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Research Article

Spatiotemporal Assessment of Physicochemical Properties and Anthropogenic Impacts on Seawater Quality in the Gulf of Durrës, Albania

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Abstract

The coastal zone of Durrës, Albania, represents one of the most anthropogenically influenced marine areas along the eastern Adriatic Sea, where intensive tourism, industrial activities, and agricultural runoff exert increasing pressure on coastal ecosystems. This study presents a year-long assessment of seawater quality based on physicochemical parameters measured across seven sampling stations in the Gulf of Durrës from January to December 2024. In situ analyses were conducted using a Horiba "U-50" multiparameter analyzer to evaluate temperature, pH, oxidation–reduction potential (ORP), conductivity, turbidity, dissolved oxygen (DO), total dissolved solids (TDS), salinity, and specific gravity. Overall, the recorded parameters indicated stable water quality within acceptable ecological limits, with limited spatial and temporal variation among most sites. However, localized deviations in ORP and turbidity were observed near the Pista Koka, Fishing Port, and Old Port stations during the summer months, corresponding to periods of intensified human activity and wastewater discharge. These findings emphasize the influence of seasonal anthropogenic inputs on nearshore water quality and underscore the need for continuous monitoring and targeted management strategies to mitigate human-induced degradation and ensure sustainable marine and tourism development in the Durrës coastal region.

Keywords: Seawater; Physicochemical Parameters; Durres Bay; Pollution.

INTRODUCTION

Albania possesses an extensive coastline along the Adriatic and Ionian Seas, forming an integral part of the Mediterranean basin. Owing to its strategic geographic position and open access to the Mediterranean Sea, the country has long held significant geopolitical and economic importance [1]. The city of Durres, located on the central Albanian coast at latitude 41.32355° N and longitude 19.45469° E, is the second-largest urban center in Albania. According to the 2023 national census, Durres has a resident population of approximately 153,614 inhabitants [2]. The region is characterized by a hot-summer Mediterranean climate, with a mean annual temperature of 16.9 °C and annual precipitation ranging between 1,000 and 1,273 mm [3]. The coastline of Durres extends from the "Ishëm" River estuary in the north to the "Agai" stream in the south, covering roughly 61.8 km. This stretch of coast is predominantly flat and accumulative, formed largely by sandy deposits transported by the "Ishëm" and "Erzen" rivers. The solid load transported by these rivers is estimated at 3.2 million tons per year for the Erzen River and 2.2 million tons per year for the "Ishëm" River [4], both of which are considered among the most polluted watercourses in Albania [1]. The Port of "Durrës" is the country's largest maritime gateway, functioning as a critical hub for both commercial transport and tourism [5]. In 2023 alone, the port handled approximately 827,852 passengers and 3,572,453 tons of cargo [6]. It maintains regular maritime connections with several Mediterranean and Balkan destinations, notably the Italian ports of Bari, Brindisi, and Ancona. However, recent population growth and intensified maritime traffic have contributed to escalating marine pollution, primarily driven by anthropogenic pressures on the coastal and marine environment [7]. The principal sources of marine contamination include land-based discharges such as untreated or insufficiently treated wastewater, agricultural runoff, and industrial effluents. Sewage discharge remains a critical environmental concern, particularly in densely populated coastal areas. Although "Durrës" is equipped with a wastewater treatment facility, not all residential and industrial wastewater is connected to the treatment network. Additionally, sea-based activities—including maritime transport, fishing, and oil refining further exacerbate pollution levels. Elevated concentrations of *Escherichia coli* have been detected at specific monitoring stations during the summer months, reflecting seasonal declines in water quality [8]. Nonetheless, gradual improvements have been recorded in recent years; 41.6% of monitored bathing waters are currently classified as "excellent" according to national and EU Bathing Water Directive criteria [9]. Despite this progress, maintaining coastal water quality within permissible ecological limits remains a continuing challenge. The study evaluates seawater physicochemical parameters in the Gulf of "Durrës", from Cape "Currila" to "Zabeli".

METHOD AND EXPERIMENTS

Seven sampling stations (Table1) were established along the Durrës Gulf: Ferrara Hotel, Currila (UAMD), Pista Koka, Fishing Port, Old Port, Pista Kupola, and Pista Teuta.

Table 1. The geographical positions of the sampling stations

No. of station	Name of the sampling station	Latitude	Longitude
1	Hotel Ferrara	41°19,08′N	19°25,50′ E
2	UAMD- Currila	41°18,46′N	10°25,57′E
3	Pista Koka	41°18,31′N	19°26,20′E
4	Porti i Peshkimit	41°18,50′N	19°26,20′E
5	Porti i vjeter	41°18,20′ N	19°27,07′E
6	Pista Kupola	41°17,59′N	19°29,29′E
7	Pista Teuta	41°18,20′N	19°29,18′E

Measurements were taken monthly between January and December 2024 at depths ranging from 0.5–1.0 m, between 09:00–13:00. Each site is influenced by varying degrees of urban runoff, port activities, and tourism infrastructure. A Horiba "U-50" multiparameter sonde—supplied through the Erasmus+ CBHE project Maritime Environmental Protection and Management (MEP&M) was used for in-situ measurements. Parameters included water temperature (°C), pH, oxidation-reduction potential (mV), electrical conductivity (mS/cm), turbidity (NTU), dissolved oxygen (mg/L), total dissolved solids (g/L), salinity (ppt), and specific gravity (σ_t). Prior to each campaign, the probe was calibrated according to manufacturer protocols. Data were logged automatically and verified through field duplicates. Statistical analysis was performed using the DataTab software package.

RESULTS AND DISCUSSION

The indicators analyzed during the monitoring period from January to December 2024 were statistically processed, and the computed results are presented in Table 2.

