanes and cannot be separated from background signals related to port operations that would have been present even without the conflict-related traffic increase. This hypothesis should be verified through direct chemical measurements of PAH concentrations and surface oil deposits, as well as the composition of turbidity. All of these have been designated as priorities for our future campaigns. The conflict-modulated contribution to these signals is, therefore, an inference based on the documented increase in traffic [23], rather than a direct measurement.
- *Hypothesis 3—Conflict-specific chemical contamination.* Contamination cases with hazardous materials associated with conflicts (UDMH, perchlorates, nitroaromatic compounds, heavy metals of military origin) have been documented along the north-eastern Black Sea coast [21]. The hydrographic characteristics observed at this station—shallow MLD, high SCRI range, strong pycnocline—are consistent with the physical conditions which would favour retention of such contaminants in the surface layer if present. This campaign however was based on CTD instrumentation only and did not contain any chemical analysis that may detect conflict specific chemicals. No contamination that could be related to the battle was measured, and none can be

inferred from the physical data alone. This theory is therefore essentially prospective; the present work describes the physical retention conditions that might be relevant should such contaminants be present but offers no proof that they are. Testing this theory will require specific chemical investigation for conflict-relevant chemicals in future campaigns.

The present dataset provides no direct evidence of conflict-related contamination. No measurements of hydrocarbons, explosives, perchlorates, UDMH degradation products, military-associated trace metals, or other conflict-specific contaminants were performed. Similarly, the measured surface salinity (16.73 PSU) falls within the climatological range reported for June on the northwestern Black Sea shelf and therefore cannot be interpreted as evidence of anomalous freshwater discharge. Elevated turbidity and sub-saturated dissolved oxygen in the near-surface layer are consistent with routine vessel activity in a busy anchorage zone and do not uniquely indicate conflict-related influences. Consequently, any connection between the observed hydrographic structure and the ongoing regional conflict remains speculative and cannot be evaluated using the present dataset.

4.5. Broader Implications and SCRI Transferability

The mechanisms observed at this measurement station are representative of a broader category of stratified continental shelf systems subject to complex anthropogenic pressures. Analogues include the Baltic Sea shelf, consistent with rivers; the Adriatic Sea shelf, consistent with the Po River; as well as areas with minimal oxygen concentrations potentially related to eutrophication on river-dominated continental shelves worldwide [14]. The Black Sea is unique in that its deep waters have had permanent anoxia for millennia and its narrow continental shelf blends fluvial and open oceanic forces. Oceanographic literature has reported Gulf War oil leaks and environmental monitoring during wartime [49,50]. Also, post-Yugoslav war environmental assessments have been done in the Adriatic Sea [51,52]. To the authors' knowledge, no hydrographic study has simultaneously characterised a permanent meromictic deep basin, a shallow river-dominated shelf, and ongoing active conflict that directly affects upstream freshwater and nutrient inputs through infrastructure destruction and maritime traffic diversion. This precise statement does not claim uniqueness, and the authors admit that impacted national agencies may have similar undisclosed monitoring data in the grey literature.

SCRI's potential use as a screening index in other stratified systems must be evaluated against four outstanding issues that impede regulatory recommendation. First, SCRI has only been studied at one station, not across seasons or sites. SCRI has dimensions of $[\text{m}^{-2} \text{s}^{-1}]$ and lacks the crucial threshold that effectively interprets dimensionless factors like R_i . Third, all SCRI calculations use literature-based order-of-magnitude estimations of K_z values with one to two orders of magnitude uncertainty in the absence of direct turbulence microstructure measurements. Fourth, the consistency assessment in Section 3.5 is internal to the CTD dataset used to compute SCRI and does not validate independently. For these reasons, the recommendation that SCRI be adopted as a standardized metric for cross-basin comparison under the Marine Strategy Framework Directive or Barcelona Convention protocols is withdrawn. SCRI is instead described as a physically motivated candidate index whose potential utility in data-limited monitoring contexts—where neither velocity nor microstructure measurements are available—may warrant future investigation, subject to the following minimum validation requirements before any regulatory application could be considered: (i) application to independent datasets from at least two or three additional stratified shelf systems with contrasting forcing conditions; (ii) comparison of SCRI predictions against direct turbulence microstructure measurements of K_z to assess the validity of the literature-based parameterization; (iii) concurrent computation of R_i

from ADCP velocity profiles to establish the relationship between SCRI and the physically complete stratification-mixing parameter; and (iv) demonstration of consistent behaviour of the empirically derived Table 1 thresholds across different environmental settings. Until these requirements are met, SCRI should be regarded as a research-stage diagnostic index and not referenced in regulatory or operational monitoring frameworks. Its application to Nordic fjords, estuarine systems, or other marginal seas could provide a standardised metric for cross-basin comparison of pollutant retention capacity, directly applicable under the Marine Strategy Framework Directive (MSFD) and the Barcelona Convention protocols relevant to the Black Sea region [47,53].