Table 2. Statistical analysis data

Parameters	Mean	SD	CV %	Range	Distribution	Interpretation
Temperature (°C)	20.84	4.76	22	13.04–28.48	Near normal	Moderate seasonal variation; typical for coastal Adriatic waters
pH	8.03	0.48	6	7.03–9.62	Normal	Within seawater norms (7.5–8.5)
ORP (mV)	178.91	56.85	31	69–441	Right-skewed	Moderate variability; anthropogenic impact evident
EC (mS/cm)	52.46	5.39	10	26.4–59.2	Slightly skewed	Stable ionic concentration
Turbidity (NTU)	37.08	15.61	42	13.2–92.2	Right-skewed	Highly variable; episodic discharges or riverine input
DO (mg/L)	7.36	0.81	21	6.04–8.91	Normal	Suitable for marine life (> 5 mg/L)
TDS (g/L)	31.34	3.49	11	14.6–35.5	Slightly skewed	Consistent with EC and salinity
Salinity (ppt)	34.38	3.84	11	15.9–39.1	Slightly skewed	Normal marine salinity (30–39 ppt)
SG (σt)	24.00	3.22	13	10.7–29.3	Slightly skewed	Density follows salinity pattern
Depth (m)	0.62	0.13	21	0.45–1.00	Normal	Consistent shallow sampling

Data obtained from seven monitoring stations exhibited a variability range between 6% and 42%, with the highest deviations observed in turbidity (42%) and oxidation–reduction potential (ORP) (31%). Excluding electrical conductivity, total dissolved solids (TDS), and salinity, the kurtosis and skewness values of the measured parameters remained within acceptable statistical thresholds, suggesting a generally normal distribution pattern. Nevertheless, two to three data points related to ORP, electrical conductivity, TDS, salinity, and specific gravity showed deviations from normality. These anomalies are likely associated with localized anthropogenic influences, such as intermittent wastewater discharges and seasonal variations in coastal activity. Overall, only 3.5% of the 84 recorded measurements deviated significantly from the mean, indicating a high level of internal consistency and reliability within the dataset

Water Temperature

Temperature is a critical parameter affecting dissolved oxygen solubility and aquatic metabolism [10–12]. Recorded values ranged between 13.04 °C (January) and 28.48 °C (July), with a mean of 20.84 °C. Seasonal averages were 14.08 °C (winter), 21.59 °C (spring), 26.48 °C (summer), and 21.20 °C (autumn), see Figure 1. A one-sample t-test was conducted to determine whether the mean temperature of the sample differed significantly from the reference value of 19.7 °C. The analysis revealed a statistically significant difference, $t(83) = 2.18$, $p = 0.032$. The sample mean temperature (M = 20.84 °C) was higher than the test value, with a mean difference of 1.14 °C (95% CI = 0.10 to 2.18). Since the confidence interval does not include zero and the p-value is below the 0.05 threshold, it can be concluded that the observed mean temperature is significantly higher than 19.7 ° [13] which is the several annual mean of the temperatures in the Durres coast results follow typical Adriatic seasonal patterns [14].

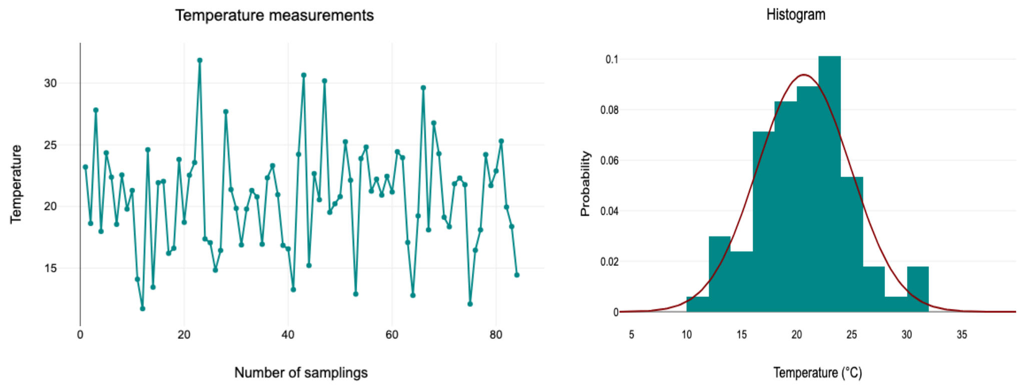

Figure 1. The variation of temperature

pH

pH is a key indicator of the chemical status of aquatic systems, as it directly influences both chemical equilibria and biological processes in seawater [15]. Approximately half of the carbon dioxide (CO_2) emitted by human activities is absorbed by the oceans, thereby mitigating global warming. However, this uptake also decreases seawater pH, leading to progressive ocean acidification. According to the European Environment Agency, the mean pH of surface seawater has declined from 8.11 in 1985 to 8.01 in 2021. This acidification reduces the availability of carbonate ions, which are essential for calcifying organisms such as corals, molluscs, and certain plankton species to build their shells and skeletons. The adverse effects of acidification are further intensified by declining dissolved oxygen concentrations, resulting in water deoxygenation [16]. In the present study, measured pH values ranged from 7.03 to 9.62, with an average of 8.03 ± 0.48. Only minimal seasonal variability was observed, and values generally remained within the optimal range

(7.5–8.5) for marine ecosystems [17–19]. Slight decreases recorded during autumn coincided with increased organic inputs and lower oxygenation levels. As illustrated in Figure 2, pH values showed limited temporal variation throughout the year, with an overall fluctuation of approximately 6%. The results confirm that pH levels (Figure 2) in the Gulf of Durrës remained within the expected range for coastal seawater, reflecting stable buffering capacity and typical regional conditions [17–20]

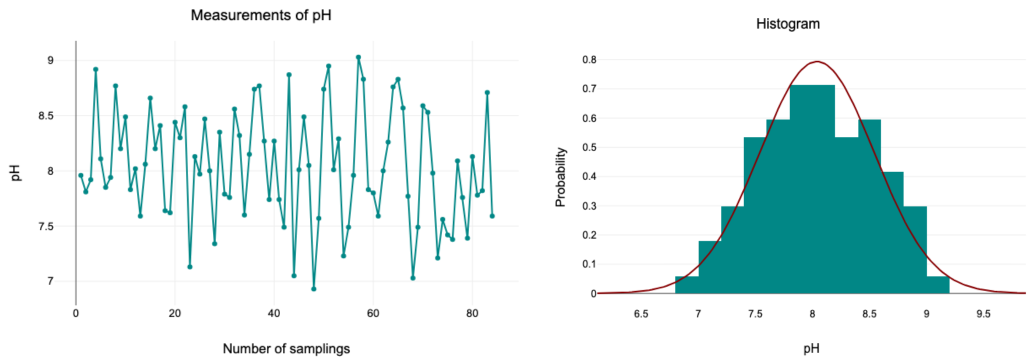

Figure 2. The variation of pH

Oxidation Reduction Potential (ORP)

Oxidation–reduction potential (ORP) is a key parameter for evaluating the oxidizing or reducing capacity of aquatic systems. It reflects the presence and balance of oxidizing and reducing agents, such as oxygen, chlorine, and hydrogen sulphide, which strongly influence water quality and ecological health. ORP serves as an important indicator of pollution and is widely used to assess the effects of anthropogenic activities, including pollution and climate change, on marine ecosystems. In surface waters, ORP represents the ability of water to degrade organic and inorganic contaminants, thereby supporting essential biological processes. Elevated ORP values generally indicate the presence of oxidizing agents such as dissolved oxygen, which sustain aerobic respiration and inhibit the proliferation of anaerobic bacteria. The ideal reference value for healthy marine waters is approximately 250 mV [11, 21]. A one-sample *t*-test revealed a statistically significant difference between the measured data and the reference mean of 250 mV, $t(83) = -11.24$, $p < 0.001$. This result confirms that the mean ORP value (178.91 mV) is significantly lower than the standard reference, suggesting moderately reduced redox conditions in the studied area. Low ORP values (< 50 mV) typically indicate environments prone to organic matter accumulation, reduced oxygen availability, and the formation of toxic substances [19]. This underscores the importance of monitoring ORP near the seabed, where organic deposits can substantially decrease redox potential [22]. As illustrated in Figure 3, the ORP dataset exhibited a coefficient of variation (CV%) of 31%, indicating moderate variability among sampling sites and observation periods. The overall mean ORP was 178.91 mV. The highest ORP readings were recorded at the Kupola station in November, whereas the lowest were observed at the Aleksandër Moisiu University (UAMD) station in August.

Seasonal averages revealed ORP values of 174.76 mV in spring, 172.04 mV in summer, 161.46 mV in autumn, and 212.61 mV in winter. These fluctuations fall within the expected range for surface marine waters and reflect the influence of environmental and climatic factors such as temperature, biological activity, and oxygen availability on redox dynamics.

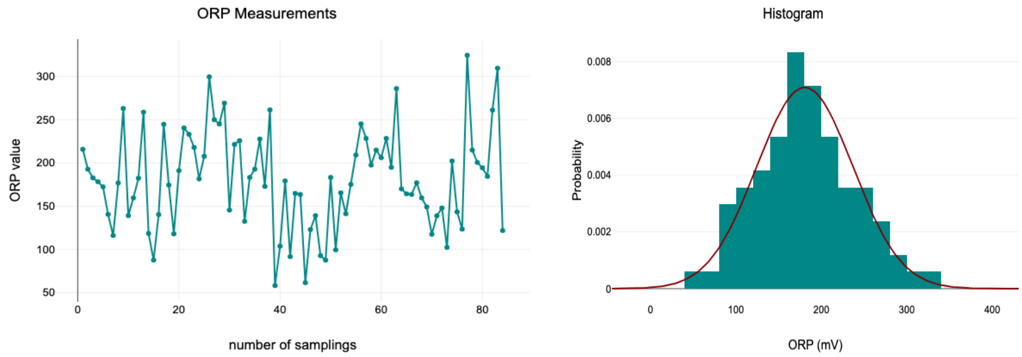

Figure 3. ORP values variation

Electrical Conductivity

Electrical conductivity (EC) in seawater is primarily controlled by temperature, salinity, and the concentration of dissolved ions [23]. Elevated EC values generally indicate higher levels of dissolved salts, minerals, and other ionic constituents, which in turn influence key physicochemical parameters such as alkalinity, hardness, and total dissolved solids [11]. Fluctuations in EC are typically associated with rainfall intensity, temperature variation, and anthropogenic inputs from municipal wastewater, agricultural runoff, and industrial effluents. Consequently, high EC values can be indicative of diminished water quality resulting from increased concentrations of inorganic salts and impurities [19]. In the present study, EC values exhibited a coefficient of variation (CV%) of 10%, suggesting low variability and stable ionic conditions across all monitoring stations. The overall mean EC was 52.46 mS/cm. The highest measurement (59.39 mS/cm) was recorded at the Ferrara station in December, whereas the lowest (45.89 mS/cm) was observed at the Aleksandër Moisiu University (UAMD) station in February. Seasonal averages ranged narrowly from 52.1 to 53.0 mS/cm, confirming that electrical conductivity remained relatively stable throughout the monitoring period, with only minor variations attributable to natural hydrological dynamics and seasonal temperature changes. Figure 4 depict electrical conductivity measurements.

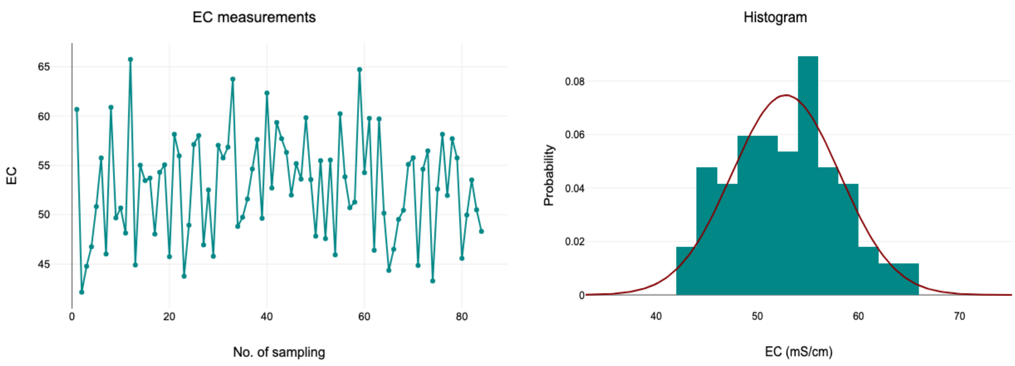

Figure 4. EC measurements

A Pearson correlation analysis was conducted to examine the relationships among the selected physicochemical parameters of seawater: electrical conductivity (EC), pH, turbidity, dissolved oxygen (DO), and salinity. The correlation coefficients (r) are presented in Table 3.

Table 3. Correlation

	pH	**EC (mS/cm)**	**Turbidity (NTU)**	**DO (mg/L)**	**Salinity (ppt)**
pH	1	-0.054	0.0723	-0.2064	-0.0441
EC (mS/cm)	-0.054	1	-0.0667	-0.0661	-0.1202
Turbidity (NTU)	0.0723	-0.0667	1	-0.0547	0.0277
DO (mg/L)	-0.2064	-0.0661	-0.0547	1	-0.0588
Salinity (ppt)	-0.0441	-0.1202	0.0277	-0.0588	1

The correlation coefficients indicate generally weak linear relationships among the measured parameters. pH showed weak and negative correlations with EC (r = −0.054), DO (r = −0.206), and salinity (r = −0.044), suggesting that variations in pH are largely independent of these parameters. The relationship between pH and turbidity was weakly positive (r = 0.072), implying a slight tendency for higher turbidity to coincide with marginally higher pH levels. Electrical conductivity exhibited small negative correlations with turbidity (r = −0.067), DO (r = −0.066), and salinity (r = −0.120), reflecting a lack of significant linear association among these variables. Similarly, turbidity and DO (r = −0.055) as well as turbidity and salinity (r = 0.028) showed negligible correlations, indicating independent behavior. The modest negative correlation between DO and salinity (r = −0.059) aligns with the known tendency of oxygen solubility to decrease slightly as salinity increases, though this association was statistically weak.