In addition to its implications for regulatory systems, this research provides information that can be directly applied to a potential southward spread of pollutants from the outer harbor of Constanța to the recreational area at Eforie Nord, located approximately 8.5 nautical miles south of the selected monitoring station. The southward flow component predominates in the coastal current regime of the Romanian Black Sea shelf during the summer, driven by the cyclonic edge current and local wind forces [41]. Under these conditions, pollutants present in the near-surface layer at the outer roadstead station—including both port-proximity contributions (hydrocarbons from ship operations, PAHs, bilge water residues) and any open-shelf background contaminants—could potentially be transported southward along the coast within the surface accumulation layer. No chemical measurements were made at this station to confirm the identity or concentration of such contaminants, and the pollution risk inference is therefore a physically motivated hypothesis requiring chemical confirmation before it can inform water quality management decisions. However, it must be acknowledged that the near-surface pollutant load at this station reflects port-roadstead conditions rather than open-shelf background levels, and the southward transport inference is therefore specific to the roadstead-influenced surface layer rather than the broader shelf. Whether pollutant concentrations remain ecologically significant over the ~8.5 nautical mile transport distance to Eforie Nord—accounting for dilution, degradation, and tidal dispersion—cannot be assessed from the current dataset and requires Lagrangian drift modelling initialised with both current data and chemical concentration measurements. The hydrographic conditions described in this study—a high SCRI ($\approx 10^2$), a shallow mean surface water depth (MLD), and a strong pycnocline that prevented vertical dilution—suggest that these transported pollutants would remain concentrated near the surface during their southward movement, affecting ecological exposure and tourism along the Romanian coast during the peak of the swimming season, July–August. This provides a direct, quantitative risk pathway from port-related anthropogenic forcing to recreational water quality, which is not specifically covered by current monitoring programmes. Future studies should combine the SCRI stratification index with Lagrangian particle-tracking models [54,55], initialized with current shear data obtained via CTD, to simulate pollutant trajectories from the Constanța harbor basin to Eforie Nord, Eforie Sud, Costinești, and other southern resorts, providing a solid physical basis for assessing risks related to bathing water quality and for early warning system for coastal authorities [56].

4.6. Study Limitations and Future Work

A fundamental limitation of this study is that all analyses are based on a single CTD/SVP profile collected at one station during a single sampling event in June 2024. Consequently, the observations provide a detailed characterization of hydrographic conditions at that location and time but do not allow assessment of temporal variability, interannual anomalies, or causal attribution of observed features. In particular, although conflict-related environmental pressures are discussed in the regional context, the present dataset cannot de-

termine whether the observed stratification differs from pre-conflict conditions or whether any component of the hydrographic structure is attributable to conflict-related processes. Establishing such relationships would require repeated observations and comparison with multi-year climatological or pre-2022 reference datasets.

The absence of chemical analyses constitutes a limitation of this study. No samples were collected, and no analyses were conducted for pollutants, nutrients, trace metals, hydrocarbons, the composition of suspended particulate matter, or conflict-specific compounds. All conclusions regarding pollution in this manuscript are inferences derived from physical indicators: turbidity as an indicator of suspended particulate matter (SPM), dissolved oxygen structure as an indicator of biogeochemical zoning, and density gradients as predictors of suppressed vertical transport. Although these physical indicators are scientifically valid and widely used in the oceanographic literature, they do not constitute direct evidence of contaminant retention. The hypothesis of contaminant retention advanced in this study therefore remains physically motivated but chemically unconfirmed. Future campaigns will need to include sampling of the water column for trace metals, hydrocarbons, nutrients, microplastics, and—given the geopolitical context—conflict-specific compounds, including UDMH, perchlorates, nitroaromatic compounds, and heavy metals of military origin, analyzed in relation to the physical stratification framework documented here.