Overall, the absence of strong correlations (|r| < 0.3) suggests that these physicochemical parameters vary largely independently within the monitored coastal environment, with no parameter exerting a dominant linear influence on another.

Total dissolved solids

Total Dissolved Solids (TDS) represent the sum of all dissolved inorganic and organic substances in water, including major ions and organic matter. These parameters are closely associated with turbidity, electrical conductivity, and total suspended solids. Elevated TDS concentrations were observed at sites with higher salinity levels, which in turn influenced turbidity, reduced dissolved oxygen (DO) concentrations, and facilitated the binding of solids with heavy metals or other toxic substances [24]. The TDS measurements exhibited a low degree of variability, as indicated by a coefficient of variation (CV) of 11%**.** The highest TDS value (35 g/L) was recorded at the Ferrara station in November, whereas the lowest value occurred at the Aleksandër Moisiu University (UAMD) station in February. Seasonal mean TDS values across all monitoring stations showed only minor fluctuations, ranging narrowly between 31.2 g/L and 31.5 g/L, supporting the overall consistency of TDS concentrations throughout the monitoring period, see Figure 5.

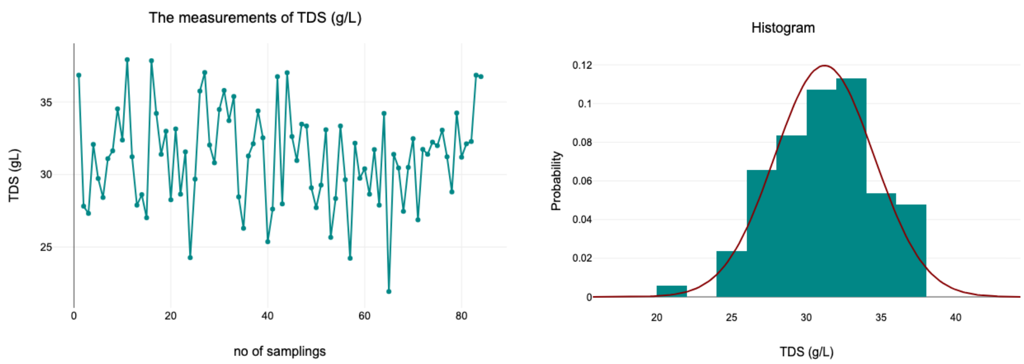

Figure 5. TDS variation

Dissolved Oxygen

Dissolved oxygen (DO) is a key indicator of marine water quality and plays a vital role in sustaining aquatic life [16, 18, 22, 24]. It is essential for most chemical and biological processes occurring in seawater. DO concentrations are primarily influenced by temperature and salinity [24] A concentration above 5 mg/L is generally required to support most marine organisms, with many species depending on even higher levels [18] Conversely, low DO concentrations often result from organic pollution, such as nutrient loading and sewage discharge [22] or from elevated water temperatures that reduce oxygen solubility [24]. An analysis of the data presented in Table 2 indicates that DO concentrations exhibited a coefficient of variation (CV) of 21%**,** reflecting moderate variability across seasons. A clear seasonal pattern was observed, with higher DO levels recorded during winter (7.0 mg/L) and spring (6.4 mg/L)**,** followed by a decline in summer (5.5 mg/L) and autumn (5.4 mg/L)**.** Overall, these results demonstrate that, despite seasonal fluctuations, DO concentrations remain within acceptable ecological thresholds, ensuring sufficient oxygen availability to sustain marine life and support key biogeochemical processes in the monitored coastal environment. Pairwise comparisons were conducted to examine the relationships among temperature (°C), dissolved oxygen (DO, mg/L), and salinity (ppt). The results are presented in Table 4. For each comparison, the null hypothesis stated that the two samples being compared did not significantly differ.

Table 4. Pairwise comparison (Dunn-Bonferroni test)

	Test statistics	Standard error	Std. test statistics	p	Adj. p
Temperature (°C) - DO (mg/L)	1.0119	0.1543	6.5579	<.001	<.001
Temperature (°C) - Salinity (ppt)	-0.9762	0.1543	-6.3264	<.001	<.001
DO (mg/L) - Salinity (ppt)	-1.9881	0.1543	-12.8843	<.001	<.001

The adjusted p-values were calculated using a Bonferroni correction by multiplying the raw *p*-value by the number of pairwise tests conducted, thereby controlling for the family-wise error rate. The results show statistically significant differences among all parameter pairs after Bonferroni adjustment. Specifically, Temperature and DO differ significantly ($Z = 6.56$, $p < .001$, adjusted $p < .001$), indicating an inverse relationship consistent with the known physical effect of temperature on oxygen solubility in seawater. Temperature and salinity also showed a significant difference ($Z = -6.33$, $p < .001$), suggesting that variations in water temperature were closely associated with changes in salinity levels. The DO and salinity comparison yielded the largest standardized test statistic ($Z = -12.88$, $p < .001$), reflecting a strong and significant contrast, whereby higher salinity corresponded to lower dissolved oxygen concentrations, see Figure 6. Collectively, these results indicate that all three physicochemical parameters differ significantly from one another, confirming that temperature, DO, and salinity vary independently and exhibit distinct environmental behaviors within the monitored aquatic system.

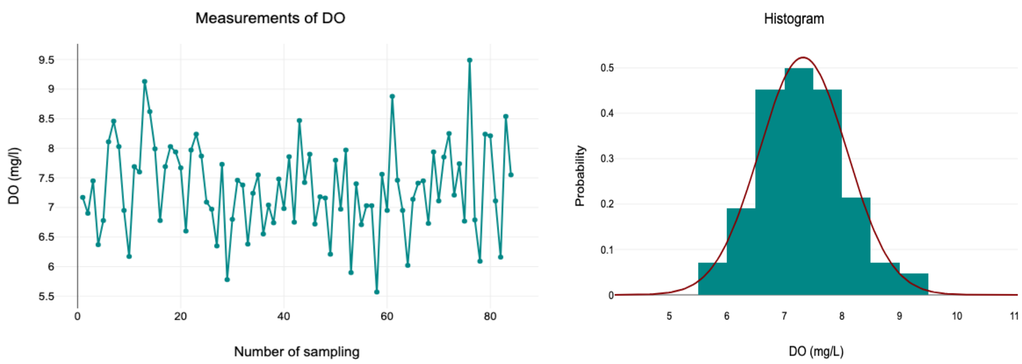

Figure 6. Dissolved oxygen (DO) variation

Turbidity

Turbidity is a key indicator of water transparency and an important parameter for assessing marine environmental quality [18]. Low turbidity levels can limit photosynthetic activity in aquatic plants by reducing light penetration [22]. In marine environments, turbidity is primarily influenced by industrial discharges, soil erosion, river runoff, phytoplankton growth, and the direct release of wastewater into coastal waters [17,25] As illustrated in Figure 7, turbidity exhibited considerable variability, with a coefficient of variation (CV) of 104%, representing the highest variability among all measured parameters. The mean turbidity across monitoring stations was 29.21 NTU, with the maximum value (129 NTU) recorded in October at the Pista Kupola station, and the minimum value (1.4 NTU) observed in July at the Old Port station. These findings align with previous research that has documented significant seasonal and spatial fluctuations in turbidity along the Adriatic coast [14]. The pronounced variability is likely associated with mesoscale eddies and hydrodynamic processes along the Albanian–Croatian coastline, which contribute to sediment resuspension and changes in water column dynamics [26].