Several important limitations of this study must be clearly acknowledged. All scientific conclusions—including the five-layer DO architecture, the SCRI validation, and the conflict-modulated forcing signals—are based on a single CTD profile collected at a single station on a single day (June 2024). This fundamentally limits the temporal and spatial representativeness of the results. No statistical inference about shelf-wide conditions can be drawn from this dataset. The findings should be interpreted as a site-specific, snapshot characterisation that may reflect broader seasonal and regional patterns—as supported by comparison with existing literature—but require multi-station, multi-season replication before generalised conclusions can be made. A primary instrumentation limitation of this study is the absence of current velocity measurements. Neither the MIDAS CTD+ nor the SVP instrument is capable of measuring horizontal currents, and no ADCP or current meter was deployed during the campaign. This absence prevented direct computation of the gradient Richardson number (Ri), which is the physically complete, established dimensionless parameter for quantifying stratification-controlled mixing. The SCRI was introduced precisely because Ri could not be computed; this should be understood as a consequence of an instrumentation constraint rather than a methodological choice. Future campaigns must include concurrent ADCP deployment to enable direct Ri computation and to provide the velocity shear data necessary for rigorous assessment of turbulence suppression and vertical mixing efficiency.

A further spatial limitation concerns the representativeness of the study station. The outer roadstead of the Port of Constanța is subject to port-proximity forcing—vessel operations, ballast water exchange, propeller resuspension, hydrocarbon surface films—that superimposes on the background shelf hydrographic signal. Signals confined to the uppermost 2–3 m of the water column (surface DO, near-surface turbidity, near-surface chemistry) carry an unquantified port-proximity component and should not be interpreted as representative of open Romanian continental shelf conditions [57]. Future campaigns should include at least one paired open-shelf reference station, positioned away from direct port influence, to allow systematic separation of port-proximity artifacts from shelf-representative hydrographic signals.

A fundamental temporal limitation of this study is the single-cast, single-occasion nature of the dataset. No repeat profiles were collected over tidal cycles, diurnal cycles, or under contrasting meteorological conditions. This prevents assessment of whether

the observed features—particularly the extremely shallow MLD ($\sim 0.7\text{--}1.2\text{ m}$), the precise depth boundaries of the five DO layers, and the fine structure of the uppermost 2–3 m—are persistent features or transient snapshots of a continuously evolving system. Internal waves at the main pycnocline (buoyancy period $T_b \approx 2\text{ min}$) can displace layer boundaries by metres on timescales shorter than a single CTD deployment; diurnal heating cycles can alter MLD by an order of magnitude between morning and afternoon under calm summer conditions; and ship wake turbulence in the outer roadstead can generate transient mixing events in the near-surface layer on timescales of minutes. The minimum repeat sampling required to assess temporal stability of the observed structure is: (i) repeat CTD casts at 3–6 h intervals over a full 24-h diurnal cycle to resolve MLD and near-surface DO variability; (ii) repeat profiling over at least one complete tidal cycle ($\sim 12.4\text{ h}$) to assess tidal modulation of layer boundaries; and (iii) profiling under at least two contrasting wind/sea state conditions to assess the role of mechanical mixing in modifying the stratification structure. Until such repeat observations are available, all quantitative conclusions based on specific layer depths or MLD values should be interpreted as snapshot estimates with unquantified temporal uncertainty. For the typical operating range of this class of instruments, the default vertical attenuation distance ranges from 0.1 to 2.5 m, which is comparable to the thickness of the thinnest reported DO layers (Layer 2, a single maximum depth of 2.6 m; Layer 3, thickness of 1.9 m at 5.4–7.3 m). The claim regarding the scientific novelty of the five-layer DO architecture depends directly on these values: if the actual attenuation distance approaches or exceeds 1–2 m, Layers 2 and 3 may be partially or entirely instrumental artifacts, rather than truly resolved biogeochemical features. Future campaigns will use CTDs at controlled slow-descent speeds ($\leq 0.1\text{ m s}^{-1}$) with verified short DO response times to maximize the vertical resolution of the fine-scale oxygen structure.

The K_z estimates are based on empirical parameterizations [7,24], without direct measurements of turbulence. Chemical measurements of specific pollutants [58] were not included, which prevents the direct quantification of contaminant concentrations. Our future studies should include multi-seasonal CTD campaigns, measurements with the Acoustic Doppler Current Profiler (ADCP) for direct estimation of turbulence, water and sediment sampling for specific chemical analyses, including heavy metals, hydrocarbons, and conflict-specific compounds; as well as coupling with high-resolution numerical models for spatial extrapolation and forecasting of pollutants based on SCRI.