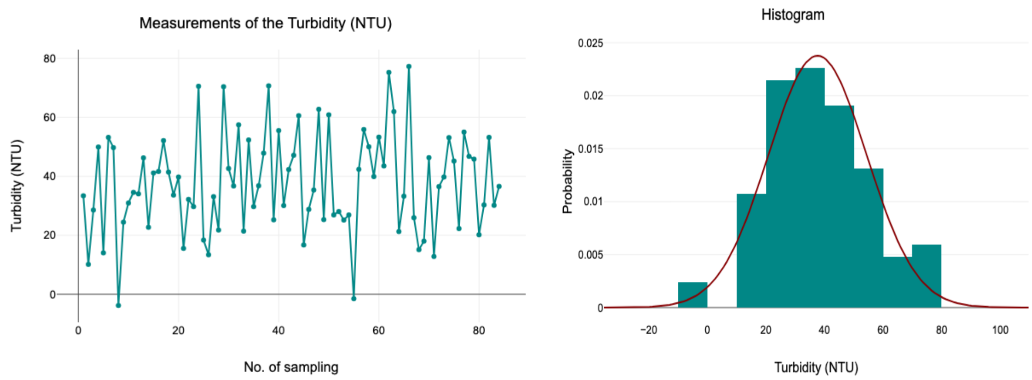

Figure 7. Turbidity variation

Salinity

Salinity represents the total concentration of dissolved salts and ions in water and contributes directly to electrical conductivity (EC). It is a major ecological factor influencing the distribution and physiology of marine species [27]. Variations in salinity, together with temperature, play an essential role in regulating biological processes such as reproduction, larval development, and species dispersal [28, 29]. Excessive or anomalous salinity levels can adversely affect the survival and growth of marine organisms [30]. As shown in Table 2 and Figure 8, salinity exhibited a coefficient of variation (CV) of 11%, reflecting relatively stable conditions across the study period. The mean salinity was 34.38 ppt. The maximum value (39.08 ppt) was recorded at the Ferrara station in December, whereas the minimum value (14.60 ppt) was observed at the Aleksandër Moisiu University station in February, representing an anomalously low value for marine waters. These unusually low readings may have resulted from episodic freshwater inputs or localized effluent discharges from nearby coastal activities. Similarly, reduced values were noted at the same station in January (20.0 ppt) and October (16.8 ppt). Despite these temporal fluctuations, all recorded salinity values remained within the typical marine range of 30.0–39.1 ppt, consistent with previously reported observations for the Adriatic and Ionian coastal zones [31]. Overall, the findings suggest that salinity levels remained ecologically stable, supporting normal marine conditions throughout the monitoring period.

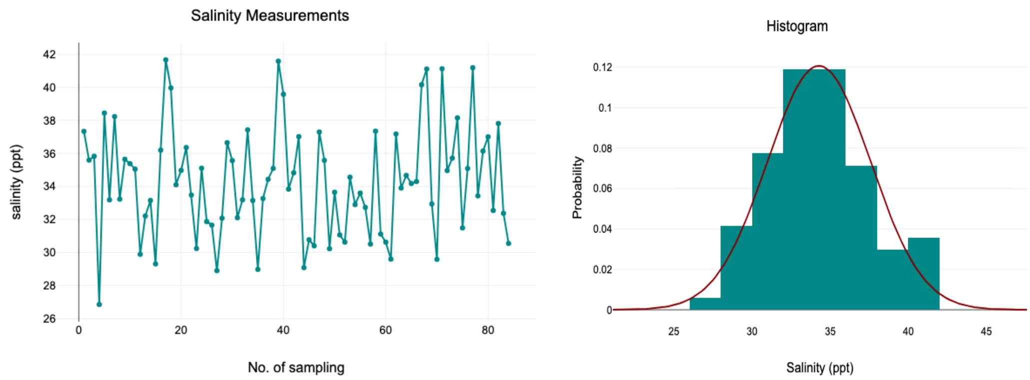

Figure 8. Variation of Salinity

Specific Gravity

Specific gravity (SSG) is an indirect measure of seawater density, which indicates that seawater is generally denser than freshwater, see Figure 9.

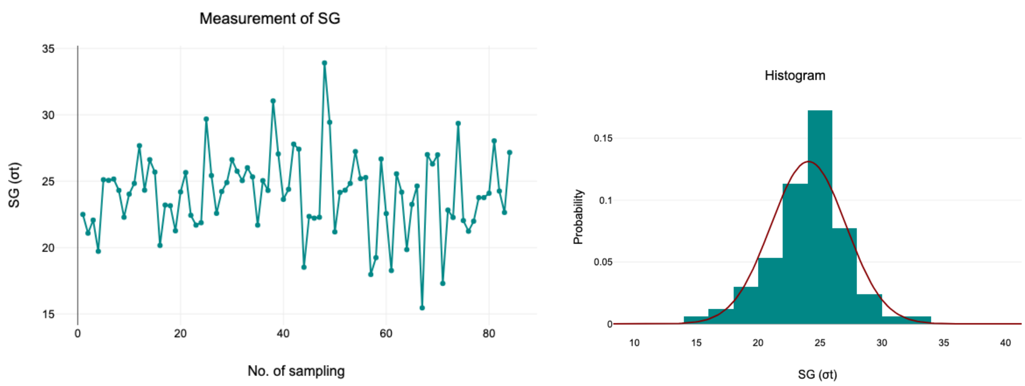

Figure 9. Variation of SSG

Different marine organisms exhibit varying tolerances to freshwater and saltwater environments, making SSG an important ecological indicator [32]. Although specific gravity depends only slightly on temperature, salinity directly influences the density of seawater [33]. In this study, seawater specific gravity was expressed as σ_t (sigma-t), automatically determined by the multiparameter sonde. The mean SSG value was 24 σ_t, with a coefficient of variation (CV) of 13%, indicating moderate variability. The highest value (29 σ_t) was recorded in December at the Ferrara *station*, while the lowest value occurred in October at the Aleksandër Moisiu University of Durrës station. Similarly reduced readings were observed at the same site in January (16.3 σ_t) and February (11.4 σ_t). Notably, these minimum values coincided with concurrent decreases in salinity and electrical conductivity during the same period and at the same location, suggesting the influence of an external freshwater input or anthropogenic discharge affecting local hydrographic conditions. Such correlations indicate that SSG variability is closely linked to fluctuations in salinity and conductivity, both of which govern seawater density and mixing dynamics in coastal zones.