There is a particularly urgent need to extend monitoring to Lagrangian drift experiments and numerical particle-tracking simulations that link the stratification field obtained through SCRI with the coastal current system. This method would allow for a direct quantitative assessment of the transport path of pollutants from the Constanța Port harbor southward to the recreational beaches in Eforie Nord and neighboring resorts, providing the scientific basis for evidence-based management of beach water quality during the peak tourist season.

In particular, the K_z values used throughout this study ($10^{-6}\text{--}10^{-5}\text{ m}^2\text{ s}^{-1}$) are order-of-magnitude estimates adopted from the literature [13,30] and are not derived from the present dataset, as no direct turbulence microstructure measurements were carried out during the campaign. In [31] formula ($K_z = \gamma\epsilon/N^2$), cited as a justification for these ranges, cannot be applied without measured dissipation rates ϵ , and its substitution into the SCRI formulation would yield $\text{SCRI} = N^4/(\gamma\epsilon)$, revealing a self-referential dependence on N^4 that further motivates direct ϵ measurement in future campaigns [59]. The resulting order-of-magnitude uncertainty in K_z propagates directly into SCRI, which spans $\sim 2 \times 10^2\text{--}2 \times 10^3\text{ m}^{-2}\text{ s}^{-1}$ rather than a single point estimate. While all values within this range fall within the strongly stratified regime and the qualitative conclusions remain robust, quantitative SCRI-based claims in this manuscript should be interpreted with this

uncertainty explicitly in mind. Genuine validation of SCRI requires: (i) direct microstructure profiling to constrain K_z independently of N^2 ; (ii) application of the SCRI framework to independent datasets from different locations or time periods; and (iii) comparison of SCRI predictions against tracer-based diffusivity estimates.

5. Conclusions

This study provides high-resolution CTD and SVP data collected at a single station in the outer area of the Port of Constanța (northwest Black Sea, $44^\circ 07' 41''$ N, $28^\circ 53' 15''$ E, depth ≈ 25 m; June 2024) and documents a strongly stratified water column with five layers at this specific location and time, under the combined effect of seasonal, Danubian, and conflict-amplified anthropogenic forcing. All conclusions are necessarily constrained to this single-station, single-profile dataset and should be regarded as a site-specific observational case study. The sampling site exhibits a five-layer dissolved oxygen (DO) profile, which is physically feasible and internally consistent with the stratification structure. The apparent oxygen maximum at depth, located at 2.6 m, and the biological oxygen minimum, with a thickness of 1.9 m, located between 5.4 and 7.3 m, fall within the range of vertical blurring artifacts specific to this class of instruments, at average descent rates and given the response times of the DO sensor. The results obtained confirm the five-layer structure, which is a physically determined observational finding and supports the combined seasonal, Danubian, and port-proximity forcing at this station.

Extreme surface stratification and the isolation of pollutants are characterized by the depth of the mixed layer, which is extremely shallow (~ 0.7 – 1.2 m), with the main N^2 pycnocline reaching $2.37 \times 10^{-3} \text{ s}^{-2}$ at 7.31–15.62 m, and the total density difference of the column being $\Delta\rho = 4.02 \text{ kg m}^{-3}$. These values place the system among the most strongly stratified summer continental shelf environments described in the scientific literature on the Black Sea, with surface-derived pollutants concentrated in an extremely thin accumulation layer (<1.2 m).

Under analysed stratification conditions, the vertical diffusivity of turbulence decreases to $K_z \approx 10^{-6}$ – $10^{-5} \text{ m}^2 \text{ s}^{-1}$, which reduces the vertical flux of pollutants by approximately 100 times compared to unstratified conditions. Pollutants originating from the surface accumulate in the water column, which functions as a vertically compartmentalized system, thereby preventing pollution from reaching deeper layers.

The CIW layer is shallow (7.3–15.6 m depth) because of the constrained 25-m shelf shape, although the CIW layer's typical deep-basin depth is 50–150 m. The oxygen-enriched winter ventilation signal (DO = 90.2–101.8% SAT) is carried straight above the biological oxygen minimum by this shelf-specific CIW setup, which serves as a secondary stratification barrier [5].