Correlation and Similarity of Variables

To examine the interrelationships among the measured physicochemical parameters, Pearson's correlation coefficient (r) was employed. This coefficient ranges from −1 to +1, representing both the strength and direction of a linear relationship between two continuous variables. Values close to +1 indicate strong positive correlations, whereas values approaching −1 reflect strong negative correlations. A value near 0 suggests no linear association. Table *5* summarizes the correlation coefficients for all parameters included in this study. Strong linear correlations were observed between TDS and EC, salinity and EC, SG and EC, salinity and TDS, and SG and salinity, indicating a high degree of interdependence among these parameters. Moderate correlations were identified between ORP and temperature, SG and temperature, turbidity and EC, TDS and turbidity, salinity and turbidity, and SG and turbidity. Conversely, weak correlations were found between DO and temperature, turbidity and pH, EC and ORP, SG and ORP, and salinity and DO, suggesting that these variables vary independently within the monitored system. In addition to the correlation analysis, linear regression models were generated to further explore the relationships among the measured parameters (see Figure 10). To assess the degree of similarity between sampling stations based on their physicochemical characteristics, hierarchical cluster analysis was performed. The resulting dendrograms revealed distinct groupings that reflect both spatial and environmental similarities. With respect to temperature, the Pista Kupola and Pista Teuta stations exhibited strong similarity, while the Ferrara station was the most distinct, displaying greater deviation in thermal conditions compared with the other sites.

Table 5. Correlation coefficients between parameters

	Temp.	*pH*	*ORP*	*Cond. (EC)*	*Turbidity*	*Dissolved Oxygen*	*TDS*	*Salinity*	*Specific gravity*
Temperature	1								
pH	-0.001	1.000							
ORP	-0.399	0.088	1.000						
Conductivity	-0.064	-0.063	0.112	1.000					
Turbidity	-0.057	-0.116	0.054	-0.403	1.000				
Dissolved Oxygen	-0.234	0.017	0.030	-0.098	-0.025	1.000			
TDS	-0.049	-0.062	0.080	0.995	-0.393	-0.093	1.000		
Salinity	-0.023	-0.066	0.074	0.995	-0.395	-0.100	0.998	1.000	
Specific gravity	-0.415	-0.078	0.248	0.930	-0.332	-0.004	0.920	**0.912**	1.000

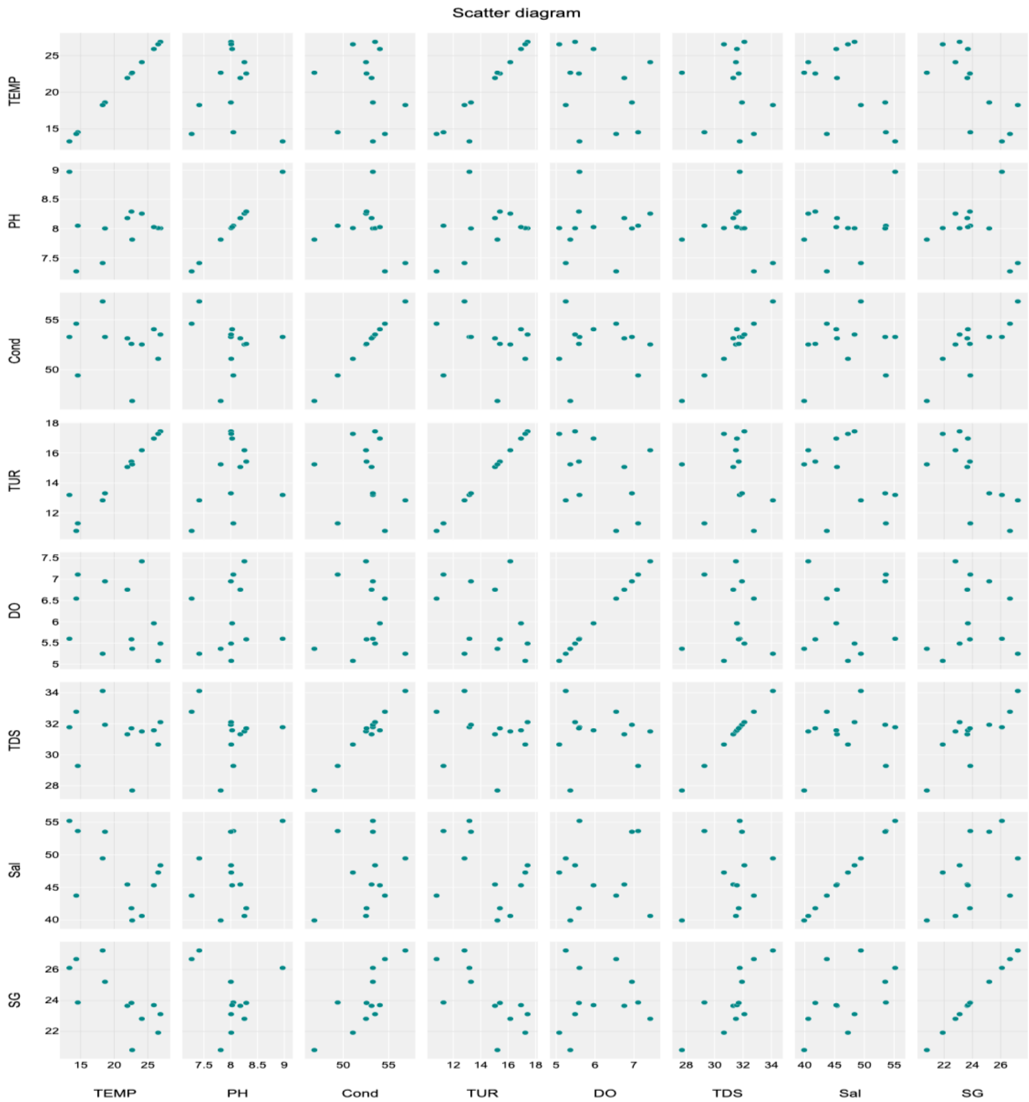

Figure 10 Scatter diagram for correlation

The results of the hierarchical cluster analysis corroborated the findings presented in Figures 1–10 and Tables 1 and 2. The clustering patterns revealed distinct groupings among the measured physicochemical parameters, see Figure 11. Specifically, three clusters were identified for temperature, electrical conductivity (EC), turbidity, and total dissolved solids (TDS). For pH, specific gravity (SG), and dissolved oxygen (DO), two clusters emerged, while oxidation-reduction potential (ORP) formed four clusters. In contrast, salinity produced a single uniform cluster, indicating consistent values across all sampling stations. Although the degree of similarity among stations varied slightly depending on the parameter considered, the overall clustering pattern was consistent with the statistical relationships observed in the correlation and regression analyses discussed above. This alignment supports the robustness of the multivariate statistical approach applied in this study.

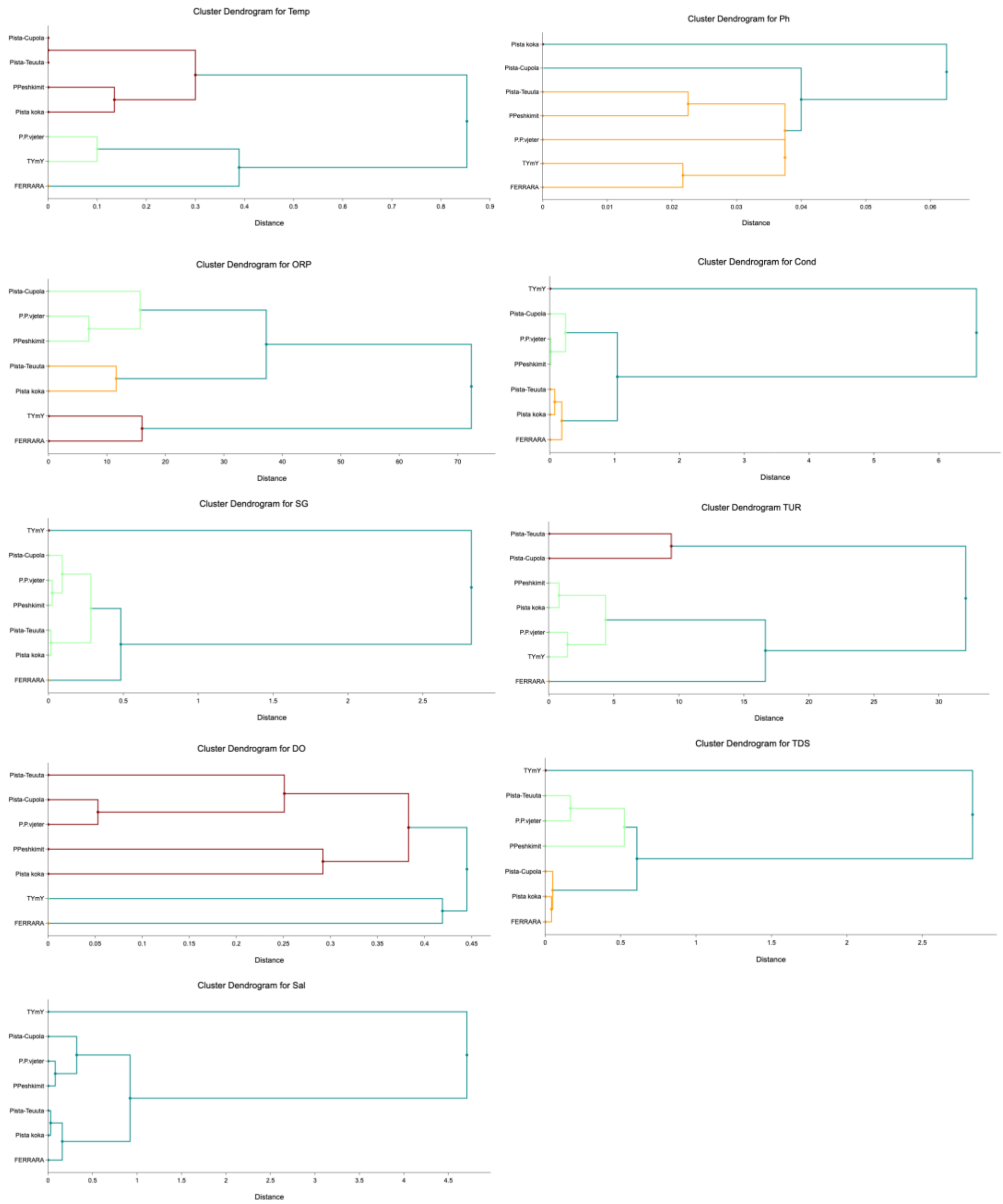

Figure 11. Hierarchical Cluster dendrograms

Calculated Water Quality Index (WQI) for the Surveyed Area of Durres Gulf

The Water Quality Index (WQI) represents an integrated quantitative tool for evaluating the overall condition of aquatic systems by combining multiple physicochemical parameters into a single value. WQI is particularly valuable for detecting spatial and temporal variations in water quality influenced by anthropogenic activities such as port operations, wastewater discharge, tourism, and riverine inflows. Even though Durres gulf is not directly affected by river flows, north of it there are two rivers that flow into the sea, Erzen and Ishem River. Both river's sediments might reach Durres gulf, depending on climate parameters (wind currents etc.).

In the context of Durrës Bay, the WQI serves as an integrative measure reflecting the combined effects of the physicochemical parameters analyzed in this study, including temperature, pH, oxidation–reduction potential (ORP), electrical conductivity (EC), turbidity, dissolved oxygen (DO), total dissolved solids (TDS), salinity, and specific gravity, see Table 6. To calculate the WQI we have used the following equation (1) [34]:

$$WQI = \frac{\sum(Q_i \times W_i)}{\sum W_i} \quad (1)$$

where:

- $Q_i = (V_i - V_{ideal})/(V_{standard} - V_{ideal}) \times 100$
- $W_i = 1/V_{standard}$

Here:

- V_i: measured mean value,
- $V_{standard}$: permissible limit (from WHO/EU/EEA guidelines for marine/coastal waters),
- V_{ideal}: ideal value for pure water or reference standard.