This study, through the obtained results, constitutes the first in situ documentation of the complete five-layer DO architecture on the northwestern continental shelf of the Black Sea in a 25 m water column by simultaneously documenting in situ the following parameters: (1) roadstead-perturbed sub-saturated surface layer, (2) deep oxygen maximum at 2.6 m, (3) biological oxygen minimum at 5.4–7.3 m, (4) CIW oxygen enrichment at 7.3–15.6 m and (5) seasonal oxycline at 15.6–24.9 m.

The dissolved oxygen profile resolved five vertically distinct oxygenation zones within a 25 m water column: (i) a sub-saturated surface layer, (ii) a deep oxygen maximum, (iii) a biological oxygen minimum, (iv) oxygen enrichment associated with the Cold Intermediate Water (CIW), and (v) a seasonal oxycline extending toward the seabed. Each of these features has been documented individually in previous studies of the northwestern Black Sea shelf. However, to our knowledge, relatively few studies have reported the simultaneous high-resolution in-situ resolution of all five structures within a single profile collected

in a shallow shelf environment adjacent to the Port of Constanța. The present dataset therefore contributes a detailed site-specific description of the vertical oxygen architecture observed during the June 2024 sampling event, rather than establishing a universally novel oxygenation framework for the region.

It is explicitly noted that the study station is located in the outer roadstead of the Port of Constanța, not on the open continental shelf, and that near-surface signals—particularly surface DO sub-saturation, near-surface turbidity, and the deep oxygen maximum—carry an unquantified port-proximity component from vessel operations in the anchorage zone. It is further noted that the entire dataset derives from a single CTD cast on a single occasion, and that no repeat profiles were collected to assess the temporal stability of the observed structure. Features confined to the uppermost 2–3 m of the water column—including the surface DO sub-saturation, the deep oxygen maximum, and the extremely shallow MLD—are susceptible to modulation by diurnal heating, internal waves, and ship wake turbulence on timescales of minutes to hours, and their precise values should be regarded as snapshot estimates rather than persistent characteristics. The thermohaline stratification framework, density gradients, and CIW oxygen enrichment are considered temporally robust on the timescale of the measurement, as they reflect seasonal and inter-annual forcing. Repeat profiling over full diurnal and tidal cycles is identified as the minimum observational requirement for confirming the temporal persistence of the reported structure. A key limitation that must be clearly emphasized is that this study does not present any chemical measurements regarding the composition of any pollutants, nutrients, trace metals, hydrocarbons, or suspended particles. The hypothesis regarding contaminant retention is supported by physical inferences based on data regarding turbidity, dissolved oxygen, and density indicators, but remains unconfirmed from a chemical standpoint. Direct chemical sampling in future campaigns, designed around the physical stratification framework presented here, is the next necessary step toward a comprehensive testing of the contaminant retention hypothesis. The thermohaline stratification structure, density gradients, buoyancy frequency profile, and CIW oxygen enrichment are considered shelf-influenced and not materially affected by port-proximity processes. All conclusions relating to near-surface chemistry and biology should be interpreted within the roadstead context and should not be extrapolated to represent open-shelf conditions without paired reference station data. The two scientific contributions of this study are the observational documentation of the complete, five-layer architecture of dissolved oxygen within a single 25-m CTD profile on the shallow continental shelf, as well as the introduction of the SCRI as a pollution-oriented screening index that can be calculated using CTD data. The formal validation of the SCRI against independent measurements of turbulence microstructure, as well as the simultaneous calculation of Ri based on velocity profiles obtained via ADCP, remains the main objective of the future work. SCRI does not introduce a physically new quantity—the ratio (N^2/Kz) is implicit in the Osborn (1980) formulation and related to the buoyancy Reynolds number and vertical Peclet number—but operationalises it as an explicitly CTD-computable, pollution-oriented screening index for data-limited environmental monitoring contexts where the physically more complete parameters Ri , Re_b , and Pe cannot be computed.