Table 6. Water Quality Evaluation Parameters and Quality Rating Matrix

Parameter	Mean value (Vi)	Ideal (v-ideal)	Standard (v-standard	Weight (Wi=1/Vs)	Qi (Quality rating)
pH	8.03	7.0	8.5	0.118	68,7
Do (mg/l)	7.36	14.6	5	0.200	44.0
ORP (mV)	178.9	250	0	0.004	71.7
EC (mS/cm)	52.46	0	55	0.018	95.4
TDS (g/L)	31.34	0	35	0.029	89.5
Turbidity (NTU)	37.08	0	50	0.020	74.2
Salinity (ppt)	34.38	35	39	0.026	88.2
Temperature (0°)	20.84	20	30	0.033	28.0
Specific gravity (σt)	24.0	0	30	0.033	80

$$\sum(Q_i \times W_i) = 68.7(0.118) + 44(0.200) + 71.6(0.004) + 95.4(0.018) + 89.5(0.029) + 74.2(0.020) + 88.2(0.026) + 28(0.033) + 80(0.033)$$
$$= 8.11 + 8.8 + 0.29 + 1.72 + 2.6 + 1.48 + 2.29 + 0.92 + 2.64 = 28.85$$

$$\sum W_i = 0.118 + 0.200 + 0.004 + 0.018 + 0.029 + 0.020 + 0.026 + 0.033 + 0.033 = 0.481$$

$$WQI = 28.85/0.481 = \mathbf{60.0}$$

Based on the WQI standards the result obtained above (WQI = 60.0) is moderate (0-25 = excellent, 26-50 = good; 51-77 = moderate; and 76-100 = poor). Itis considered acceptable for recreation and marine life, but requires regular monitoring. The calculated WQI values derived from the 2024 dataset indicate that the coastal waters of the Gulf of Durrës generally fall within the "good to excellent" category. This classification is consistent with the recorded parameter ranges, which remained largely within permissible limits established for marine ecosystems. The mean pH (8.03 ± 0.48) and DO (7.36 ± 0.81 mg/L) values confirm well-oxygenated and chemically balanced conditions favorable for aquatic life. Likewise, the mean salinity (34.38 ppt) and electrical conductivity (52.46 mS.cm) demonstrate stable ionic characteristics typical of Adriatic coastal waters. Moderate deviations were detected in oxidation–reduction potential and turbidity, particularly at the Pista Koka, Fishing Port, and Old Port stations during the summer months, when port operations and seasonal tourism reach their peak. These localized anomalies slightly reduced the WQI but did not shift the overall classification below acceptable thresholds. The observed variations are likely attributable to short-term anthropogenic discharges and reduced water circulation in semi-enclosed port areas. The analysis reveals a high degree of spatial consistency, supported by low coefficients of variation (CV < 15%) for most parameters, indicating stable physicochemical conditions across the Gulf. The strong intercorrelations among salinity, EC, TDS, and specific gravity further validate the reliability of the measurements and the internal coherence of the dataset. Consequently, the computed WQI reflects a robust environmental status for Durrës Bay, confirming that despite localized pressures the area maintains good ecological integrity and supports safe recreational use throughout most of the year.

Limitations

Despite providing valuable insights into the physicochemical dynamics of the Durrës Gulf, this study has several limitations. First, the temporal resolution of sampling conducted monthly may not fully capture short-term fluctuations in water quality associated with tidal cycles, storm events, or episodic discharges from port and urban areas. Second, the spatial coverage, although extending to seven representative stations across the gulf, may still be insufficient to describe finer-scale heterogeneity in physicochemical conditions. Third, the study relied exclusively on in situ physicochemical parameters, without incorporating biological or chemical indicators such as nutrient concentrations (nitrates, phosphates), chlorophyll-a, or microbial and heavy metal analyses. The absence of these indicators limits the ability to correlate physicochemical variations with trophic status, pollution sources, or ecological impacts. Fourth, the data were collected using a single multiparameter instrument Horiba "U-50". Although regularly calibrated, potential instrumental drift and sensor cross-sensitivity (especially under high turbidity or salinity conditions) could have introduced minor measurement uncertainties. Similarly, the use of single-point depth sampling (0.5–1.0 m) might not fully represent column-integrated conditions, particularly in areas influenced by freshwater inflows or thermal stratification. Fifth, the statistical analyses applied (t-tests, correlation matrices, and cluster analyses) primarily describe relationships among parameters but do not establish causality or predictive dynamics. The lack of advanced multivariate or time-series modelling (e.g., PCA, ARIMA, or machine-learning regression) constrains the study's ability to forecast seasonal or anthropogenic impacts with higher precision. Finally, the Water Quality Index (WQI) derived from physicochemical parameters offers an integrated assessment of general water quality, but it remains sensitive to the selection of reference standards and weighting factors, which can vary among international frameworks (EU, WHO, EPA). Future studies should therefore aim to combine high-frequency automated monitoring, expanded parameter suites, and integrated modelling approaches to provide a more comprehensive and predictive understanding of coastal water dynamics in the Durrës Gulf and adjacent Adriatic sub-basins.

CONCLUSION

This study demonstrates that the multiparameter instrument provided reliable and consistent measurements of seawater quality, showing broadly consistent with previous analytical study conducted in "Durrës" [14]. The present research applied a spatially extensive, monthly sampling strategy across seven coastal stations, thereby capturing horizontal gradients and anthropogenic influences throughout the gulf. Although continuous monitoring could generate a more extensive dataset, it would inherently limit observations to a single location. To achieve a comprehensive spatial assessment, measurements were conducted at seven monitoring stations across the Bay of "Durrës", each influenced by diverse environmental factors such as temperature fluctuations, sea currents, and anthropogenic and natural inputs. These influences include wastewater discharges, port activity, seasonal tourism, riverine inflows, wind dynamics, and coastal erosion. Across the monitoring stations, most measured parameters—excluding oxidation–reduction potential (ORP) exhibited minimal variability, indicating overall stability in coastal water quality. A notable deviation was observed at the Aleksandër Moisiu University Durrës station, where electrical conductivity (EC), total dissolved solids (TDS), salinity, and specific gravity (SSG) displayed lower values compared to other locations during the same sampling period. Nevertheless, all recorded parameters, including pH and dissolved oxygen (DO), remained within acceptable environmental thresholds, indicating no immediate risk to marine ecosystems or to public health for recreational users of the "Durrës" coastline during peak tourist seasons. In light of these findings and previous research, it is recommended that continuous, real-time coastal water monitoring systems be established in "Durrës". Such systems should be complemented by routine microbiological assessments, given the persistent exposure of the coastal zone to pollutants of both anthropogenic and natural origin. The integration of these monitoring efforts would support evidence-based management of coastal water quality and promote sustainable marine and tourism development in the region.

AUTHOR CONTRIBUTIONS

Conceptualization, B.M.; Methodology, B.M., and M.O.; Validation, B.M., M.O., and S.S.; Formal Analysis, S.S.; Investigation, P.S. and G.A.; Resources, B.M., and M.O.; Data Curation, M.O.; Writing – Original Draft Preparation, B.M.; Writing – Review & Editing, B.M., M.O., S.S., and P.S.; Visualization, B.M.; Supervision, M.O.

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CONFLICT OF INTERESTS

We, the authors of the present paper, hereby declare that there are no conflicts of interest related to the subject matter, materials, or methods used in this publication.

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