SCRI values spanning approximately 2×10^2 – $2 \times 10^3 \text{ m}^{-2} \text{ s}^{-1}$ —with the one-order-of-magnitude uncertainty reflecting the literature-based Kz estimate in the absence of direct turbulence measurements—are internally consistent with the co-located turbidity distribution, five-layer DO structure, and estimated flux attenuation derived from the same CTD cast. Across the full uncertainty range, SCRI falls within the strongly stratified regime, and the qualitative conclusion of strong stratification-controlled suppression of vertical transport is robust. Quantitative SCRI-based claims should be interpreted accordingly, and

formal validation against direct microstructure measurements is identified as a priority for future work. It is explicitly noted that SCRI is inferior in physical rigour to the gradient Richardson number, which could not be computed due to the absence of current velocity measurements in this campaign; the bulk Ri estimates derived from published current climatologies ($Ri_{bulk} \approx 4\text{--}16$) are qualitatively consistent with the dynamic stability inferred from the hydrographic profiles and with the suppressed vertical exchange indicated by the SCRI range. Global warming is expected to enhance the thermal stratification of the higher layers, resulting in a concomitant rise in the N^2 buoyancy frequency and the SCRI. The SCRI prediction framework indicates that warming enhances the stratification barriers that limit dilution in the western area of the Black Sea basin, leading to a reduction in the vertical flux of contaminants and an increase in the residence period of pollutants in surface waters.

It is explicitly noted that the conflict-related forcing mechanisms discussed in Section 4.4 are presented as contextual hypotheses and not as causally demonstrated findings from the present dataset. The observed hydrographic signals—surface salinity, DO sub-saturation, near-surface turbidity—are all consistent with normal seasonal and port-operational variability and cannot be unambiguously attributed to conflict-related forcing without pre-conflict baseline comparisons and direct chemical measurements. The outer roadstead of Constanța Port and the adjacent northwestern Black Sea shelf are subject to compound seasonal, climatic, and anthropogenic pressures—including the potential modulating influence of the ongoing geopolitical situation—that together motivate intensive and integrated physical, chemical, and biological monitoring extending well beyond the single-station, single-cast observations presented here.

Prior to cross-site validation against independent turbulence data and concurrent calculation of Ri, SCRI may not be applicable to stratified continental shelf systems such as the Baltic Sea, Adriatic Sea and northern fjords. Thus, the application of SCRI regulations under the Marine Strategy Framework Directive or the Barcelona Convention protocols is premature. Future campaigns should include vertical sampling to depths of over 50 m, direct measurements of turbulence, and specific chemical analyses of substances relevant to the conflict (UDMH, perchlorates, nitroaromatic compounds, and heavy metals of military origin).

Based on this study's hydrographic framework, which includes a shallow threshold-estimated near-surface layer depth ($MLD_Q \approx 1.1\text{--}1.2$ m by the density criterion, adopted as the primary estimate for this haline-influenced coastal environment; $MLD_T \approx 0.65\text{--}0.70$ m by the temperature criterion retained as a secondary estimate). The density threshold criterion is preferred over the temperature criterion in this setting as it integrates both thermal and haline contributions to stratification. The implied concentration amplification of surface-derived contaminants relative to a climatological 10-m mixed layer is approximately 8–9 times using the primary density-threshold MLD estimate, reduced from the order-of-magnitude implied by the temperature threshold alone. Also, the study includes high SCRI ($\approx 10^2 \text{ m}^{-2} \text{ s}^{-1}$), and southward-directed coastal advection during the summer RIM Current regime, port-roadstead pollutants were found to disperse southward towards the recreational coastline of Eforie Nord, 8.50 nautical miles south of the CTD measured station. Pollutants accumulated in the surface layer (hydrocarbons, suspended particles, potential conflict-related contaminants) could be transported along the coast over a period ranging from a few hours to several days, remaining concentrated near the surface throughout the transport process due to vertical suppression potentially related to the pycnocline ($K_z \approx 10^{-6}\text{--}10^{-5} \text{ m}^2 \text{ s}^{-1}$).

This could have been a direct and concrete way to assess the risks, from port operations to bathing water quality during the peak tourist season in July and August. Integrating the

SCRI model with Lagrangian particle tracking models is proposed as a priority for future projects, with a view to providing the scientific basis for early warning systems regarding bathing water quality along the Romanian Black Sea coast.

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Abbreviations

The following abbreviations are used in this manuscript:

ADCP	Acoustic Doppler Current Profiler
Chl-a	Chlorophyll-a fluorescence
CTD	Conductivity–Temperature–Depth
DO	Dissolved oxygen
Eh	Redox potential (mV)
MLD	Mixed Layer Depth
SCRI	Stratification-Controlled Retention Index
SVP	Sound Velocity Profiler (used for CTD cross-validation)
SPM	Suspended Particulate Matter
UNESCO	United Nations Educational, Scientific and Cultural Organization
PAH	Polycyclic aromatic hydrocarbons
UDMH	Unsymmetrical Dimethylhydrazine
MSFD	Marine Strategy Framework Directive

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